and monitor heart rate during intensive physical activity, respectively. Both approaches make use of PPG and accelerometer information to obtain an accurate estimation of heart rate while running on a treadmill. TROIKA has two extra stages of signal decomposition and reconstruction using singular spectrum analysis (SSA) and then applies temporal difference operations on the SSA-reconstructed PPG. SSA components are compared to the accelerometer signals and those components with close frequencies to the accelerometer signals are discarded and the rest are used to reconstruct the signal. In JOSS and TROIKA, spectral peak tracking with verification aims to select the spectral peaks corresponding to HR. JOSS, which has been shown to estimate HR more accurately than TROIKA, is based on the idea that the spectra of PPG signals and simultaneous acceleration signals have some common spectrum structures, and, thus, formulates the spectrum estimation of these signals into a joint sparse signal recovery model using the multiple measurement vector (MMV) model. MMV is used for joint spectrum estimation based on PPG and accelerometer data, which is in contrast to the single measurement vector (SMV) model that was used in TROIKA and was based on only a single PPG signal. Although JOSS has been shown to be much more accurate than previous methods for reconstruction of heart rate from MA-contaminated PPG signals, the main disadvantage of the method is it can merely provide smoothed HR reconstruction estimations. Neither time-domain PPG signal reconstruction nor heart rate variability analysis can be done using JOSS or TROIKA. Temko proposed an approach to HR estimation based on Wiener Filtering and the Phase Vocoder (WFPV) (Temko, A. Estimation of Heart Rate from Photoplethysmography during Physical Exercise using Wiener Filtering and the Phase Vocoder. in IEEE EMBS International Conference on Engineering in Medicine and Biology. 2015. Milan, Italy: IEEE). This work showed that WFPV on average can perform better than JOSS. The main idea of WFPV is to estimate motion artifacts from accelerometer signals and then use a Weiner filter to attenuate the motion components in the PPG signal. Phase vocoder is also applied to overcome the limited resolution of the Fourier transform and to refine the initial dominant frequency estimation.

[0066] According to embodiments disclosed herein, a motion-corrupted heart-related signal, such as a PPG signal, may be reconstructed by employing a method that is based on a time-varying spectral analysis. A method for reconstructing a heart-related signal based on the time-varying spectral analysis for HR estimation may be referred to interchangeably herein as a spectral approach for filtering motion artifacts (SpaMA) method or SpaMA. A

method for reconstructing the heart-related signal based on the time-varying spectral analysis for SpO2 estimation may be referred to interchangeably herein as a spectral approach for filtering motion artifacts for oxygen saturation estimation (OxiMA) method or OxiMA.

[0067] FIG. 1 is a block diagram 100 of an example application for which embodiments disclosed herein may be applied. In FIG. 1, a subject 102 is running on a treadmill 104. The subject 102 is wearing a wrist band 106 that includes a biomedical sensor 108 that produces a heart-related signal 110. The heart-related signal 110 that is produced by the biomedical sensor 108 includes motion artifacts that are signal artifacts produced by movement of the biomedical sensor 108 relative to a sensing location (not shown). The wrist band 106 may be any suitable type of wrist band, for example, the wrist band 106 may be a smart watch.

[0068] The biomedical sensor 108 may be a PPG sensor, or any other suitable biomedical sensor, and the heart-related signal 110 may be a PPG signal, or any other suitable heart-related signal. The sensing location may a skin surface of an area on the subject's wrist where the wrist band 106 is worn, or any other suitable sensing location at which the biomedical sensor 108 senses the heart-related signal 110. For example, the sensing location may be a skin surface on the subject's forehead, and a head band including the biomedical sensor 108 or maintain the biomedical sensor 108 at the sensing location may be used instead of the wrist band 106.

[0069] Physical activity of the subject 102 may cause movement of the wrist band 106, and, thus, movement of the biomedical sensor 108, resulting in a gap between the PPG sensor and the sensing location. Ambient light may leak into the gap inducing spectrum corruption in the PPG signal. This is because the power of the PPG signal is dependent on a depth and reflection of the PPG light from the PPG sensor to the subject's skin. As such, strenuous and high intensity exercise of the subject 102, such as running or any other suitable activity, may result in movement that rises to a level causing motion artifacts in the heart-related signal 110. According to embodiments disclosed herein, the heart-related signal 110 may be reconstructed 112, producing a reconstructed heart-related signal with the motion artifacts suppressed 114. The reconstructed heart-related signal with the motion artifacts suppressed 114 may be used to accurately estimate HR, SpO2, or any other suitable heart-related estimate. As such, the reconstructed heart-related signal may be employed to detect or predict a heart-related ailment. The heart-related ailment may include at least one of a heart

rate variability (HRV) condition, atrial fibrillation condition, congestive heart failure condition, and tachycardia condition.

[0070] It should be understood that the PPG sensor is one example of a biomedical sensor, the PPG signal is one example of a heart-related signal, and that any suitable type of biomedical sensor may be employed to produce any suitable type of a heart-related signal. Further, movement of the biomedical sensor 108 relative to the sensing location may be caused by any suitable source of the movement that causes movement of the biomedical sensor 108 relative to the sensing location. It should also be understood that a subject referred to herein may be any living being, such as a person or an animal, and may be referred to interchangeably herein as a user.

[0071] FIG. 2 is a flow diagram 200 of an example embodiment of a method for reconstructing a heart-related signal output by a biomedical sensor. The example embodiment of the method of FIG. 2 may be applied to either SpaMA or OxiMA and may be applied to other applications that produce a heart-related estimate. The method may start (202) and reconstruct a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal. The reconstructing may be based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of movement (204). The method may output the reconstructed representation of the heart-related signal (206), and the method thereafter ends (208) in the example embodiment.

[0072] The method may comprise segmenting the heart-related signal into a plurality of windowed heart-related signal data segments and the motion signal into a corresponding plurality of windowed motion signal data segments and repeating the reconstructing and the outputting for each windowed heart-related signal data segment and each corresponding motion signal data segment. The time window may be a value in a range from 2 to 32 seconds. For example, the *window[k]* of raw PPG data of FIG. 3A, element 304, disclosed below, and the *window[k]* of raw accelerometer data shown in FIG. 3A, element 310, disclosed below, may each include data from the respective PPG and accelerometer signals that may be collected over a time window from 2 to 32 seconds. According to one embodiment, the time window may be 8 seconds.

[0073] The method may employ the reconstructed representation to determine a heart rate estimate. The method may employ the reconstructed representation to determine an arterial oxygen saturation (SpO2) estimate. The method may employ the reconstructed representation to detect or predict a heart-related ailment. The heart-related ailment may include at least one of a heart rate variability (HRV) condition, atrial fibrillation condition, congestive heart failure condition, and tachycardia condition.

[0074] The heart-related signal and the motion signal may be produced, concurrently.

[0075] According to some embodiments, the biomedical sensor may be at least one of: a photoplethysmogram (PPG) sensor, piezoelectric sensor, Light Emitting Diode (LED) based sensor, camera sensor, and pulse oximeter sensor. The motion sensor may be an accelerometer, or any other suitable device that produces a motion signal. If an accelerometer, the accelerometer may be a 3-axial type accelerometer, or any other suitable type of accelerometer. The biomedical sensor and the motion sensor may be co-located. For example, the wrist band 106 of FIG. 1, disclosed above, may be a smartwatch and the biomedical sensor and motion sensor may be a PPG sensor and an accelerometer, respectively, that are both disposed in the smartwatch or other suitable wearable device.

[0076] FIGS. 3A-C are flow diagrams of example embodiments of a method for reconstructing a heart-related signal output by a biomedical sensor based on embodiments disclosed in Tables 1-3, disclosed below. The method may be either a SpaMA or OxiMA method.

Table 1. Stages 1 and 2

Stage 1. Time-Varying Spectral analysis (*see* FIG. 3A)

1.1. Filter the PPG and Accelerometer signal with cutoff frequency [1, 50]/Fs/2 Hz.
1.2. Down sample the PPG and Accelerometer signal to ¼ of original sampling rate (Fs).
1.3. Compute the time frequency spectrum of both PPG and Accelerometers [0-10 Hz].

Stage 2. Movement Classification (*see* FIG. 3A)

2.1. Check each accelerometer (X, Y or Z) amplitude modulation at each window and compare to a pre-defined motion amplitude threshold. (The threshold varies depending on the type of accelerometer sensor).

Signal is clean if $AM[Acc_{x\ or\ y\ or\ z}(k)] < Motion\_Threshold$ and the signal is corrupted by motion otherwise. If the signal is clean calculate the Heart Rate from peak-to-peak intervals, otherwise go to step 2.2.

2.2. If the signal is corrupted check if the movement is pseudo-periodic (e.g. during walk, jog,

run) or non-periodic (e.g. any random movements)

The assumption is when movement is pseudo-periodic the accelerometer data should comprised of a fundamental frequency component and harmonics of the fundamental frequency at its double and third frequency band. This means the ratio of the first harmonic to the fundamental frequency should be almost 2 and the second harmonic to the fundamental should be around 3.

2.2.1. Extract the fundamental frequency component, the 1st and 2nd harmonics from (*e.g.*,VFCDM) time-frequency spectrum of accelerometers. The first three highest peaks in spectral array should represent the fundamental, 1st and 2nd harmonics as long as the movement is pseudo-periodic.

2.2.2. Calculate the ratio of the extracted 1st and 2nd fundamental frequency to the extracted fundamental frequency. If the ratios are close to 2 and 3, this indicates that the movement is most likely pseudo-periodic otherwise it is non-periodic.

2.2.3. If the movement is pseudo-periodic do the Stages 3-5 (*See* Table 2 and FIG. 3B), otherwise go to Stage 6 (*See* Table 3 and FIG. 3C).

Table 2. Stages 3-5

Stage 3. Spectral Filtering (*see* FIG. 3B)

3.1. Assume HR to be in the frequency range of [0.5Hz – 3Hz], this accounts for both low and high heart rates.
3.2. The first highest three peaks and their corresponding frequencies in the PPG filtered spectrum are assumed to have HR information.
3.3. Only the largest frequency peak (that represents the fundamental frequency of movement) of the accelerometers' spectra is used for motion artifact detection in Stage 4.

Stage 4. Motion Artifact Detection (*see* FIG. 3B)

4.1. Compare the frequencies of the three peaks in the PPG spectrum with the frequency of the largest peak in the accelerometers' spectra. If the first or second largest peaks in the PPG spectrum are similar to that of the accelerometers' peaks, then motion artifact is present in the PPG.
4.2. If motion artifact is detected from 3.1, then the corresponding frequency peak (usually the first or second largest peak) in the PPG spectrum should be discarded.

Stage 5. Heart Rate Tracking and Extraction from PPG Spectrum (*see* FIG. 3B)

Case (1): From 3.1- if the spectrum is corrupted by movement and only the first largest peak is corrupted, then the HR frequency should be the frequency of the second peak in the spectrum.
Case (2): From 3.1- if the spectrum is corrupted by movement and both the first and second largest peaks have similar frequencies to those of the accelerometers' peaks, then the HR

frequency should be the frequency of the third peak in the spectrum.
Case (3): Due to a gap between the pulse oximeter and a subject's skin, the HR frequency cannot be extracted from the spectrum and in this case the previous HR frequency is used or for offline implementation a cubic spline interpolation can be applied to fill in the missing HR information.

Table 3. Stage 6

Stage 6. Adaptive Bandpass Filtering (non-periodic movements) (*see* FIG. 3C)

When the movement is random and non-periodic it is difficult or not possible to identify HR trace from time-frequency spectrum (for example if stage 5 is not applicable). In this case which may happen more often, a new procedure is adopted that is called adaptive bandpass filtering. The assumption here is that HR does not deviate more than 10 bpm from the average of previous m HR values within 2 seconds.

6.1. Set averaging window length to m (e.g. m=5) and calculate the average of recent m estimated HR values.

$$HR_{mavg} = \frac{1}{m}\sum_{j=1}^{m} HR(k-j)$$

Where k is the current window. The window length m=5 should only be used for up to 10 seconds of consecutive motion artifact corrupted datapoints. If motion corrupted data last more than 10 seconds, m should be increased to more than 5.

6.2. Take the most recent estimated HR value and calculate bandpass filter cutoff frequency.

$$F_{CutOff} = [HR_{mavg} - 10, HR_{mavg} + 10\,]/60/Fs/2$$

Design a bandpass filter of order 4 with cutoff frequency (F_{CutOff}). Apply the filter on the PPG segment.
6.3. Calculate HR from peak-to-peak intervals of the filtered data segment obtained from 6.2. Take the average of the instantaneous HR as estimated HR value at window k.

[0077] FIG. 3A is a flow diagram (300) of an example embodiment of a method for a time-varying spectral analysis and movement classification, as disclosed in Stage 1 (time-varying spectral analysis) and Stage 2 (movement classification), respectively, in Table 1, for reconstructing the representation. The method may start (302) and the time-varying spectral analysis may be employed on a first windowed segment *window[k]* of raw PPG data (304) and a second windowed segment *window [k]* of raw accelerometer (ACC) data (310). The raw PPG data (304) and the raw ACC data (310) may be extracted from a heart-related signal that is a PPG signal and a motion signal that is an accelerometer signal, respectively.

[0078] As disclosed in Stage 1 of Table 1, the time-varying spectral analysis of FIG. 3A may include pre-processing the heart-related signal (306) to produce a pre-processed heart-related signal. The pre-processing (306) may include filtering the heart-related signal to produce a filtered heart-related signal. The pre-processing (306) may further include down-sampling the filtered heart-related signal, the down-sampling being at a sampling rate less than an original sampling rate, to produce a down-sampled, filtered heart-rate signal. The time-varying spectral analysis may further include pre-processing the motion signal (312) to produce a pre-processed motion signal. The pre-processing (312) may include filtering the motion signal to produce a filtered motion signal. The pre-processing (312) may further include down-sampling the filtered motion signal to produce a down-sampled, filtered motion signal, the down-sampling being at a sampling rate less than an original sampling rate.

[0079] As further disclosed in Stage 1 of Table 1, the time-varying spectral analysis of FIG. 3A may include computing a first time-frequency spectrum (TFS) to produce a first TFS (308) of the down-sampled, filtered heart-related signal and computing a second TFS to produce a second TFS (314) of the down-sampled, filtered motion signal. According to some embodiments, filtering and down-sampling of the heart-related signal and motion signal for computing the first TFS (308) and the second TFS (314), respectively, may be optional. The first TFS (308) (also referred to interchangeably herein as the first TFS computed) and the second TFS (314) (also referred to interchangeably herein as the second TFS computed) may be 3-dimensional spectra, the first TFS computed and the second TFS computed each including a respective time-varying amplitude or power distribution with respect to time and frequency.

[0080] For example, the first TFS computed may be a first time-varying power spectral density (PSD) and the second TFS computed may be a second time-varying PSD. A time-frequency technique, such as a variable frequency complex demodulation (VFCDM), disclosed in U.S. Patent No. 8,388,543 B2, incorporated herein in its entirety by reference, may be used for computing the first TFS (308), that is, a TFS of the PPG signal, and the second TFS (314), that is, a TFS of the accelerometer signal. However, it should be understood that any suitable time-frequency technique may be used, such as a smoothed pseudo wigner-ville method, or a wavelet based method.

[0081] As disclosed in Stage 2 of Table 1, classifying the classification of the movement (316) in FIG. 3A may include comparing an amount of amplitude modulation in the second

TFS (314) computed to an amplitude modulation threshold. The amplitude modulation threshold may be dependent on a type of the motion detector sensor, such as a type of the accelerometer. The classification of the movement may indicate whether the movement rises to a level causing motion artifacts in the heart-related signal, that is, the PPG signal, based on a result of the comparing, as disclosed in Stage 2 of Table 1.

[0082] In an event the movement classification (316) of FIG. 3A indicates that the movement does not rise to a level causing the motion artifacts (322), a peak-peak interval (PP) of the filtered heart-related signal, or alternatively, the filtered, down-sampled heart-rate signal, may be computed (318) and the reconstructed representation *HR(k)* may be based on an average value of peak-to-peak intervals (320) in the pre-processed heart-related signal, and the method thereafter ends (325) in the example embodiment.

[0083] In an event the movement classification (316) indicates that the movement does rise to the level causing the motion artifacts (323), classifying the classification of the movement may further include determining (324) whether the movement is either a pseudo-periodic movement or a periodic movement, versus a random movement, as disclosed in Stage 2 of Table 1.

[0084] With reference to Stage 2 of Table 1, in determining whether the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement, the method may further include identifying a first, second, and third frequency associated, respectively, with a first, second, and third spectral peak in the second TFS at a point in time in the second TFS. The first, second, and third peaks may have largest power or amplitude values relative to other peaks in the second TFS at the point in time. The first spectral peak may be a largest spectral peak amongst the first, second, and third spectral peaks.

[0085] In determining whether the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement, the method may compute a first ratio of the second frequency identified to the first frequency identified. The method may determine a first comparison result by comparing the first ratio computed to a first ratio value. The method may compute a second ratio of the third frequency identified to the first frequency identified and determine a second comparison result by comparing the second ratio computed to a second ratio value. The classification may further indicate the movement is either the pseudo-periodic movement or the periodic movement, versus the random

movement, based on the first comparison result and the second comparison result. The first ratio value may be 2 and the second ratio value may be 3. The classification of the movement may be periodic if the first ratio and the second ratio are exactly 2 and 3, respectively, while the classification of the movement may be pseudo-periodic if the first ratio and the second ratio are approximately 2 and 3, respectively, within a pre-determined level of accuracy.

[0086] In an event the classification of the movement is periodic or pseudo-periodic, the method of FIG. 3A may continue with the method of FIG. 3B, disclosed below. In an event the classification of the movement is random, the method of FIG. 3A continues to the method of FIG. 3C, disclosed below.

[0087] FIG. 3B is a flow diagram (330) of an example embodiment of a method for spectral filtering, motion artifact detection, and heart rate tracking and extraction, as disclosed in Stages 3, 4, and 5, respectively, of Table 2, for reconstructing the representation. The reconstructed representation may be referred to herein as a current reconstructed representation or *HR(k)*. As disclosed above with regard to FIG. 3A, in an event the classification of the movement (316) is periodic or pseudo-periodic, the method of FIG. 3A may continue with the method of FIG. 3B.

[0088] The method of FIG. 3B may start (331) and retain (332) up to a pre-determined number N of candidate spectral peaks located at a first point in time in the first TFS, that is, the first TFS from FIG. 3A. It should be understood that the method of FIG. 3B may be performed for each point in time of the first TFS and the second TFS. According to one embodiment, the pre-determined number N may be 3. The candidate spectral peaks retained may be based on having corresponding frequencies within a given frequency range. The candidate spectral peaks may be N peaks in the given frequency range that have highest amplitude or power values relative to other spectral peaks, that is, the first N highest peaks. It should be understood that the other spectral peaks have respective frequencies also within the given frequency range and are peaks located at the first point in time in the first TFS. The given frequency range may be 0.5 Hz to 3 Hz. As such, the N first highest peak in the range 0.5 Hz to 3 Hz in the first TFS may be retained at the first time point. Since no peaks in the given frequency range may be present at the first time point, the method may determine (336) whether at least one spectral peak is present.

[0089] Based on the determination (336) that no peak is present, the current reconstructed representation *HR(k)* may be based on a prior reconstructed representation *HR(k-1)* (340), the prior reconstructed representation *HR(k-1)* associated with a previous point in time, such as the previous window *k-1*, in the first TFS computed, and the method thereafter ends (354) in the example embodiment.

[0090] Based on a determination (336) that the at least one spectral peak is present, the method may discard (338) each of the candidate spectral peaks retained, that is, each peak of the *N* first highest peaks determined at (332), if the peak is associated with a same frequency as a dominant spectral peak located at a second point in time in the second TFS (314) computed as disclosed above with regard to FIG. 3A. The first point in time and the second point time may have same time values. The dominant spectral peak may have a largest power or amplitude value relative to other peaks located at the second point in time in the second TFS. The method may determine (342) whether any peaks are retained after the discarding (338). The discarding (338) may be referred to herein as a first discarding.

[0091] In an event the discarding (338) discards each of the candidate spectral peaks retained, reconstructing the current representation *HR(k)* may be based on the prior reconstructed representation, *HR(k-1)* (340), and the method thereafter ends (354) in the example embodiment.

[0092] In an event the first discarding (338) results in at least one remaining candidate spectral peak retained, reconstructing the current representation may further include second discarding (348). The second discarding (348) may discard remaining candidate spectral peaks, of the at least one remaining candidate spectral peak retained, based on whether a corresponding frequency of the at least one remaining candidate spectral peak retained is distanced (346) by at least a frequency difference threshold, such as 10bpm, from a prior reconstructed representation's frequency, that is, a frequency associated with, for example, *HR(k-1)*.

[0093] Based on each at least one remaining candidate spectral peak retained having been discarded by the second discarding (348), reconstructing the current representation may be based on the prior reconstructed representation *HR(k-1)* (350), and the method thereafter ends (354) in the example embodiment.

[0094] Based on at least one last candidate spectral peak remaining from the second discarding (348), reconstructing the current representation may be based on a selected

candidate spectral peak (352). The selected candidate spectral peak may be selected from amongst the at least one last candidate spectral peak remaining having a closest corresponding frequency to the prior reconstructed representation's frequency relative to respective frequencies of each of the at least one last candidate spectral peak remaining, and the method thereafter ends (354) in the example embodiment.

[0095] As disclosed above with regard to FIG. 3A, in an event the classification of the movement (316) is random, the method of FIG. 3A may continue with the method of FIG. 3C.

[0096] FIG. 3C is a flow diagram (330) of an example embodiment of a method for adaptive bandpass filtering of non-periodic movements, that is, random movements, for reconstructing the representation, as disclosed in Stage 6 of Table 3. The method of FIG. 3C may start (362) and compute an average value of a number m of prior reconstructed representations outputted prior to the reconstructing (362). The number m may be based on a duration of consecutive motion artifacts, detected prior to the reconstructing of the representation $HR(k)$. For example, if motion artifacts were detected for windows $k-1$, $k-2$, and $k-3$, m may be understood to be 3.

[0097] The method may compute a bandpass filter cutoff frequency (366). The cutoff frequency F_c may be based on the average value computed HR_{mavg}. The method may filter the pre-processed heart-rate signal (306), disclosed in FIG. 3A, above, by applying the band pass filter computed (368) to produce a filtered, pre-processed heart-related signal. The reconstructed representation $HR(k)$ may be based on an average peak-to-peak interval value (372) of the filtered, pre-processed heart-rate signal, and the method thereafter ends (374) in the example embodiment.

[0098] FIG. 4 is a block diagram of an example embodiment of a system (400). The system includes an apparatus 420 for reconstructing a heart-related signal 410c output by a biomedical sensor (not shown). The apparatus 420 includes a reconstruction unit 416 and an output unit 418. The reconstruction unit 416 may be configured to produce a reconstructed representation of the heart-related signal 414c. The reconstructing may be based on (i) a time-varying spectral analysis of the heart-related signal 410c and a motion signal 411c, the motion signal 411c output by a motion sensor (not shown) and representative of motion artifacts in the heart-related signal 410c, the motion artifacts being signal artifacts produced by movement of the biomedical sensor (not shown) relative to a sensing location (not shown),

and (ii) a classification of the movement. The output unit 418 may be configured to output the reconstructed representation of heart-related signal 414c.

[0099] The apparatus 420 may be communicatively coupled to a network 401 to receive the heart related signal 410c and the motion signal 411c. The network may be a wireless network or any other suitable network. The reconstructing and the outputting may be performed in near real-time with respect to production of the heart-related signal 410c and the motion signal 411c. Alternatively, the apparatus may be coupled to a database (not shown) storing representations of the heart related signal 410c and the motion signal 411c, and the reconstructing and the outputting may be performed in non-real-time with respect to production of the heart-related signal 410c and the motion signal 414c.

[00100] The heart-related signal 410c may include raw heart-related signal data that includes the raw heart-related signal data 410a and the raw heart-related signal data 410b produced by biometric sensors (not shown) that sense the heart-related signal data 410a and the raw heart-related signal data 410b from sensing locations (not shown) on a first user 406a and a second user 406b, respectively. The motion signal 411c may include raw motion signal data that includes the raw motion signal data 411a and the raw motion signal data 411b from motion sensors (not shown). The raw motion signal data 411a and the raw motion signal data 411b may represent motion artifacts in the heart-related signal data 410a and the raw heart-related signal data 410b, respectively.

[00101] It should be understood that the raw heart-related signal data 410a-b and the raw motion signal data 411a-b may be sent to the apparatus 420 in any suitable way. For example, the raw heart-related signal data 410a and the raw motion signal data 411a may be sent in a payload of a packet; alternatively the raw heart-related signal data 410a and the raw motion signal data 411a may be sent in payloads of different packets. Similarly, the raw heart-related signal data 410b and the raw motion signal data 411b may be sent in a payload of a packet; alternatively, the raw heart-related signal data 410b and the raw motion signal data 411b may be sent in payloads of different packets.

[00102] The user 406a may be at a gym where the user 406a is exercising, and such physical activity by the user 406a may cause motion artifacts in the raw heart-related signal data 410a. The user 406b may be in a different location, such as a hospital. The user 406b may perform movements out of boredom, such wrist shaking, causing motion artifacts in the raw heart-related signal data 410b. As such, the corresponding motion artifacts may be

suppressed in the reconstructed representations 414a and 414b of the heart-related signals 414a and 414b, respectively, according to embodiments disclosed herein. The reconstructed representations 414a and 414b, or information derived therefrom, may sent to biometric devices or other devices communicatively coupled to the network 401 the user 406a and 406 may have access to such device, respectively. Alternatively, the reconstructed representations 414a and 414b, or information derived therefrom, may sent in any suitable manner to another device communicatively coupled to the network 401 such that the reconstructed representations 414a and 414b, or information derived therefrom, may be accessible to a third party, such as doctor, or any other suitable party.

[00103] FIG. 5 is a block diagram 500 of an example embodiment of an apparatus (520) for reconstructing a heart-related signal 510 output by a biomedical sensor 508. The apparatus 520 includes a reconstruction unit 516 and an output unit 518. The reconstruction unit 516 may be configured to produce a reconstructed representation of the heart-related signal 514. The reconstructing based on (i) a time-varying spectral analysis of the heart-related signal 510 and a motion signal 511, the motion signal 511 output by a motion sensor 509 and representative of motion artifacts in the heart-related signal 510. The motion artifacts may be signal artifacts produced by movement of the biomedical sensor 508 relative to a sensing location (not shown), and (ii) a classification of the movement.

[00104] The output unit 518 may be configured to output the reconstructed representation of the heart-related signal 514. The apparatus 520 may include the biomedical sensor 508 and the motion sensor 509. The reconstructing and the outputting may be performed in real-time with respect to production of the heart-related signal 510 and the motion signal 511.

[00105] The apparatus 520 may be a wearable device, such as a smartwatch, or any other suitable device, such as a wearable personal biometric monitoring device. The apparatus 520 may have a user interface (not shown) to present the reconstructed representation of the heart-related signal 514 or information derived therefrom, such as a characteristic, notification, alarm, or any other suitable information. The reconstructed representation of heart-related signal 514 or the information derived therefrom may be presented to a user via a user interface that may be a visual or audio based user interface.

[00106] According to one embodiment, the apparatus 520 may include a heart rate unit (not shown) configured to employ the reconstructed representation of the heart-related signal 514 to determine a heart rate estimate. According to another embodiment, the apparatus 520

may include an arterial oxygen saturation (SpO2) unit (not shown) configured to employ the reconstructed representation of the heart-related signal 514 to determine a SpO2 estimate. According to yet another embodiment, the apparatus may include an ailment unit (not shown) configured to employ the reconstructed representation of the heart-related signal 514 to detect or predict a heart-related ailment, the heart-related ailment including at least one of a heart rate variability (HRV) condition, an atrial fibrillation condition, a congestive heart failure condition, and a tachycardia condition. It should be understand that any combination of the heart rate unit, SpO2 unit, and ailment unit may be included in the apparatus 520 in combination with any other units disclosed herein.

[00107] SpaMA Results

[00108] According to embodiments disclosed herein, HR reconstruction and PPG signal reconstruction may be based on a time-varying spectral analysis. As disclosed above with reference to FIGS. 3A-F, embodiments disclosed herein may be based on power spectral densities (PSDs) of both PPG and accelerometer signals for each time shift of a corresponding windowed data segment of the respective signal. According to embodiments disclosed herein, by comparing time-varying spectra of the PPG and accelerometer data, those frequency peaks resulting from motion artifacts may be suppressed from the PPG spectrum.

[00109] According to some embodiments, the method may be comprised of six stages, such as the six stages disclosed above in reference to FIGS. 3A-F. According to another embodiment the method may have five distinct stages: (1) time-varying power spectral density (PSD) calculation, (2) spectral filtering, (3) motion artifact detection, (4) HR reconstruction and (5) signal reconstruction. According to embodiments disclosed herein, the method may include computing a window-segmented power spectral density of both PPG and accelerometer signals in real-time to scale each estimate of the PSD by the equivalent noise bandwidth of the window (Stoica, P. and R.L. Moses, Introduction to Spectral Analysis. 1997: Prentice Hall).

[00110] The simplest way to approach the PSD calculation may be to employ a periodogram. However, a periodogram has drawbacks in that it is an inconsistent spectrum estimator, has high variance, and has leakage effects (Stoica, P. and R.L. Moses, Introduction to Spectral Analysis. 1997: Prentice Hall). Thus, a dominant spectral peak can lead to an estimated spectrum that contains power in frequency bands where there should be no power.

However, both problems can be solved by down-sampling the raw signal, as disclosed above with reference to FIGS. 3A-F, and then using a sufficiently small frequency step by setting a large number of frequency points. Thus, embodiments disclosed herein may resample the signal from the original sampling frequency to, for example 1/4 of it, that is, down-sample the signal, and then apply a periodogram method with frequency resolution of 0.001.

[00111] Embodiments disclosed herein may limit the spectrum to the heart rate frequency range of [0.5Hz – 3 Hz], as disclosed above with reference to FIGS. 3A-F, and take the frequency and power information of the first three peaks in the PSD at each window and signal segment. Embodiments disclosed herein may be based on an understanding that the heart rate component in a typical clean (motion free) PPG signal is always the dominant frequency component in the time-varying power spectrum, thus, the highest peak of the spectrum corresponds to the HR frequency. Thus, when movement happens the dominant component can be replaced by movement components which shift the HR to the second or third peak in the spectrum. As such, embodiments disclosed herein may compare the first N peaks, such as 3 peaks, disclosed above, and corresponding frequencies of the PPG spectrum to the first peak and frequency of the accelerometers' spectra at each window and choose the frequency components (out of three) that are different from the accelerometers' frequency.

[00112] Embodiments disclosed herein may be further based on an understanding that there is coherence between a spectral peak in the PPG and the accelerometers' spectra that signifies a motion noise artifact in the PPG signal and that peak should be discarded in the HR reconstruction. After discarding these movement peaks in the spectrum, the next highest peak that is closest to the estimated HR of the previous window may be chosen at each window. By reconstructing the HR frequency at each window, simultaneously, the PPG signal may be reconstructed by using the power, frequency and phase of the signal that corresponds to the HR frequency. That is, the time-domain signals may be reconstructed from the time-frequency domain.

[00113] The SpaMA method was applied to three different datasets and 4 types of activities. The three different datasets included: 1) training datasets from the 2015 IEEE Signal Processing Cup Database recorded from 12 subjects while performing treadmill exercise from 1 km/h to 15 km/h; 2) test datasets from the 2015 IEEE Signal Processing Cup Database recorded from 11 subjects while performing forearm and upper arm exercise; and 3) Chon Lab dataset including 10 min recordings from 10 subjects during treadmill exercise.

[00114] Electrocardiogram (ECG) signals from all three datasets provided the reference HRs which were used to determine the accuracy of the SpaMA method. The performance of the SpaMA method was calculated by computing the mean absolute error between the estimated HR from the PPG and the reference HR from the ECG. The average estimation errors using the SpaMA method on the first, second and third datasets are 0.89, 1.93 and 1.38 beats/min respectively, while the overall error on all 33 subjects is 1.86 beats/min and the performance on only treadmill experiment datasets (22 subjects) is 1.11 beats/min. Moreover, it was found that dynamics of heart rate variability (HRV) can be accurately captured using the SpaMA method where the mean Pearson's correlation coefficient was found to be 0.98 between the power spectral densities of the reference and the reconstructed heart rate time series. These results show that the SpaMA method has a potential for PPG-based HR monitoring in wearable devices for fitness tracking and health monitoring during intense physical activities.

[00115] Embodiments disclosed herein not only provide PPG signal and HR reconstruction but also the potential to do heart rate variability analysis on the results. As disclosed below, embodiments disclosed herein can outperform the JOSS technique in heart rate estimation by providing less error to the reference, which yields higher accuracy.

[00116] Embodiments disclosed herein were evaluated on three different datasets. The first two datasets were provided for the IEEE Signal Processing Cup and are publically available. The three datasets are: 1.) 12 PPG training datasets (running on treadmill) from an IEEE signal processing competition (Available from: http://www.signalprocessingsociety.org/spcup2015/index.html) which was initially used in (Zhilin, Z., P. Zhouyue, and L. Benyuan, TROIKA: A General Framework for Heart Rate Monitoring Using Wrist-Type Photoplethysmographic Signals During Intensive Physical Exercise. Biomedical Engineering, IEEE Transactions on, 2015. 62(2): p. 522-531; Zhang, Z., Photoplethysmography-Based Heart Rate Monitoring in Physical Activities via Joint Sparse Spectrum Reconstruction. Biomedical Engineering, IEEE Transactions on, 2015. PP(99): p. 1-1, 2.) 11 PPG test datasets (e.g., arm exercise) from the IEEE signal processing competition and 3.) 10 PPG recordings from the Chon lab (running on treadmill).

[00117] (1) IEEE Signal Processing Competition Training Dataset: A single-channel PPG signal, a three-axis acceleration signal, and an ECG signal simultaneously recorded from 12 Asian male subjects ranging in age from 18 to 35. For each subject, the PPG signal was

recorded from their wrist using a pulse oximeter (PO) with green LED (wavelength: 609 nm). The acceleration signal was also recorded from each subject's wrist using a three-axis accelerometer. Both the PO and the accelerometer were embedded in a wristband, which was comfortably worn. The ECG signal was recorded from the chest and it is used as the reference heart rate. All signals were sampled at 125 Hz.

[00118] (2) IEEE Signal Processing Competition Test Dataset: The dataset consists of 11 five minute recordings which were collected from 19 to 58 year old subjects performing intensive arm movements (e.g. boxing). For each subject, PPG signals were recorded with a sensing location at the wrist using a pulse oximeter with green LEDs (wavelength: 515nm). The acceleration signal was also recorded from at the sensing location at the wrist using a three-axis accelerometer. Both the PO and the accelerometer were embedded in a wristband. An ECG signal was recorded simultaneously from each subject's chest using wet ECG sensors. All signals were sampled at 125 Hz and sent to a nearby computer via Bluetooth.

[00119] (3) Chon Lab Dataset: This dataset was recorded in the Chon Lab from 10 healthy subjects (9 male/1 female), with ages ranging from 26 to 55. For each subject, the PPG signal was recorded from their forehead using a PO with red and infrared LED (wavelength: 660 and 940 nm). The acceleration signal was also recorded from each subject's forehead using a three-axis accelerometer. Both the pulse oximeter and the accelerometer were embedded in a headband and the signals were sampled at 80 Hz. The ECG signal was recorded as a reference from the chest using ECG sensors, sampled at 400Hz. During data recording, the subjects walked, jogged and ran on a treadmill with speeds of 3, 5 and 7 mph, respectively, for 9 min. At the end, all experimental subjects were asked to perform random arbitrary movements for 1 min.

[00120] For all three datasets, the data was down-sampled to 20 Hz since the estimation of heart rate is carried out in the frequency domain and this sampling rate is sufficiently high to obtain even heart rates that are as high as 240 beats/min or 4 Hz. Moreover, this down-sampling enables a focus on heart rates in the lower frequencies rather than in the physiologically irrelevant higher frequency ranges. Further details of this study's databases are given in Table 4, below. Four types of activities were involved:

- Type (1): activity involved walking or running on a treadmill for intervals of 0.5 min-1 min-1 min-1 min-1 min-0.5 min with speeds of 1-2 km/h, 6-8 km/h, 12-15 km/h, 6-

8 km/h, 12-15 km/h, 1-2 km/h, respectively. The subjects were asked to purposely move the hand with the wristband to generate motion artifacts.

- Type (2): activity included various forearm and upper arm exercise which are common arm motions (*e.g.*, shaking hands, stretching, pushing objects, running, jumping, and push-ups).
- Type (3): activity consisted of intensive forearm and upper arm movements (*e.g.*, boxing).
- Type (4): activity involved 1 min rest, 1 min walking (3 mph), 1 min rest, 2 min jogging (5 mph), 1 min rest, 2 min running (7 mph), 1 min rest, 1 min arbitrary movement. The ECG-based reference HR was recorded in order to assess the performance of the methods under test.

[00121] In summary, the first dataset includes only Type (1) activities, the second dataset includes both Type (1) and (2) activities, and the third dataset includes only Type (4) activities.

Table 4. PPG Datasets and Experiments Settings

Subject	Dataset	Activity Type	Pulse Oximeter Type	Subject's Age/Sex
1	1 (IEEE Cup)	Type (1)	Wrist: green LED (wavelength: 609nm)	18-38 y (All Male)
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13	2 (IEEE Cup)	Type (2)	Wrist: green LED (wavelength: 515nm)	19-58 y (9 Male, 1 Female)
14				
15				
16		Type (3)		
17				
18				
19				
20		Type (2)		
21		Type (3)		
22				
23		Type (2)		
24	3 (Chon Lab)	Type (4)	Forehead: Red and Infrared LED (wavelength: 660 nm, 940nm)	26-55 y (9 Male, 1 Female)
25				
26				
27				
28				
29				
30				
31				
32				
33				

[00122] An example embodiment for reconstructing a heart-related signal during intensive movements is disclose by the HR monitoring method presented below in Table 5. Details of each stage are described in subsections *i* to *v*.

Table 5. HR and PPG signal reconstruction method

Stage 1. Time-Varying Spectral analysis

1.1. Down sample the PPG and Accelerometer signal to 20 Hz.
1.2. Compute the power spectral density of both PPG and Accelerometers [0-10 Hz].

Stage 2. Spectral Filtering

2.1. Assume HR to be in the frequency range of [0.5Hz – 3Hz], this accounts for both low and high heart rates.
2.2. The first highest three peaks and their corresponding frequencies in the PPG filtered spectrum are assumed to have HR information.
2.3. Only the largest frequency peak of the accelerometers' spectra is used for MA detection in stage 3.

Stage 3. Motion Artifact Detection

3.1. Compare the frequencies of the three peaks in the PPG spectrum with the frequency of the largest peak in the accelerometers' spectra. If the first or second largest peaks in the PPG spectrum are similar to that of the accelerometers' peaks, then motion artifact is present in the PPG.
3.2. If motion artifact is detected from 3.1, then the corresponding frequency peak (usually the first or second largest peak) in the PPG spectrum should be discarded.

Stage 4. Heart Rate Tracking and Extraction from PPG Spectrum

Case (1): From 3.1- if the spectrum is corrupted by movement and only the first largest peak is corrupted, then the HR frequency should be the frequency of the second peak in the spectrum.
Case (2): From 3.1- if the spectrum is corrupted by movement and both the first and second largest peaks have similar frequencies to those of the accelerometers' peaks, then the HR frequency should be the frequency of the third peak in the spectrum.
Case (3): Due to a gap between the pulse oximeter and a subject's skin, the HR frequency cannot be extracted from the spectrum and in this case the previous HR frequency is used or for offline implementation a cubic spline interpolation can be applied to fill in the missing HR information.

Stage 5. PPG Signal Reconstruction

5.1. The PPG signal is reconstructed by using the amplitude, frequency and phase information corresponding to the HR components (extracted in stage 4) that are calculated from the spectrum at each window.

- Heart Rate Variability Analysis

By using a sample-by-sample windowing strategy, HR can be extracted, from which dynamics of heart rate variability analysis can be obtained on the motion artifact-removed reconstructed HR time series.

[00123] i. Time-Varying Spectral Analysis of PPG and Accelerometer Data

[00124] Embodiments disclosed herein may produce a time-varying spectrum by taking a T-sec window of the signal and computing the power spectral density (PSD) of the segment and then sliding the window through the whole dataset which yields a time-frequency matrix in which each array represents the power of the signal corresponding to a specific frequency and sliding time-step (shift) of S-sec. The sliding process and frequency step specify the resolution and dimension of the time-frequency matrix. According to embodiments disclosed herein, two different sliding window approaches may be used, depending on the application. For estimating either heart rates or heart rate variability, data may be shifted sample-by-sample with no overlap for the entire dataset. Such an approach enables capturing beat-to-beat dynamics of HRV which requires sample-to-sample estimation of PSD. Since some data is down-sampled data to 20 Hz in some of the database, as disclosed above, each data point may be shifted by 0.05 seconds. For estimating only the heart rates, the shift may be a data segment-by-segment shift rather than a sample-by-sample shift. This coarse-grain windowing approach has less computational cost and it can provide good tracking of heart rates, but does not apply well to HRV.

[00125] As such, according to some embodiments, a window segment length T may be set to 8 seconds and shifted by 2 seconds. The 8 second data segment and a shift of 2 seconds was chosen to compare results according to embodiments disclosed herein to other methods (TROIKA, JOSS and WFPV) which have used this chosen data segment length and time shift (Zhilin, Z., P. Zhouyue, and L. Benyuan, TROIKA: A General Framework for Heart Rate Monitoring Using Wrist-Type Photoplethysmographic Signals During Intensive Physical Exercise. Biomedical Engineering, IEEE Transactions on, 2015. 62(2): p. 522-531; Zhang, Z., Photoplethysmography-Based Heart Rate Monitoring in Physical Activities via Joint Sparse Spectrum Reconstruction. Biomedical Engineering, IEEE Transactions on, 2015. PP(99): p. 1-1). Moreover, the assumption of 8 second data length largely stems from the fact that heart rates do not change instantaneously, hence, an 8 second duration is a reasonable choice.

[00126] As a representative example, the resultant frequency components in the time-frequency matrix of recordings from subject #8 from the competition training dataset, for a window length of 8 seconds that is shifted by every 2 seconds, is shown in FIG. 6A, disclosed below.

[00127] FIGS. 6A-6C show Time-Frequency spectra of recording #8 from dataset (1).

[00128] FIG. 6A shows the PPG signal.

[00129] FIG. 6B shows the simultaneous Accelerometer-Z signal.

[00130] FIG. 6C (Top-Left) shows the TF spectrum of the PPG signal. FIG. 6C (Top-Right) shows the TF spectrum of ACC(x). FIG. 6C (Bottom-Left) shows the TF spectrum of ACC(y),. FIG. 6C (Bottom-Right) shows the TF spectrum of ACC(z); all computed from stage (1) of Table 5. The blue circles and letters represent movement elements in all four spectra.

[00131] The panels of FIG. 6A and FIG. 6B show a PPG time series and the z-axis accelerometer data, respectively. From the upper left panel of FIG. 6C, which represents the time-frequency plot of the PPG signal, it is observed that there are three dominant frequency components - one of them represents HR and the other two are similar to those of the accelerometers' spectra shown in the upper right and lower left and right panels of FIG. 6C. FIG. 6C illustrates 4 motion artifact elements (A, B, C, D) that are present in exactly the same areas among all spectra. By comparing the time-frequency (TF) spectrum of PPG to those of the accelerometers' spectra, the marked dynamics (A, B, C and D) in the PPG spectrum can be detected as sharing the same frequency dynamics as those of the accelerometer spectra marked in circles. Hence, both the top and bottom marked lines in the PPG spectrum most likely represent the motion artifacts, and the unmarked frequency represents the HR. The next section details how these motion artifact frequency dynamics may be detected and filtered according to embodiments disclosed herein.

[00132] ii. Spectral Filtering

[00133] After obtaining the power spectral density at each window, as disclosed above, embodiments disclosed herein may confine the HR frequency to the range [0.5 Hz – 3 Hz], which takes into account both at rest and high HR due to either tachycardia or exercise scenarios. Hence, for HR estimation, the strategy is to eliminate frequencies that are outside of this HR frequency range as they are most likely due to motion artifacts or harmonics of the HR frequency.

[00134] In general, HR frequency in the power spectral density of PPG at each window can have three different scenarios: (1) PPG is devoid of MA and there is no spatial gap between the sensor and the subject's skin during recording, (2) PPG is corrupted by MA and there is no spatial gap between the sensor and the subject's skin during recording and (3) There is a spatial gap between the sensor and the subject's skin during recording. For the ideal case (1), HR can be extracted and it is most likely represented as the highest peak in the PPG spectrum. For case (2), MA dynamics can result in predominately either one or two dominant peaks depending on the severity of repetitive motions, and the HR peak may be relegated to either the second or third highest peak. Non-repetitive motion artifacts will show up as a broadband spectrum without a dominant peak if they are not severe (Marmarelis, V.Z., et al., Nonlinear analysis of renal autoregulation under broadband forcing conditions. Ann Biomed Eng, 1993. 21(6): p. 591-603). The only scenario that makes it difficult to extract HR from the spectrum is scenario (3) when there is a spatial gap between the PPG sensor and the subject's skin during recording. In this scenario, assuming that the motion artifacts are short lasting, the missing HR values can be interpolated using a cubic spline approach.

[00135] FIG. 7 is an example embodiment of spectral filtering. FIG. 7 shows a representative filtered time-frequency spectral plot of a PPG signal. As disclosed above, embodiments disclosed herein may retain only the three largest frequency peaks at each time point within the defined HR range (30-180 bpm) and such retained frequency peaks are represented as blue, green and red colors, respectively. Retaining only the three largest frequency peaks at each time point may be reasonable for the first two cases, as outlined above. In the PPG time-frequency spectrum of FIG. 7, the Blue, Green and Red circles correspond to the first three highest peaks in the defined HR frequency range of (30-180 bpm), respectively, at each sliding window.

[00136] iii. Motion Artifact Detection

[00137] FIGS. 8A-8B show motion artifact detection in the PPG spectrum according to embodiments disclosed herein.

[00138] FIG. 8A shows a filtered PPG spectrum with movement and HR components. FIG. 8A is an example embodiment of a PPG spectrum which is identical to FIG. 7, but it also identifies the frequencies associated with accelerometers, as marked by the shaded areas and the letters A-D, in the top left and two bottom panels of FIG. 6C, disclosed above. The

shaded yellow elements (A, B, C, D) of FIG. 8A represent motion frequency components in the PPG spectrum, and the light blue line is the reference HR from a clean reference ECG signal. By removing the accelerometers' related frequencies in FIG. 8A, the remaining frequency dynamics which should represent HR frequency and its harmonics are shown in FIG 8B.

[00139] FIG. 8B shows a filtered PPG spectrum after removing motion artifact frequency components.

[00140] iv. Heart Rate Tracking & Extraction

[00141] A flow diagram for heart rate tracking and extraction is disclosed above, with reference to FIG. 3B. Embodiments disclosed herein may identify HR frequencies with time, such as HR frequencies from FIG. 8B. Note that in FIG. 8B, there are three peaks at each time instance (also referred to interchangeably herein as a time point). Embodiments disclosed herein may identify which of the three peaks represents the HR at each time point. For the initial time window of 8 seconds, a clean data segment may be used so that true HR can be determined. This scenario is case (1), disclosed above, in the spectral filtering section, and the detection of HR is simply the highest peak in the spectrum. Embodiments disclosed herein may estimate HR for each sliding window of data. Embodiments disclosed herein may choose a HR peak in the PPG spectrum with the knowledge of estimated HR values in previous time windows. Two main scenarios may present: (1) no peak exists in the spectrum that can represent HR, and (2) there is a spectral peak among the first three highest peaks of spectrum that belongs to the HR component.

[00142] In case (1), where HR is not detectable in the window (*e.g.*, due to spatial gap between the PO sensor and skin), in real-time implementation embodiments disclosed herein may take a previous window's HR value as the current HR (or simply use a moving average of several past HR beats or some other variant). In post-processing, or offline processing, a cubic spline interpolation may be used to fill in the missing HR information. In the more general case (2), where the HR peak is among the first three highest peaks in the spectrum, three possible scenarios can occur: (2-A) the windowed PPG signal is clean and the first highest peak in the spectrum represents the HR fundamental frequency, (2-B) the windowed PPG signal is corrupted by movement and at most two of the spectral peaks represent the accelerometers' frequency components, thus, the second or the third peak corresponds to HR, (2-C) while the HR spectral peak is detectable, the difference between its value and that of

the previous HR is more than 10 bpm, as such, embodiments disclosed herein may replace the HR by the most recent HR value from a previous window segment (or a moving average of several past HR beats or some other variant).

[00143] According to embodiments disclosed herein, criterion may be set that the HR value cannot change more than 10 BPM from a previous time window. In FIG. 8B, these cases are illustrated. For example, in most cases, the blue circle which represents the largest spectral peak is chosen but in other cases, either green or red circles are chosen for certain time points. For the HR peaks associated with either the green or red circles, embodiments disclosed herein may choose those peaks because either the first two highest peaks are related to accelerometers or the highest magnitude peak deviates more than 10 BPM from the previous HR value.

[00144] FIG. 9 shows a comparison of reconstructed HR obtained, according to embodiments disclosed herein, to reference HR obtained from simultaneous ECG recordings. In FIG. 9, the extracted HR (red color) from PPG spectra of recording#8 from the competition training dataset, according to embodiments disclosed herein, is shown in red color and the reference ECG-derived HR is shown in black color. In order to calculate the performance of HR reconstruction according to embodiments disclosed herein, the error value in each time window was calculated from the estimated HR to the reference ECG-derived HR. Two measurement indices of absolute error similar to the indices in (Krishnan, R., B. Natarajan, and S. Warren, Two-Stage Approach for Detection and Reduction of Motion Artifacts in Photoplethysmographic Data. Biomedical Engineering, IEEE Transactions on, 2010. 57(8): p. 1867-1876) were used.

$$Error(1) = \frac{1}{W}\sum_{k=1}^{w}\left|HR_{SpaMA}(k) - HR_{ref}(k)\right| \quad (1)$$

$$Error(2) = \frac{1}{W}\sum_{k=1}^{w}\frac{\left|HR_{SpaMA}(k) - HR_{ref}(k)\right|}{HR_{ref}(k)} \times 100\% \quad (2)$$

where W is the total number of windows.

[00145] v. PPG Signal Reconstruction for HRV analysis

[00146] For an HRV analysis application, the above-disclosed embodiments are identical except that the beat-by-beat shift is of data rather than the 8 second data segment shift or its variant. According to embodiments disclosed herein, the PPG signal may be reconstructed

using heart rate frequency, amplitude and phase changes, window-by-window using the sample-by-sample windowing process:

$$Rec_{Signal}(k) = A_{HR}(k) \times \sin\left(2\pi t(k) f_{HR}(k) + \varphi_{HR}(k)\right) \quad (3)$$

where $k = 1, \ldots, N$ and N is number of signal samples and total number of windows. $A_{HR}(k)$ and $\varphi_{HR}(k)$ are calculated according to the power of the signal for HR frequencies in the PSD and phase angles of complex elements in a Fast Fourier Transform (FFT) matrix that correspond to HR frequencies.

[00147] FIG. 10A is an example embodiment of PPG signal reconstruction according to embodiments disclosed herein. FIG. 10A shows a comparison between reconstructed PPG and original recording #8 from IEEE competition training dataset. The left and right panels of FIGS. 10A-B show the reconstructed PPG versus the original PPG and their HRV time series, respectively.

[00148] FIG. 10B is a zoomed-in version of FIG. 10A.

[00149] Given that embodiments disclosed herein estimate quite accurate heart rates, it is not surprising to observe similar frequency dynamics between the reference and reconstructed HRV time series, as shown in FIGS. 11A-B.

[00150] FIGS. 11A-B show comparisons of HRV spectra between the reference and the reconstructed HRV time series (*e.g.*, as shown in FIGS. 10A-B) from the MA-contaminated PPG signal for dataset #8. Note that for computing HRV, matching the amplitude of the reference HR is not a concern, as the focus is only in the dynamics of the fluctuations in the heart rates.

[00151] FIG. 11A shows a time-domain comparison of a reconstructed HR and a reference HR.

[00152] FIG. 11B shows a spectral comparison of heart rate variability between reconstructed HR and reference HR calculated from the reference ECG using Pan & Tompkins peak detection approach (Pan J, T.W., A real-time QRS detection algorithm. IEEE Trans Biomed Eng, 1985. 32(3): p. 230-236).

[00153] Results

[00154] Table 6 represents the average absolute error (E1) and the average absolute error percentage (E2) of embodiments disclosed herein as applied to all 3 datasets, respectively. Embodiments disclosed herein are compared to three methods: TROIKA, JOSS and WFPV. The results in Table 6 show that better performance from embodiments disclosed herein as

comparted to JOSS and TROIKA for all 12 subjects in the first datasets. In comparison to WFPV, embodiments disclosed herein outperform WFPV on average across all 23 subjects in both datasets (1) and (2). The total average of E1 for embodiments disclosed herein is less than 2 beats per minutes for all 33 subjects. The average of E1 across the treadmill experiment recordings (activity Type 1- IEEE dataset and Type 4- Chon Lab dataset) is around 1 beat per minute for all 22 subjects.

Table 6. SpaMA Method Performance Comparison

Subject	Dataset	Activity Type	TROIKA		JOSS		WFPV		SpaMA	
			E1	E2%	E1	E2%	E1	E2%	E1	E2%
1	1 (IEEE Cup)	Type (1)	2.87	2.18	1.33	1.19	1.23	-	**1.23**	**1.14**
2			2.75	2.37	1.75	1.66	1.26	-	1.59	1.30
3			1.91	1.50	1.47	1.27	0.72	-	**0.57**	**0.45**
4			2.25	2.00	1.48	1.41	0.98	-	**0.44**	**0.31**
5			1.69	1.22	0.69	0.51	0.75	-	**0.47**	**0.31**
6			3.16	2.51	1.32	1.09	0.91	-	**0.61**	**0.45**
7			1.72	1.27	0.71	0.54	0.67	-	**0.54**	**0.40**
8			1.83	1.47	0.56	0.47	0.91	-	**0.40**	**0.33**
9			1.58	1.28	0.49	0.41	0.54	-	**0.40**	**0.32**
10			4.00	2.49	3.81	2.43	2.61	-	2.63	1.59
11			1.96	1.29	0.78	0.51	0.94	-	**0.64**	**0.42**
12			3.33	2.30	1.04	0.81	0.98	-	1.20	0.86
mean±std			2.42±0.8	1.82±0.5	1.28±0.9	1.02±0.6	1.04±0.5	-	**0.89±0. 6**	**0.65±0.4**
13	2 (IEEE Cup)	Type (2)					3.58	-	**3.41**	**4.25**
14							9.66	-	**7.29**	**9.80**
15		Type (3)					2.31	-	2.73	2.21
16							4.93	-	**3.18**	**2.11**
17							3.07	-	**3.01**	**2.52**
18							2.67	-	4.46	3.23
19							3.11	-	3.58	3.98
20		Type (2)					2.10	-	**1.94**	**1.66**
21		Type (3)					3.22	-	**2.56**	**2.02**
22							4.35	-	**3.12**	**3.28**
23		Type (2)					0.75	-	1.72	1.97
mean±std							3.61±2.2	-	**3.36±1.5**	**3.33±2.2**
Type (1,2) mean±std							2.27±2.0	-	**1.93±2.0**	**2.07±1.7**
24	3 (Chon Lab)	Type (4)							**0.88**	**0.91**
25									**1.03**	**0.83**
26									**1.10**	**0.90**
27									**1.64**	**1.54**
28									**1.41**	**1.12**
29									**0.82**	**0.70**
30									**0.63**	**0.58**
31									**4.78**	**3.87**
32									**0.95**	**0.79**
33									**0.62**	**0.52**
mean±std									**1.38±1.2**	**1.17±1.0**
Total: mean±std									**1.86±1.6**	**1.70±1.8**

[00155] FIGS. 12A, 12B, 13A, 13B, 14A, and 14B show the reconstructed HR and corresponding PSD of a sample-sample windowed HR, according to embodiments disclosed herein, in comparison to a reference HR from an ECG. The results for recording #9 from the first dataset (IEEE Competition Training dataset) and activity Type 1 (*e.g.*, running on treadmill) are shown in FIGS. 13A-B. As shown, E1 for this particular subject is as low as 0.4 bpm and the correlation between the PSD of reconstructed HR and reference HR is as high as 96%.

[00156] FIG. 12A shows a reconstructed HR vs. reference HR. FIG. 12B shows a spectral comparison of reconstructed HR and reference HR (estimated from reference ECG).

[00157] FIG. 13A illustrates the comparison between the reconstructed HR and the reference HR for Subject #14 (IEEE Competition Test Dataset) which has the highest errors. Subject #14 belongs to the second dataset (IEEE Competition Test dataset) and Type 2 activities (e.g. jumping). It can be seen that the largest error is obtained when both the physiological HR and the motion artifacts change rapidly so that the true HR cannot be reliably estimated.

[00158] FIG. 13B shows a reconstructed HR vs. reference HR for Subject 16 (IEEE Competition Test Dataset). FIG. 13B shows the comparison results of reconstructed HR and reference HR for recording #16 of the second dataset (IEEE Competition Test dataset) which has the Type 3 activities (*e.g.*, arm exercise).

[00159] FIG. 14A shows a reconstructed HR vs. reference HR for Subject #30 (Chon Lab Dataset). FIG. 14B shows a spectral comparison of reconstructed HR and reference HR (estimated from reference ECG). The results for recording #30 from the third datasets (Chon Lab datasets) and activity Type 4 (*e.g.*, running on treadmill) are shown in FIGS. 14A-B. It can be seen that the E1 for this subject is around 0.6 bpm and the correlation between the PSD of reconstructed HR and reference HR is as high as 99% for LF and 0.96 for HF frequency range. All subjects' results are provided in Table 7, disclosed below.

[00160] Table 7 represents the correlation and statistical difference using the student's t-test between PSD of estimated and reference HRV in both LF (0.04-0.15 Hz) and HF (0.15-0.4 Hz) frequency ranges. The correlation values in the table are calculated based on Pearson's linear correlation coefficient. As shown in Table 7, there was no difference between the reference and the derived HRV for LF, according to embodiments disclosed herein, and a difference was seen in only 4 out of 10 subjects for HF.

Table 7. Frequency Domain HRV analysis Comparison: PSD of SpaMA Method vs. reference

Subjects	Correlation	
	LF (LF is [0.04-0.15] Hz and HF is [0.15-0.4] Hz)	**HF**
1	0.99	0.98
2	0.99	0.96
3	0.99	0.95* (*) indicates significantly different (P-value>0.05)
4	1.00	0.99
5	1.00	0.99
6	0.99	0.96*
7	0.98	0.92*
8	0.97	0.90*
9	1.00	0.99
10	1.00	0.99
mean	0.99	0.96

[00161] Table 8 shows some of the widely-reported time-domain HRV parameters such as the mean HR, standard-deviation (SDNN) of the normal-to-normal (NN) interval, root-mean-square of successive difference (RMSSD) of the NN interval, and the number of interval differences of successive NN intervals greater than 50 ms divided by the total number of NN intervals (pNN50) estimated from embodiments disclosed herein in comparison to the reference ECG NN interval. None of these parameters were found to be significantly different between those derived according to embodiments disclosed herein and the reference HRV.

Table 8. Time Domain HRV analysis Comparison: SpaMA Method vs. reference HRV

Subjects	SDNN		meanNN		RMSSD		pNN50	
	SpaMA	Reference	SpaMA	Reference	SpaMA	Reference	SpaMA	Reference
1	2620.75	2566.47	10481.89	10480.72	33.24	18.05	0.001	0.020
2	2115.44	2079.58	9908.00	10020.00	25.93	16.32	0.011	0.019
3	3173.73	3177.68	10764.20	10829.06	89.70	56.15	0.019	0.207
4	2517.78	2533.20	10376.95	10426.26	13.54	19.58	0.001	0.030
5	2654.42	2670.32	10846.04	10990.08	11.88	18.59	0.003	0.018
6	2012.53	1974.65	9737.35	9827.63	39.64	21.17	0.004	0.025
7	3056.36	2925.19	12519.74	13134.05	27.66	30.61	0.015	0.071
8	3133.76	2756.66	10504.00	10530.00	32.57	36.38	0.002	0.003
9	2195.08	2142.53	10499.81	10470.06	8.23	13.01	0.002	0.004
10	2454.57	2406.96	12936.62	12981.21	41.52	20.28	0.006	0.024
p-value	> 0.05		> 0.05		> 0.05		> 0.05	

[00162] As such, the SpaMA method, according to embodiments disclosed herein, that may be based on time-varying spectral analysis of the PPG signal addresses Heart Rate monitoring in the real world with challenges ranging from a subject who makes sudden movements but is otherwise sedate, to intensive physical activities. Embodiments disclosed herein compare spectral changes in PPG and accelerometer signals. As disclosed above, three different datasets have been used to verify the SpaMA performance. Each dataset reflects different types of activities and movements. In all of the experiments, the reference HR was calculated from an ECG signal that was collected simultaneously with the PPG signal. The estimated HR was calculated from the spectrum of PPG in 8 second time windows. Based on the results, disclosed above, the SpaMA method may be used for tracking HR changes during severe motion artifacts with an average error of just 1.86 bpm compared to that of the reference ECG; these results are superior to three other methods tested: TROIKA, JOSS and WFPV (Zhilin, Z., P. Zhouyue, and L. Benyuan, TROIKA: A General Framework for Heart Rate Monitoring Using Wrist-Type Photoplethysmographic Signals During Intensive Physical Exercise. Biomedical Engineering, IEEE Transactions on, 2015. 62(2): p. 522-531; Zhang, Z., Photoplethysmography-Based Heart Rate Monitoring in Physical Activities via Joint Sparse Spectrum Reconstruction. Biomedical Engineering, IEEE Transactions on, 2015. PP(99): p. 1-1).

[00163] Out of 33 recordings, 23 are from a wrist pulse oximeter, and the rest of the data were recorded by a forehead pulse oximeter. The results from Table 8, disclosed above, show that the SpaMA method can be applied to monitor HR from both wrist and forehead pulse oximeters. By comparing the performance of the method for treadmill experiments (dataset 1 and dataset 3), the error is lower by almost 1 beat using a wrist pulse oximeter. However, it should be noted that from this result a conclusion that the wrist PPG provides less error than the forehead should not be drawn, as the experiments used different subjects and were two separate studies. The prior methods (TROIKA, JOSS and WFPV) were tested using only on the wrist-based PPG signals as the implementers of those methods did not have access to forehead PPG sensors. The SpaMA method, according to embodiment disclosed herein, was tested on data from both PPG sensor locations, and proved to be effective regardless of the location of the PPG sensor.

[00164] Several observations were made while analyzing the data, disclosed above. The tracking ability of the SpaMA method decreased as the frequency changes during recordings

increased. This phenomenon mostly was observed while dealing with the second set of datasets from the IEEE competition, which involved Type (2) and Type (3) activities. These types of exercises involved more abrupt movements which consequently made it more difficult to track the HR-related frequencies in the spectrum. In the three datasets that have been analyzed, recordings #10 and 14 are examples of this phenomenon.

[00165] A strength of the PPG's LED is one of the most important factors determining the SpaMA method performance. Movement induces much less spectrum corruption (shift) in the PPG if the LED is sufficiently strong. A reduction in the strength of the PPG signal can also be caused by ambient light leaking into the gap between a PPG sensor and the skin surface (Zhang, Z., Photoplethysmography-Based Heart Rate Monitoring in Physical Activities via Joint Sparse Spectrum Reconstruction. Biomedical Engineering, IEEE Transactions on, 2015. PP(99): p. 1-1). This is because the power of the signal is dependent on the depth and reflection of the light from the pulse oximeter to the subject's skin. This gap between skin and the planar substrate where the LEDs and PD are mounted may be the result of movement during physical activities or the shape of tissue that the sensors touch. Among the three datasets, low performance for recordings #16 and 31 is the result of a weak PPG signal most likely due to a gap between the sensor and skin caused by motion artifacts.

[00166] By using the sample-by-sample windowing process, SpaMA, according to embodiments disclosed herein, can be utilized for both Heart Rate monitoring and HRV analysis in both frequency- and time-domains. From the results, disclosed above, it can be observed that embodiments disclosed here are able to replicate both the low frequency (0.04-0.15Hz) and the high frequency (0.15-0.4) dynamics well, albeit better the former than the latter, when compared to a reference HRV. For time-domain HRV measures, the mean HR, SDNN, RMSSD, and pNN50 based on embodiments disclosed herein were all found to be not significantly different than the reference HRV. It has long been shown that during dynamic exercise, heart rate increases due to both a parasympathetic withdrawal and an augmented sympathetic activity (Iellamo, F., Neural mechanisms of cardiovascular regulation during exercise. Auton Neurosci, 2001. 90(1-2): p. 66-75; Bernardi, L. and M.F. Piepoli, [Autonomic nervous system adaptation during physical exercise]. Ital Heart J Suppl, 2001. 2(8): p. 831-9). The relative role of the two drives depends on the exercise intensity (Perini, R., et al., The influence of exercise intensity on the power spectrum of heart rate variability. Eur J Appl Physiol Occup Physiol, 1990. 61(1-2): p. 143-8; Sarmiento, S., et al., Heart rate

variability during high-intensity exercise. Journal of Systems Science and Complexity, 2013. 26(1): p. 104-116; Roure, R., et al., Autonomic nervous system responses correlate with mental rehearsal in volleyball training. Eur J Appl Physiol Occup Physiol, 1998. 78(2): p. 99-108). Analysis of HRV permits insight into this control mechanism (Aubert, A.E., B. Seps, and F. Beckers, Heart rate variability in athletes. Sports Med, 2003. 33(12): p. 889-919). Also, being able to do HRV analysis from PPG even during movement and physical activities would be an advantage for detecting and diagnosing many cardiovascular diseases using only PPG recordings.

[00167] The SpaMA method, according to embodiments disclosed herein, can be potentially implemented in real time. The method written in Matlab®, version R2014 and CPU 3.4 GHz takes only 110 msec per 8 second segments. Therefore, given the high accuracy of the method in estimating HR despite severe motion artifacts, the SpaMA method, according to embodiments disclosed herein, has the potential to be applicable for implementation on wearable devices such as smart watches and PPG-based fitness sensors.

[00168] As disclosed above, accurate estimation of changing arterial oxygen saturation (SpO2) from photoplethysmogram (PPG) signals during movement is a very challenging problem. This is because strenuous and high intensity movements can result in severe motion artifacts (MA), making accurate SpO2 estimation from PPG signals difficult. As such, embodiment disclosed herein may applied the methods for reconstructing a PPG signal, as disclosed above, and include an additional stage of SpO2 estimation.

[00169] According to one embodiment, OxiMA may be comprised of the 6 stages disclosed above, with reference to FIGS. 3A-F, and include Stage 7, that is SpO2 Estimation.

[00170] According to another embodiment, OxiMA may be comprised of 6 stages: (1) Time-frequency Spectral Analysis, (2) Signal Decomposition, (3) Spectral Filtering, (4) Heart Rate (HR) extraction and tracking, (5) Signal Reconstruction, (6) SpO2 Estimation.

[00171] OxiMA

[00172] According to some embodiments, OxiMA may decompose the PPG signal into its frequency components by using a complex demodulation-based technique and may choose the components with frequencies close to the HR frequency for reconstructing the clean PPG signal. Next, SpO2 may be estimated from the reconstructed PPG signal. Such a method is applied to 22 minute datasets recorded from 10 subjects. A Nellcor OxiMax transmission sensor was used to collect analog PPG signals, while reference SpO2 and HR were collected

simultaneously from the FDA approved Masimo SET Radical RDS-1 pulse oximeter. The performance of the OxiMA method according to embodiments disclosed herein, was determined by computing the mean absolute error between the estimated HR/SpO2 from the PPG and reference HR [Masimo]/SpO2[Masimo] oximeter. The results show the average estimation error using OxiMA are only 2.4 beats/minute for HR and 1.8% for SpO2, respectively. As such, the OxiMA method has great potential for MA reduction for both SpO2 and HR monitoring.

[00173] Vital signs and clinical symptoms have been shown to be poor predictors of hypoxia, and in order to rationalize oxygen therapy, measurement of arterial oxygen saturation by pulse oximetry is being increasingly recommended (Laman, M., et al., Can clinical signs predict hypoxaemia in Papua New Guinean children with moderate and severe pneumonia? Ann Trop Paediatr, 2005. 25(1): p. 23-7) Arterial oxygen saturation (SpO2) reflects the relative amount of oxyhemoglobin in the arterial blood. The most common method to measure SpO2 is based on pulse oximetry, whereby oxidized hemoglobin and reduced hemoglobin have significantly different optical spectra.

[00174] Specifically, at a red wavelength of about 660 nm, there is a significant difference in light absorbance between reduced (Hb) and oxidized hemoglobin (HbO2). A measurement of the percent oxygen saturation of blood is defined as the ratio of oxyhemoglobin to the total concentration of hemoglobin present in the blood. Pulse oximetry assumes that the fluctuations of the PPG signal are caused by changes in arterial blood volume associated with each heartbeat, where the magnitude of the fluctuations depends on the amount of arterial blood rushing into the peripheral vascular bed, the optical absorption of the blood, skin and tissue, and the wavelengths used to illuminate the blood. The photoplethysmogram (PPG) can be used to derive not only the SpO2 and heart rate (HR) data, but also other vital physiological information (Laman, M., et al., Can clinical signs predict hypoxaemia in Papua New Guinean children with moderate and severe pneumonia? Ann Trop Paediatr, 2005. 25(1): p. 23-7; Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263; Tamisier, R., et al., A new model of chronic intermittent hypoxia in humans: effect on ventilation, sleep, and blood pressure. J Appl Physiol (1985), 2009. 107(1): p. 17-24; Jubran, A., Pulse oximetry. Crit Care, 1999. 3(2): p. R11-r17). As disclosed above, utilizing a pulse oximeter

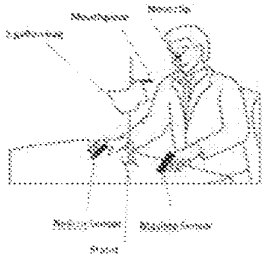
as a multi-purpose vital sign monitor has clinical appeal, since it is familiar to clinicians and comfortable for the patient (Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263).

[00175] In healthy persons, SpO2 is typically near 98%. A lower reading indicates a level of hypoxia. SpO2 readings below 95% are usually a cause for concern, indicating the need for supplemental oxygen therapy. In certain individuals, such as those with chronic respiratory or cardiac diseases, SpO2 readings below 95% may be considered normal. However, in general, SpO2 readings between 90%-95% represent mild hypoxia, while 85%-90% indicates serious hypoxia, and readings below 85% are considered critical hypoxia (Tamisier, R., et al., A new model of chronic intermittent hypoxia in humans: effect on ventilation, sleep, and blood pressure. J Appl Physiol (1985), 2009. 107(1): p. 17-24).

[00176] As disclosed below, the OxiMA method according to embodiments disclosed herein, provides HR reconstruction with accurate SpO2 estimation even during movement. The most recent methods as noted above (e.g., TROIKA and JOSS) do not show their ability to obtain SpO2 estimates as they were mainly designed for HR calculations in the presence of intense motion artifacts.

[00177] The OxiMA method was evaluated on a lab controlled dataset that was recorded during voluntary induced hypoxia. In an IRB approved study which recruited 10 subjects, one set of data was collected from each subject for a duration of 22 min. Reference arterial SpO2 and HR were collected from the FDA approved Masimo SET Radical RDS-1 pulse oximeter (mounted on the left hand), while a Nellcor OxiMax sensor (mounted on the right hand) was used to collect analog PPG signals, simultaneously (Table 9).

TABLE 9
PPG DATASETS AND EXPERIMENTS SETTINGS

Scenario	Sensor Type	Age/Sex Ethnicity
Oxygen Saturation Variations 	[Actual PPG] Finger Pulse Oximeter Nellcor [Ref SpO_2] Finger Pulse Oximeter [Ref HR] SilverRest ECG Electrode	23-58 yr (10 Males) 3 Asian 2 Hispanic 3 American 2 White

[00178] Each subject sat in a chair and was asked to re-breathe into a 1-gallon bag four times for approximately two minutes each time. During the first and third time the subject rebreathed into the bag, subjects were asked to remain still. During the second and fourth time the subject rebreathed into the bag, subjects were asked to introduce motion artifacts into the measurement by shaking their right hand. Each subject wore a disposable nose clip to prevent accidental breathing of room air. The Masimo reference sensor placed in the left hand remained motionless for the entire duration of the study. Subjects had at least two minutes of rest between successive breathing maneuvers, with more time if requested. The protocol for this experiment is presented in Table 10. Worcester Polytechnic Institute IRB approved the study protocol and informed consent was required by all subjects prior to data recording.

[00179] This sequence of data recording allowed us to test the efficacy of the OxiMA method while a subject experienced different levels of short lasting hypoxia during motion artifacts. For reference, other clinical studies showed that SpO2 levels in patients suffering from mild to moderate sleep apnea can drop to about 80% for short periods of time until the patient is awakened without irreversible physiological effects (Maeda, Y., M. Sekine, and T. Tamura, Relationship between measurement site and motion artifacts in wearable reflected photoplethysmography. J Med Syst, 2011. 35(5): p. 969-76).

[00180] Methodology

[00181] The protocol for testing performance of the OxiMA method is presented in Table 10.

TABLE 10
EXPERIMENT PROTOCOL

End Time (min)	Event
2	Rest (baseline)
4	Bag breathing (motion)
5	Rest (oxygen recovery)
7	Rest
9	Bag breathing (motion)
10	Rest (oxygen recovery)
12	Rest
14	Bag breathing (no motion)
15	Rest (oxygen recovery)
17	Rest
19	Bag breathing (motion)
20	Rest (oxygen recovery)
22	Rest

[00182] Details of each stage of the OxiMA method as applied in the experiment are disclosed below.

[00183] Time-Varying Spectral Analysis of PPG and Accelerometer Data

[00184] To compute the time-frequency spectrum, a variable frequency complex demodulation technique was employed. Table 11, disclosed below, presents the OxiMA method, according to one embodiment.

[00185] The time-varying spectrum is estimated by taking a T-sec window of the PPG signal and computing the VFCDM time-frequency of the segment and then sliding the window through the whole dataset. There is no overlapping between the sliding time windows. The window segment length T was set to 8 seconds and was shifted by 8 seconds. The assumption of 8 second data length largely stems from the fact that SpO2 and heart rates do not change instantaneously; hence, an 8 second duration is a reasonable choice.

TABLE 11
OXIMA METHOD: HR AND SPO2 RECONSTRUCTION

Stage 1. VFCDM Time-Frequency Spectrum
1.1. Downsample the PPG signal to ¼ of the original sampling frequency.
1.2. Compute the VFCDM based time-frequency spectrum (TFS)

Stage 2. Signal Decomposition
2.1. Decompose the PPG signal into its frequency components according to frequency bands in the TFS

Stage 3. Spectral Filtering
3.1. Assume HR to be in the frequency range of [0.5Hz – 3Hz], to account for both low and high HR values.
3.2. The first highest two peaks and their corresponding frequencies in the PPG filtered spectrum are assumed to have HR information.

Stage 4. Heart Rate Tracking and Extraction from PPG Spectrum
Case (1): From 3.1- if the spectrum is corrupted by movement and only the first largest peak is corrupted, then the HR frequency should be the frequency of the second peak in the spectrum.
Case (2): Due to the sensor-skin interface interruption, which could be a result of gap between the pulse oximeter and a subject's skin or slight sensor alignment variations relative to skin, the HR frequency cannot be extracted from the spectrum and in this case the previous HR frequency is used or for offline implementation a cubic spline interpolation can be applied to fill in the missing HR information.

Stage 5. PPG Signal Reconstruction
5.1. The PPG signal is reconstructed by using the summation of VFCDM components with frequency close to the HR frequency at each window.

Stage 6. Oxygen Saturation Estimation
6.1. Calculate the SpO2 estimations from reconstructed infrared and red PPG signals using the following empirical calibration equation [2]

$$SpO_2(\%) = (110 - 25R)$$

where,

$$R = \frac{AC_{Red}/DC_{Red}}{AC_{IR}/DC_{IR}}$$

[00186] FIGS. 15A-B show the resultant VFCDM time-frequency spectrum of recordings from subject #5, as a representative example.

[00187] The panels in FIGS. 15A-B show infrared PPG time series data. FIG. 15B represents the time-frequency plot of the infrared PPG signal. The next section details how the PPG data is decomposed into its frequency components using VFCDM.

[00188] Signal Decomposition

[00189] The original PPG signal was decomposed into sinusoidal modulations using a VFCDM method, as disclosed in Table 12 below.

$$x(t) = \sum_{i=1}^{N} Component\{i\} = \sum_{i=1}^{N} dc_i(t)A_i(t)cos\big(2\pi f_i(t) + \phi_i(t)\big) \quad (4)$$

[00190] By assuming N=12 fixed frequency bands each with a distinct central frequency, the PPG and accelerometer signals may be decomposed using the VFCDM method of Table 12 which yields 12 components.

TABLE 12
VFCDM METHOD

Consider a sinusoidal signal $x(t)$ to be a narrow band oscillation with a time-varying center frequency $f(\tau)$, instantaneous amplitude $A(t)$, phase $\phi(t)$, and the direct current component $dc(t)$:

$$\boldsymbol{x(t) = dc(t) + A(t)\cos\left(\int_0^t 2\pi f(\tau)d\tau + \phi(t)\right)}$$

Step (1) For a given center frequency, we can extract the instantaneous amplitude information $A(t)$ and phase information $\phi(t)$ by multiplying (1) by $e^{-j\int_0^t 2\pi f(\tau)d\tau}$ which results in the following:

$$z(t) = x(t)e^{-j\int_0^t 2\pi f(\tau)d\tau} = dc(t)e^{-j\int_0^t 2\pi f(\tau)d\tau} + \frac{A(t)}{2}e^{j\phi(t)} + \frac{A(t)}{2}e^{-j\left(\int_0^t 4\pi f(\tau)d\tau + \phi(t)\right)}$$

Step (2) From (2), if $z(t)$ is filtered with an ideal low-pass filter (LPF) with a cutoff frequency $f_c < f_0$, where f_0 is the center frequency of interest. Then the filtered signal $z_{lp}(t)$ will contain only the component of interest $z_{lp}(t) = \frac{A(t)}{2}e^{j\phi(t)}$.

Step (3) By changing the center frequency followed by using the variable frequency approach as well as the LPF, the signal, $x(t)$, will be decomposed into the sinusoid modulations, d_i, by the CDM technique as follows:

$$\boldsymbol{x(t) = \sum_i d_i = dc(t) + \sum_i A_i(t)\cos\left(\int_0^t 2\pi f_i(\tau)d\tau + \phi_i(t)\right)}$$

Step (4) The instantaneous frequency and amplitude of d_i can be calculated using the Hilbert transform

$$A(t) = 2|z_{lp}(t)| = [X^2(t) + Y^2(t)]^{1/2}$$
$$X(t) = real(z_{lp}(t))$$
$$Y(t) = imag\left(z_{lp}(t)\right) = H[X(t)] = \frac{1}{\pi}\int \frac{X(t')}{t-t'}dt'$$
$$\phi(t) = \arctan\left(\frac{imag\left(z_{lp}(t)\right)}{real\left(z_{lp}(t)\right)}\right) = \arctan\left(\frac{Y(t)}{X(t)}\right) \qquad f(t) = f_0 + \frac{1}{2\pi}\frac{d\phi(t)}{dt}$$

[00191] FIG. 16 shows the twelve components corresponding to the IR and Red signal for subject #5. Among the twelve frequency bands, bands 1 to 5 correspond to frequency range of [0.5 Hz to 3 Hz], which is typically the HR frequency range accounting for both normal and elevated heart rates. Embodiments disclosed herein select a component of these 5 components to reconstruct the signal that preserves the HR and is less corrupted by the

motion artifacts. For the selection, an accurate HR may be estimated by selecting the components that match closest to the actual HR frequency in order to reconstruct a less noisy PPG signal than the original motion corrupted data.

[00192] Spectral Filtering

[00193] After obtaining the power spectral density at each window, HR frequency may be assumed to be confined in the range [0.5 Hz – 3 Hz], which takes into account both at rest and high HR values due to either tachycardia or exercise scenarios. Next, for HR estimation, the strategy is to keep only frequencies that correspond to the first and second peak at each column of time-frequency matrix, as disclosed above, with reference to FIG. 3B.

[00194] In general, HR frequency in the VFCDM based power spectral density of the PPG at each window can have three different scenarios: (1) PPG is devoid of MA and there is no sensor-skin interface problems like a spatial gap between the sensor and the subject's skin during recording, (2) PPG is corrupted by MA and there is no spatial gap between the sensor and the subject's skin during recording and (3) There is a spatial gap between the sensor and the subject's skin during recording. For the ideal case (1), HR can be extracted and it is most likely represented as the highest peak in the PPG spectrum. For case (2), MA dynamics can result in the dominant peak and HR frequency peak's magnitude become smaller than the MA frequency peak in the spectrum. The only scenario that makes it difficult to extract HR from the spectrum is scenario (3) when there is a spatial gap between the PPG sensor and the subject's skin during recording. In this scenario, assuming that the motion artifacts are short lasting, the missing HR values can be interpolated using the cubic spline approach.

[00195] FIGS. 17A-C are plots of the above three scenarios. In FIG. 17A and FIG. 17B, the true HR frequency is close to the first and second peak respectively, while in FIG. 17C, the true HR frequency is far from the dominant peaks in the spectrum. As long as the PPG data is clean, an assumption may be made that the HR frequency belongs to the frequency component with the highest power (peak) at the each column of the TFS matrix. On the other hand, when the data becomes corrupted by MA, it might shift the HR frequency to the next highest peak in the spectrum or might lose the dominant HR frequency.

[00196] Embodiments disclosed herein employ a TFS filtering step to search for N first highest spectral peaks and their associated frequencies in each column of the TFS. Hence, the original TFS of FIG. 15B can be filtered to select only N, for example, 2, in the example embodiments, highest spectral peaks.

[00197] FIG. 18A shows a representative filtered time-frequency spectral plot of PPG recording from subject #5. This portion of the OxiMA method involves retaining only the two largest frequency peaks at each time point within the defined HR range (30-180 bpm) and they are represented as blue and green traces, respectively.

[00198] Heart Rate Tracking and Extraction

[00199] After filtering the TFS, the HR may be extracted. The HR tracking method may be summarized as: Assume there is only knowledge of the initial HR, the HR at each window is extracted by comparing the peaks to the previous HR value.

[00200] As disclosed above with reference to FIG. 3B, if the largest peak is within the 10 bpm range from the previous value of HR, it is chosen; if not, the second largest peak is checked for compliance of this scenario. If the HR value deviates by more than 10 bpm, the HR from the previous window may be adopted by the method.

[00201] FIG. 18B illustrates the tracking of HR based on OxiMA method, disclosed above.

[00202] FIGS. 19A and 19B represent comparisons, of the estimated 8 second moving averaged HR from the OxiMA method, to the reference HR, and the HR calculated from the motion-corrupted PPG signal, compared to the reference HR from the ECG, respectively. In order to calculate the performance of the OxiMA method for HR reconstruction, the error value in each time window was calculated from the estimated HR to the reference ECG-derived HR. Two measurement indices of absolute and normalized errors similar to the indices in (Wang, H., et al., A high resolution approach to estimating time-frequency spectra and their amplitudes. Ann Biomed Eng, 2006. 34(2): p. 326-3) were used.

$$Error(1) = \frac{1}{W}\sum_{k=1}^{W}\left|HR_{OxiMA}(k) - HR_{ref}(k)\right| \quad (5)$$

$$Error(2) = \frac{1}{W}\sum_{k=1}^{W}\frac{\left|HR_{OxiMA}(k) - HR_{ref}(k)\right|}{HR_{OxiMA}(k)} \times 100\% \quad (6)$$

where, W is the total number of windows.

[00203] PPG signal reconstruction

[00204] Now that HR values at each time window are estimated from the time-frequency spectrum, the signal reconstruction phase of the OxiMA method may be performed. An assumption may be made that the signal components corresponding to the HR frequency are more robust against motion and, thus, a less corrupted signal can be reconstructed using the summation of these components.

[00205] By calculating the components from the Signal Decomposition, using Eq (4) and the time-frequency spectrum of the PPG, at each 8-sec window a signal component may be chosen that has a frequency close to estimated HR frequency and that component may be employed to reconstruct infrared and red PPG data at each window. This yields a less motion-corrupted data that can be used for oxygen saturation estimation, as disclosed in FIG. 20A and FIG. 20B.

[00206] Oxygen Saturation Estimation

[00207] In order to calculate SpO2 from PPG signals, red and infrared PPG signals with clearly separable DC and AC components are required. Let the pulsatile components of the red and infrared PPG signals be denoted as AC_{Red} and AC_{IR}, respectively, then the "ratio-of-ratio" R is estimated (Thakor, N.V. and Y.S. Zhu, Applications of adaptive filtering to ECG analysis: noise cancellation and arrhythmia detection. IEEE Trans Biomed Eng, 1991. 38(8): p. 785-94; Diniz, P., Adaptive filtering: algorithms and practical implementation. 2008: . Springer Science, Business Media L.L.C) as

$$\boldsymbol{R = \frac{AC_{Red}/DC_{Red}}{AC_{IR}/DC_{IR}}} \qquad (7)$$

[00208] Accordingly, SpO2 may be computed by substituting the R value in an empirical linear approximated relation given by $SpO_2(\%) = (110 - 25R)$.

[00209] FIG. 20C represents the reconstructed SpO2 values obtained from OxiMA in comparison to the reference SpO2 values and the estimated values before reconstruction.

[00210] OxiMA Results

[00211] Table 13 represents the average absolute error (E1) and the average absolute error percentage (E2) of HR and SpO2 estimations of the OxiMA method on the varying hypoxia level dataset.

TABLE 13
OXIMA METHOD PERFORMANCE COMPARISON (HR ESTIMATIONS)

Subject	Actual HR estimation error		OxiMA HR estimation error	
	E1	E2%	E1	E2%
1	3.84	4.83	**1.53**	**2.10**
2	6.84	9.57	**2.72**	**3.97**
3	8.15	9.59	**1.69**	**2.29**
4	4.55	5.39	**2.61**	**3.18**
5	10.53	11.96	**4.04**	**4.60**
6	4.46	5.52	**2.04**	**2.66**
7	12.41	19.65	**2.81**	**4.37**
8	3.84	4.35	**2.10**	**2.46**
9	3.80	4.13	**2.57**	**2.83**
10	3.65	4.20	**1.85**	**2.41**
mean±std	6.20±3.2	7.91±5.0	2.40±0.73	3.09±0.90

[00212] The OxiMA method is compared to the HR and SpO2 estimations prior to the reconstruction method, where both pre- and post-reconstruction estimations are compared to the reference HR and reference SpO2 values obtained from the Masimo pulse oximeter.

[00213] The results presented in Table 13 show that OxiMA on average improves the HR and SpO2 estimations by 100% and 105%, respectively when compared to those estimations without the reconstruction method. Improvement rates are calculated as follow:

$$\boldsymbol{ImRate1}(\%) = \frac{\mathbf{1}}{\boldsymbol{W}}\sum_{\boldsymbol{k=1}}^{\boldsymbol{W}}\frac{|\boldsymbol{Error1_{OxiMA}(k)-Error1_{Act}(k)}|}{\boldsymbol{Error1_{OxiMA}(k)}} \times \mathbf{100}\% \quad (8)$$

$$\boldsymbol{ImRate2}(\%) = \frac{\mathbf{1}}{\boldsymbol{W}}\sum_{\boldsymbol{k=1}}^{\boldsymbol{W}}\frac{|\boldsymbol{Error2_{OxiMA}(k) - Error2_{Act}(k)}|}{\boldsymbol{Error2_{OxiMA}(k)}} \times \mathbf{100}\% \quad (9)$$

[00214] FIGS. 21A-C and FIGS. 22A-B show the reconstructed SpO2 and HR in comparison to the reference HR from ECG recordings for subject #5. The largest error

among all recordings was found to be from this recording, as shown in Tables 13 and 14. The larger error could be due to rapid movements or skin-sensor gap during the recordings.

TABLE 14
OXIMA METHOD PERFORMANCE COMPARISON (SpO_2 ESTIMATIONS)

Subject	Actual SpO_2 estimation error		OxiMA SpO_2 estimation error	
	E1	E2%	E1	E2%
1	2.51	2.63	**0.86**	**0.90**
2	7.14	9.63	**2.45**	**3.10**
3	6.21	6.59	**1.61**	**1.67**
4	1.89	2.46	**0.95**	**1.16**
5	7.13	7.80	**3.25**	**3.47**
6	2.85	2.99	**1.10**	**1.14**
7	5.83	9.09	**2.57**	**4.52**
8	3.51	4.63	**1.73**	**2.22**
9	1.81	2.10	**1.50**	**1.61**
10	4.85	5.91	**1.93**	**2.07**
mean±std	4.37±2.1	5.38±2.8	1.79±0.8	2.19±1.2

[00215] As such, the E1 (HR) for this particular subject is as low as 4.05 bpm while the E1 (SpO2) is as low as 3.25%. It can be seen from Table 15, disclosed below, that HR and SpO2 both improved by 160% and 119%, respectively, post reconstruction method.

TABLE 15
OXIMA METHOD PERFORMANCE COMPARISON (SpO_2 ESTIMATIONS)

Subject	HR Improvement Rate		SpO_2 Improvement Rate	
	ImRate1%	ImRate2%	ImRate1%	ImRate2%
1	150.90	130.00	191.86	192.22
2	151.47	141.05	191.43	210.64
3	323.08	318.78	285.71	294.61
4	74.33	69.50	98.95	112.07
5	160.17	160.66	119.38	124.78
6	118.63	107.52	159.09	162.28
7	377.22	372.54	126.85	101.10
8	82.86	76.83	102.89	108.55
9	47.86	45.94	20.67	30.43
10	97.30	74.27	151.30	185.5
mean±std	158.38±108.2	149.71±109.9	144.81±70.5	152.2±73.2

V. Conclusions

[00216] As such, the OxiMA method that may be based on time-varying spectral analysis of the PPG signal combats motion artifacts that can degrade the accuracy of SpO2 and HR estimations. According to embodiments disclosed herein, the OxiMA method may decompose the PPG signal into many frequency bands using a VFCDM method (Chon, K.H.,

S. Dash, and J. Kihwan, Estimation of Respiratory Rate From Photoplethysmogram Data Using Time–Frequency Spectral Estimation. Biomedical Engineering, IEEE Transactions on, 2009. 56(8): p. 2054-2063), or any other suitable time-frequency technique, such as a wavelet analysis (Chon, K.H., S. Dash, and J. Kihwan, Estimation of Respiratory Rate From Photoplethysmogram Data Using Time–Frequency Spectral Estimation. Biomedical Engineering, IEEE Transactions on, 2009. 56(8): p. 2054-2063). According to embodiments disclosed herein, those components that are within the heart rate ranges including both extreme ranges of the low and high heart rates may be decomposed and used to reconstruct the PPG signal based on those components. As such, frequencies that are not within the prescribed HR ranges may be removed. From this reconstructed time series HR may be estimated and SpO2 may be estimated, as disclosed above.

[00217] The dataset used to verify the OxiMA method's performance was collected from 10 subjects during hypoxic experiments. The results show accurate estimation of both HR and SpO2 even during the presence of severe motion artifacts where the average error was only 2.4 bpm. More importantly, the average improvements in these estimates are astoundingly high for both HR (149%) and SpO2 (152%) when the reconstruction method applied, according to embodiments disclosed herein. Other methods for estimates of HR during severe motion artifacts for PPG signal Zhilin, Z., P. Zhouyue, and L. Benyuan, TROIKA: A General Framework for Heart Rate Monitoring Using Wrist-Type Photoplethysmographic Signals During Intensive Physical Exercise. Biomedical Engineering, IEEE Transactions on, 2015. 62(2): p. 522-531; Zhang, Z., Photoplethysmography-Based Heart Rate Monitoring in Physical Activities via Joint Sparse Spectrum Reconstruction. Biomedical Engineering, IEEE Transactions on, 2015. PP(99): p. 1-1; Salehizadeh, S., et al., A Novel Time-Varying Spectral Filtering Algorithm for Reconstruction of Motion Artifact Corrupted Heart Rate Signals During Intense Physical Activities Using a Wearable Photoplethysmogram Sensor. Sensors, 2015. 16(1): p. 10) produced good results (Kalman, R.E., A New Approach to Linear Filtering and Prediction Problems Transactions of the ASME – Journal of Basic Engineering, 1960. Series D (82)). However, these methods are only confined to HR estimation and not SpO2. Specifically, previous PPG reconstruction methods, such as (Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263; Kim, B.S.

and S.K. Yoo, Motion artifact reduction in photoplethysmography using independent component analysis. IEEE Trans Biomed Eng, 2006. 53(3): p. 566-8), have been tested under MA conditions but not with concomitant hypoxia. The results, disclosed abele, illustrate the efficacy of a method which provides accurate estimates of both SpO2 and HR even when there are significant MA and concomitant low oxygen saturation values.

[00218] Observations were made while analyzing the OxiMA data. The tracking ability of the OxiMA method decreased as the frequency changes during recordings increased. This is mostly likely because OxiMA tracks a dominant frequency through an 8-second window. Since each subjects' motion varied throughout each hypoxic maneuver, the dominant frequency can change within the observed window. The strength of the PPG's LED is one of the most important factors determining the performance. A reduction in the strength of the PPG signal can be caused by ambient light leaking into the gap between a PPG sensor and the skin surface (Zhang, Z., Photoplethysmography-Based Heart Rate Monitoring in Physical Activities via Joint Sparse Spectrum Reconstruction. Biomedical Engineering, IEEE Transactions on, 2015. PP(99): p. 1-1). This is because the power of the signal is dependent on the depth and reflection of the light from the pulse oximeter sensor to the subject's skin. This gap between the skin and the sensor may be the result of movement during physical activities or the shape of tissue that the sensors touch. In the datasets that have been analyzed, recordings #5 and #7 are examples of the above two scenarios.

[00219] Additionally, the local blood perfusion of the monitored region affects the signal-to-noise ratio of the PPG signal. When performing the hypoxic maneuvers, subjects' HR and breathing rate normally increase as oxygen saturation decreases. These physiologic changes cause more distinct pulsations in the digits, which increase the signal-to-noise ratio.

[00220] The OxiMA method can be easily implemented in real-time. Execution time of the method has been found to be only 180 msec on data divided into 8 second segments using Matlab® R2014a and CPU 3.6GHz. Therefore, given the high accuracy of the OxiMA method in estimating HR and SpO2 despite severe motion artifacts, this method has the potential to be applicable for implementation on wearable devices such as smart watches and PPG-based fitness sensors.

[00221] FIG. 23 is a block diagram of an example of the internal structure of a computer 2300 in which various embodiments of the present disclosure may be implemented. The computer 2300 contains a system bus 2302, where a bus is a set of hardware lines used for

data transfer among the components of a computer or processing system. The system bus 2302 is essentially a shared conduit that connects different elements of a computer system (*e.g.*, processor, disk storage, memory, input/output ports, network ports, *etc.*) that enables the transfer of information between the elements. Coupled to the system bus 2302 is an I/O device interface 2304 for connecting various input and output devices (*e.g.*, keyboard, mouse, displays, printers, speakers, *etc.*) to the computer 2300. A network interface 2306 allows the computer 2300 to connect to various other devices attached to a network. Memory 2308 provides volatile storage for computer software instructions 2310 and data 2312 that may be used to implement embodiments of the present disclosure. Disk storage 2314 provides non-volatile storage for computer software instructions 2310 and data 2312 that may be used to implement embodiments of the present disclosure. A central processor unit 2318 is also coupled to the system bus 2302 and provides for the execution of computer instructions.

[00222] Further example embodiments disclosed herein may be configured using a computer program product; for example, controls may be programmed in software for implementing example embodiments. Further example embodiments may include a non-transitory computer-readable medium containing instructions that may be executed by a processor, and, when loaded and executed, cause the processor to complete methods described herein. It should be understood that elements of the block and flow diagrams, such as the reconstruction unit 416, output unit 418, reconstruction unit 516, output unit 518, heart rate unit, arterial oxygen saturation (SpO2) unit, and ailment unit, disclosed above, may be implemented in software, hardware, such as via one or more arrangements of circuitry of FIG. 23, disclosed above, or equivalents thereof, firmware, a combination thereof, or other similar implementation determined in the future. In addition, the elements of the block and flow diagrams described herein may be combined or divided in any manner in software, hardware, or firmware. If implemented in software, the software may be written in any language that can support the example embodiments disclosed herein. The software may be stored in any form of computer readable medium, such as random access memory (RAM), read only memory (ROM), compact disk read-only memory (CD-ROM), and so forth. In operation, a general purpose or application-specific processor or processing core loads and executes software in a manner well understood in the art. It should be understood further that the block and flow diagrams may include more or fewer elements, be arranged or oriented differently, or be represented differently. It should be understood that implementation may

dictate the block, flow, and/or network diagrams and the number of block and flow diagrams illustrating the execution of embodiments disclosed herein.

[00223] The teachings of all patents, published applications and references cited herein are incorporated by reference in their entirety.

[00224] While this invention has been particularly shown and described with references to example embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the invention encompassed by the appended claims.

CLAIMS

What is claimed is:

1. A method for reconstructing a heart-related signal output by a biomedical sensor, the method comprising:

reconstructing a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal, the reconstructing based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of the movement; and

outputting the reconstructed representation of the heart-related signal.

2. The method of Claim 1, wherein the motion artifacts are suppressed in the reconstructed representation of the heart-related signal.

3. The method of Claim 1, wherein:

the time-varying spectral analysis includes pre-processing the heart-related signal to produce a pre-processed heart-related signal; and

in an event the classification indicates that the movement does not rise to a level causing the motion artifacts, the reconstructed representation is based on an average value of peak-to-peak intervals in the pre-processed heart-related signal.

4. The method of Claim 3, wherein the pre-processing includes filtering the heart-related signal to produce a filtered heart-related signal.

5. The method of Claim 4, wherein the pre-processing further includes down-sampling the filtered heart-related signal, the down-sampling being at a sampling rate less than an original sampling rate.

6. The method of Claim 1, wherein the time-varying spectral analysis includes:

computing a first time-frequency spectrum (TFS) of the heart-related signal; and

computing a second TFS of the motion signal.

7. The method of Claim 6, wherein the first TFS computed and the second TFS computed are 3-dimensional spectra, the first TFS computed and the second TFS computed each including a respective time-varying amplitude or power distribution with respect to time and frequency.

8. The method of Claim 6, wherein the first TFS computed is a first time-varying power spectral density (PSD) and the second TFS computed is a second time-varying PSD.

9. The method of Claim 6, wherein the reconstructed representation is a current reconstructed representation and wherein, based on the classification indicating that the movement does rise to a level causing the motion artifacts and is a pseudo-periodic movement or a periodic movement, the reconstructing includes:

determining whether at least one spectral peak is present having a corresponding frequency within a given frequency range at a point in time in the first TFS computed, the current reconstructed representation being reconstructed for the point in time; and

wherein, based on a determination that the at least one spectral peak is not present, the current reconstructed representation is based on a prior reconstructed representation, the prior reconstructed representation associated with a previous point in time in the first TFS computed.

10. The method of Claim 9, wherein the given frequency range is 0.5 Hz to 3 Hz.

11. The method of Claim 6, wherein the reconstructing includes:

retaining up to a pre-determined number of candidate spectral peaks located at a first point in time in the first TFS computed, the candidate spectral peaks retained based on having corresponding frequencies within a given frequency range and

highest amplitude or power values relative to other spectral peaks located at the first point in time, the other spectral peaks having respective frequencies within the given frequency range; and

discarding each of the candidate spectral peaks retained that is associated with a same frequency as a dominant spectral peak located at a second point in time in the second TFS computed, the first point in time and the second point in time having same time values.

12. The method of Claim 11, wherein the given frequency range is 0.5 Hz to 3 Hz.

13. The method of Claim 11, wherein the representation is a current representation, wherein the reconstructed representation is a current reconstructed representation, and wherein, in an event the discarding discards each of the candidate spectral peaks retained, reconstructing the current representation is based on a prior reconstructed representation, the prior reconstructed representation associated with a previous point in time in the first TFS computed, the previous point in time being an earlier point in time with respect to the first point in time.

14. The method of Claim 11, wherein the discarding is a first discarding and wherein the representation is a current representation and, wherein, in an event the first discarding results in at least one remaining candidate spectral peak retained, reconstructing the current representation further includes:

second discarding, wherein the second discarding discards remaining candidate spectral peaks, of the at least one remaining candidate spectral peak retained, based on whether a corresponding frequency of the at least one remaining candidate spectral peak retained is distanced by at least a frequency difference threshold from a prior reconstructed representation's frequency, the prior reconstructed representation associated with a previous point in time in the first TFS computed, the previous point in time being an earlier point in time with respect to the first point in time.

15. The method of Claim 14, wherein:

based on each of the at least one remaining candidate spectral peak retained having been discarded by the second discarding, reconstructing the current representation is based on the prior reconstructed representation; and

based on at least one last candidate spectral peak remaining, the at least one last candidate spectral peak remaining not discarded by the second discarding, reconstructing the current representation is based on a selected candidate spectral peak selected from amongst the at least one last candidate spectral peak remaining having a closest corresponding frequency to the prior reconstructed representation's frequency relative to respective frequencies of each of the at least one last candidate spectral peak remaining.

16. The method of Claim 11, wherein the dominant spectral peak has a largest power or amplitude value relative to other peaks located at the second point in time in the second TFS.

17. The method of Claim 11, wherein the retaining and the discarding are based on:

the classification indicating that the movement is a pseudo-periodic movement or a periodic movement; and

determining that at least one spectral peak with a corresponding frequency in the given frequency range is present at the first point in time.

18. The method of Claim 6, wherein the time-varying spectral analysis further includes pre-processing the heart-related signal and the motion signal for the computing of the first TFS and the second TFS.

19. The method of Claim 6, wherein the pre-processing includes filtering the heart-related signal and the motion signal to produce a filtered heart-related signal and a filtered motion signal, respectively.

20. The method of Claim 19, wherein the pre-processing further includes down-sampling both the filtered heart-related signal and the filtered motion signal, the down-sampling being at a sampling rate less than an original sampling rate.

21. The method of Claim 6, further including:

classifying the classification of the movement by comparing an amount of amplitude modulation in the second TFS computed to an amplitude modulation threshold, wherein the classification indicates whether the movement rises to a level of causing the motion artifacts based on a result of the comparing.

22. The method of Claim 21, wherein the amplitude modulation threshold is dependent on a type of the motion detector sensor.

23. The method of Claim 21, wherein, in an event the result indicates that the movement does rise to the level causing the motion artifacts, classifying the classification of the movement further includes determining whether the movement is either a pseudo-periodic movement or a periodic movement, versus a random movement.

24. The method of Claim 23, wherein, in determining whether the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement includes, the method further includes:

identifying a first, second, and third frequency associated, respectively, with a first, second, and third spectral peak in the second TFS at a point in time in the second TFS, the first, second, and third peaks having largest power or amplitude values relative to other peaks in the second TFS at the point in time, the first spectral peak being a largest spectral peak amongst the first, second, and third spectral peaks;

computing a first ratio of the second frequency identified to the first frequency identified and determining a first comparison result by comparing the first ratio computed to a first ratio value; and

computing a second ratio of the third frequency identified to the first frequency identified and determining a second comparison result by comparing the second ratio computed to a second ratio value, wherein the classification further indicates that the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement, based on the first comparison result and the second comparison result.

25. The method of Claim 24, wherein the first ratio value is 2 and the second ratio value is 3.

26. The method of Claim 1, wherein the time-varying signal analysis includes pre-processing the heart-related signal to produce a pre-processed heart-related signal and, in an event the classification of the movement indicates random movement, the reconstructing includes:

computing an average value of a number of prior reconstructed representations outputted prior to the reconstructing, the number based on a duration of consecutive motion artifacts, detected prior to the reconstructing;

computing a bandpass filter cutoff frequency based on the average value computed;

filtering the pre-processed heart-related signal by applying the band pass filter computed to produce a filtered, pre-processed heart-related signal; and

wherein the reconstructed representation is based on an average peak-to-peak interval value of the filtered, pre-processed heart-related signal.

27. The method of Claim 1, wherein the heart-related signal and the motion signal are produced, concurrently.

28. The method of Claim 1, further comprising:

segmenting the heart-related signal into a plurality of windowed heart-related signal data segments and the motion signal into a corresponding plurality of windowed motion signal data segments; and

repeating the reconstructing and the outputting for each windowed heart-related signal data segment and each corresponding motion signal data segment.

29. The method of Claim 28, wherein the time window is a value in a range from 2 to 32 seconds.

30. The method of Claim 1, wherein the biomedical sensor is at least one of: a photoplethysmogram (PPG) sensor, piezoelectric sensor, Light Emitting Diode (LED) based sensor, camera sensor, and pulse oximeter sensor, and wherein the motion sensor is an accelerometer.

31. The method of Claim 1, wherein the biomedical sensor and the motion sensor are co-located.

32. The method of Claim 1, further comprising employing the reconstructed representation to determine a heart rate estimate.

33. The method of Claim 1, further comprising employing the reconstructed representation to determine an arterial oxygen saturation (SpO2) estimate.

34. The method of Claim 1, further comprising employing the reconstructed representation to detect or predict a heart-related ailment, the heart-related ailment including at least one of a heart rate variability (HRV) condition, atrial fibrillation condition, congestive heart failure condition, and tachycardia condition.

35. The method of Claim 1, wherein the reconstructing and the outputting are performed in real-time with respect to production of the heart-related signal and the motion signal.

36. The method of Claim 1, wherein the reconstructing and the outputting are performed in non-real-time with respect to production of the heart-related signal and the motion signal.

37. An apparatus for reconstructing a heart-related signal output by a biomedical sensor, the apparatus comprising:

a reconstruction unit configured to reconstruct a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal, the reconstructing based on (i) a time-varying spectral analysis of the heart-related signal

and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of the movement; and

an output unit configured to output the reconstructed representation of the heart-related signal.

38. The apparatus of Claim 37, wherein the motion artifacts are suppressed in the reconstructed representation of the heart-related signal.

39. The apparatus of Claim 37, wherein:

the time-varying spectral analysis includes pre-processing the heart-related signal to produce a pre-processed heart-related signal; and

in an event the classification indicates that the movement does not rise to level causing the motion artifacts, the reconstructed representation is based on an average value of peak-to-peak intervals in the pre-processed heart-related signal.

40. The apparatus of Claim 39, wherein the pre-processing includes filtering the heart-related signal to produce a filtered heart-related signal.

41. The apparatus of Claim 40, wherein the pre-processing further includes down-sampling at a sampling rate less than an original sampling rate, the filtered heart-related signal, the down-sampling being at a sampling rate less than an original sampling rate.

42. The apparatus of Claim 37, wherein the time-varying spectral analysis includes:

computing a first time-frequency spectrum (TFS) of the heart-related signal; and

computing a second TFS of the motion signal.

43. The apparatus of Claim 42, wherein the first TFS computed and the second TFS computed are 3-dimensional spectra, the first TFS computed and the second TFS

computed each including a respective time-varying amplitude or power distribution with respect to time and frequency.

44. The apparatus of Claim 42, wherein the first TFS computed is a first time-varying power spectral density (PSD) and the second TFS computed is a second time-varying PSD.

45. The apparatus of Claim 42, wherein the reconstructed representation is a current reconstructed representation and wherein, based on the classification indicating that the movement does rise to a level causing the motion artifacts and is a pseudo-periodic movement or a periodic movement, to reconstruct the representation includes:

determining whether at least one spectral peak is present having a corresponding frequency within a given frequency range at a point in time in the first TFS computed, the current reconstructed representation being reconstructed for the point in time; and

wherein, based on a determination that the at least one spectral peak is not present, the reconstructed current representation is based on a prior reconstructed representation, the prior reconstructed representation associated with a previous point in time in the first TFS computed.

46. The apparatus of Claim 45, wherein the given frequency range is 0.5 Hz to 3 Hz.

47. The apparatus of Claim 42, wherein to reconstruct the representation includes:

retaining up to a pre-determined number of candidate spectral peaks located at a first point in time in the first TFS computed, the candidate spectral peaks retained based on having corresponding frequencies within a given frequency range and highest amplitude or power values relative to other spectral peaks located at the first point in time, the other spectral peaks having respective frequencies within the given frequency range; and

discarding each of the candidate spectral peaks retained that is associated with a same frequency as a dominant spectral peak located at a second point in time in the second TFS computed, the first point in time and the second point in time having same time values.

48. The apparatus of Claim 47, wherein the given frequency range is 0.5 Hz to 3 Hz.

49. The apparatus of Claim 47, wherein the representation is a current representation, wherein the reconstructed representation is a current reconstructed representation, and wherein, in an event the discarding discards each of the candidate spectral peaks retained, reconstructing the current representation is based on a prior reconstructed representation, the prior reconstructed representation associated with a previous point in time in the first TFS computed, the previous point in time being an earlier point in time with respect to the first point in time.

50. The apparatus of Claim 47, wherein the discarding is a first discarding and wherein the representation is a current representation and, wherein, in an event the first discarding results in at least one remaining candidate spectral peak retained, reconstructing the current representation further includes:

second discarding, wherein the second discarding discards remaining candidate spectral peaks, of the at least one remaining candidate spectral peak retained, based on whether a corresponding frequency of the at least one remaining candidate spectral peak retained is distanced by at least a frequency difference threshold from a prior reconstructed representation's frequency, the prior reconstructed representation associated with a previous point in time in the first TFS computed, the previous point in time being an earlier point in time with respect to the first point in time.

51. The apparatus of Claim 50, wherein:

based on each of the at least one remaining candidate spectral peak retained having been discarded by the second discarding, reconstructing the current representation is based on the prior reconstructed representation; and

based on at least one last candidate spectral peak remaining, the at least one last candidate spectral peak remaining not discarded by the second discarding, reconstructing the current representation is based on a selected candidate spectral peak selected from amongst the at least one last candidate spectral peak remaining having a closest corresponding frequency to the prior reconstructed representation's frequency relative to respective frequencies of each of the at least one last candidate spectral peak remaining.

52. The apparatus of Claim 47, wherein the dominant spectral peak has a largest power or amplitude value relative to other peaks located at the second point in time in the second TFS.

53. The apparatus of Claim 47, wherein the retaining and the discarding are based on:

the classification of the movement indicating that the movement is a pseudo-periodic movement or a periodic movement; and

determining that at least one spectral peak with a corresponding frequency in the given frequency range is present at the first point in time.

54. The apparatus of Claim 42, wherein the time-varying spectral analysis further includes pre-processing the heart-related signal and the motion signal for the computing of the first TFS and the second TFS.

55. The apparatus of Claim 42, wherein the pre-processing includes filtering the heart-related signal and the motion signal to produce a filtered heart-related signal and a filtered motion signal, respectively.

56. The apparatus of Claim 55, wherein the pre-processing further includes down-sampling both the filtered heart-related signal and the filtered motion signal, the down-sampling being at a sampling rate less than an original sampling rate.

57. The apparatus of Claim 42, further including a classification unit, the classification unit configured to:

classify the classification of the movement by comparing an amount of amplitude modulation in the second TFS computed to an amplitude modulation threshold, wherein the classification indicates whether the movement rises to a level causing the motion artifacts based on a result of the comparing.

58. The apparatus of Claim 57, wherein the amplitude modulation threshold is dependent on a type of the motion detector sensor.

59. The apparatus of Claim 57, wherein, in an event the result indicates that the movement does rise to the level causing the motion artifacts, the classification unit is further configured to classify the classification of the movement by determining whether the movement is either a pseudo-periodic movement or a periodic movement, versus a random movement.

60. The apparatus of Claim 59, wherein to determine whether the movement is either the pseudo-periodic movement or the periodic movement versus a random movement includes:

identifying a first, second, and third frequency associated, respectively, with a first, second, and third spectral peak in the second TFS at a point in time in the second TFS, the first, second, and third peaks having largest power or amplitude values relative to other peaks in the second TFS at the point in time, the first spectral peak being a largest spectral peak amongst the first, second, and third spectral peaks;

computing a first ratio of the second frequency identified to the first frequency identified and determining a first comparison result by comparing the first ratio computed to a first ratio value; and

computing a second ratio of the third frequency identified to the first frequency identified and determining a second comparison result by comparing the second ratio computed to a second ratio value, wherein the classification further indicates that the movement is either the pseudo-periodic movement or the periodic

movement, versus the random movement, based on the first comparison result and the second comparison result.

61. The apparatus of Claim 60, wherein the first ratio value is 2 and the second ratio value is 3.

62. The apparatus of Claim 59, wherein the time-varying signal analysis includes pre-processing the heart-related signal to produce a pre-processed heart-related signal and, in an event the classification of the movement indicates random movement, the reconstructing includes:

computing an average value of a number of prior reconstructed representations outputted prior to the reconstructing, the number based on a duration of consecutive motion artifacts, detected prior to the reconstructing;

computing a bandpass filter cutoff frequency based on the average value computed;

filtering the pre-processed heart-related signal by applying the band pass filter computed to produce a filtered, pre-processed heart-related signal; and

wherein the reconstructed representation is based on an average peak-to-peak interval value of the filtered, pre-processed heart-related signal.

63. The apparatus of Claim 37, wherein the heart-related signal and the motion signal are produced, concurrently.

64. The apparatus of Claim 37, further comprising segmentation unit configured to:

segment the heart-related signal into a plurality of windowed heart-related signal data segments and the motion signal into corresponding plurality of windowed motion signal data segments, wherein the reconstruction unit and the output unit reconstruct the representation and output the reconstructed representation, respectively, based on each windowed heart-related signal data segment and each corresponding motion signal data segment.

65. The apparatus of Claim 64, wherein the time window is a value in a range from 2 to 32 seconds.

66. The apparatus of Claim 37, wherein the biomedical sensor is at least one of: a photoplethysmogram (PPG) sensor, piezoelectric sensor, Light Emitting Diode (LED) based sensor, camera sensor, and pulse oximeter sensor, and wherein the motion sensor is an accelerometer.

67. The apparatus of Claim 37, wherein the apparatus includes the biomedical sensor and the motion sensor.

68. The apparatus of Claim 37, further comprising a heart rate estimator configured to employ the reconstructed representation to determine a heart rate estimate.

69. The apparatus of Claim 37, further comprising an arterial oxygen saturation (SpO2) unit configured to employ the reconstructed representation to determine a SpO2 estimate.

70. The apparatus of Claim 37, further comprising an ailment unit configured to employ the reconstructed representation to detect or predict a heart-related ailment, the heart-related ailment including at least one of a heart rate variability (HRV) condition, an atrial fibrillation condition, a congestive heart failure condition, and a tachycardia condition.

71. The apparatus of Claim 37, wherein the reconstruction unit and the output unit are configured to reconstruct and to output, respectively, in real-time with respect to production of the heart-related signal and the motion signal.

72. The apparatus of Claim 37, wherein the reconstruction unit and the output unit are configured to reconstruct and to output, respectively, in non-real-time with respect to production of the heart-related signal and the motion signal.

73. A non-transitory computer-readable medium having encoded thereon a sequence of instructions which, when loaded and executed by a processor, causes the processor to reconstruct a heart-related signal output by a biomedical sensor, the processor reconstructing the heart-related signal by:

reconstructing a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal, the reconstructing based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of the movement; and

outputting the reconstructed representation of the heart-related signal.

Petitioner Ex-1004, 0652

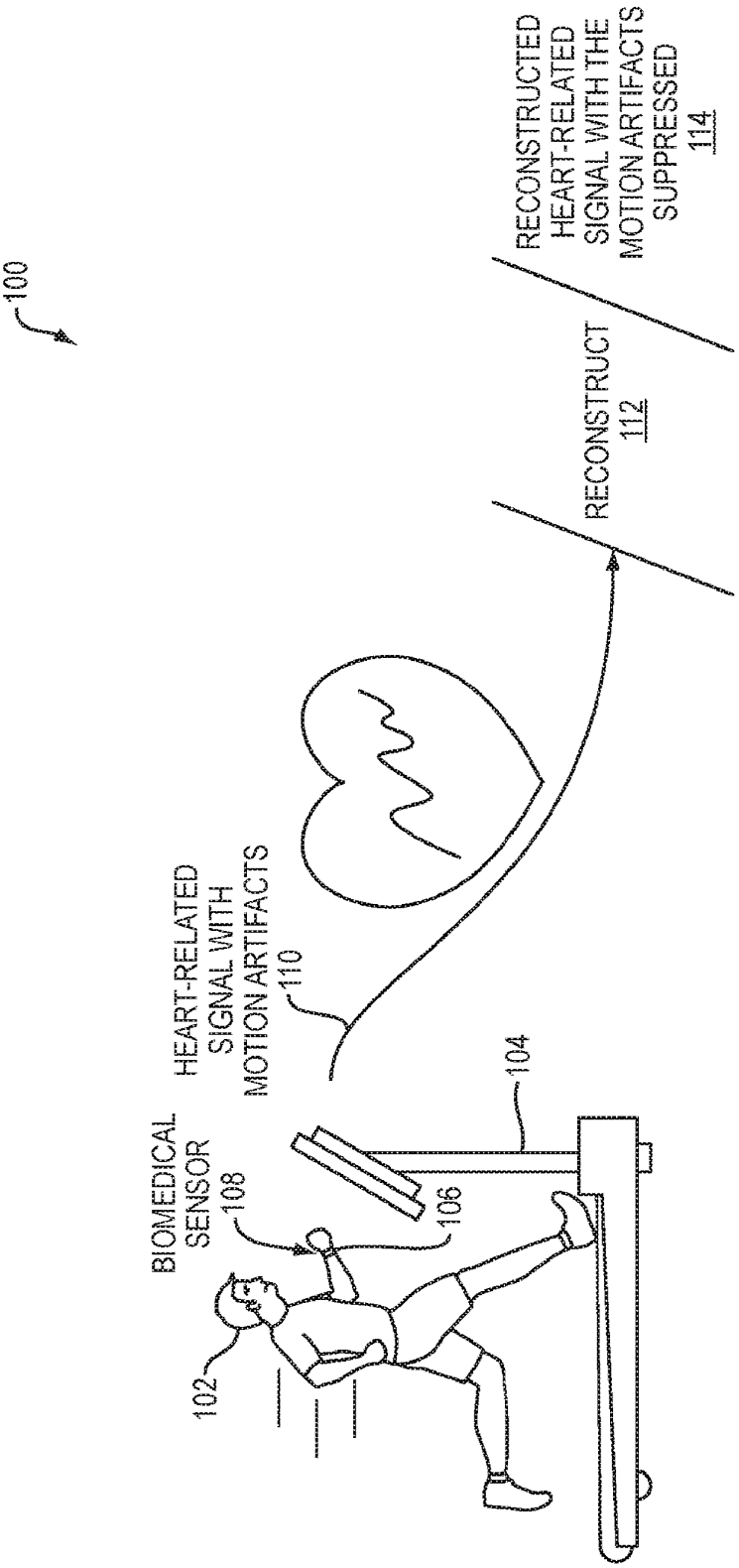


FIG. 1

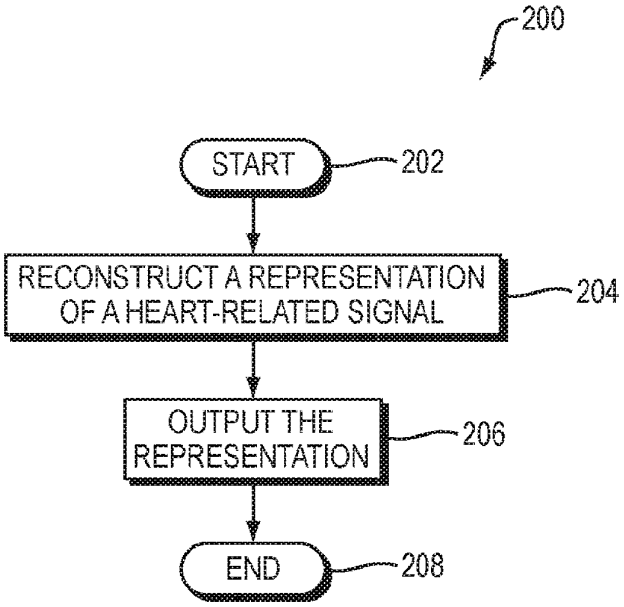

200
START
202
RECONSTRUCT A REPRESENTATION OF A HEART-RELATED SIGNAL
204
OUTPUT THE REPRESENTATION
206
END
208

FIG. 2

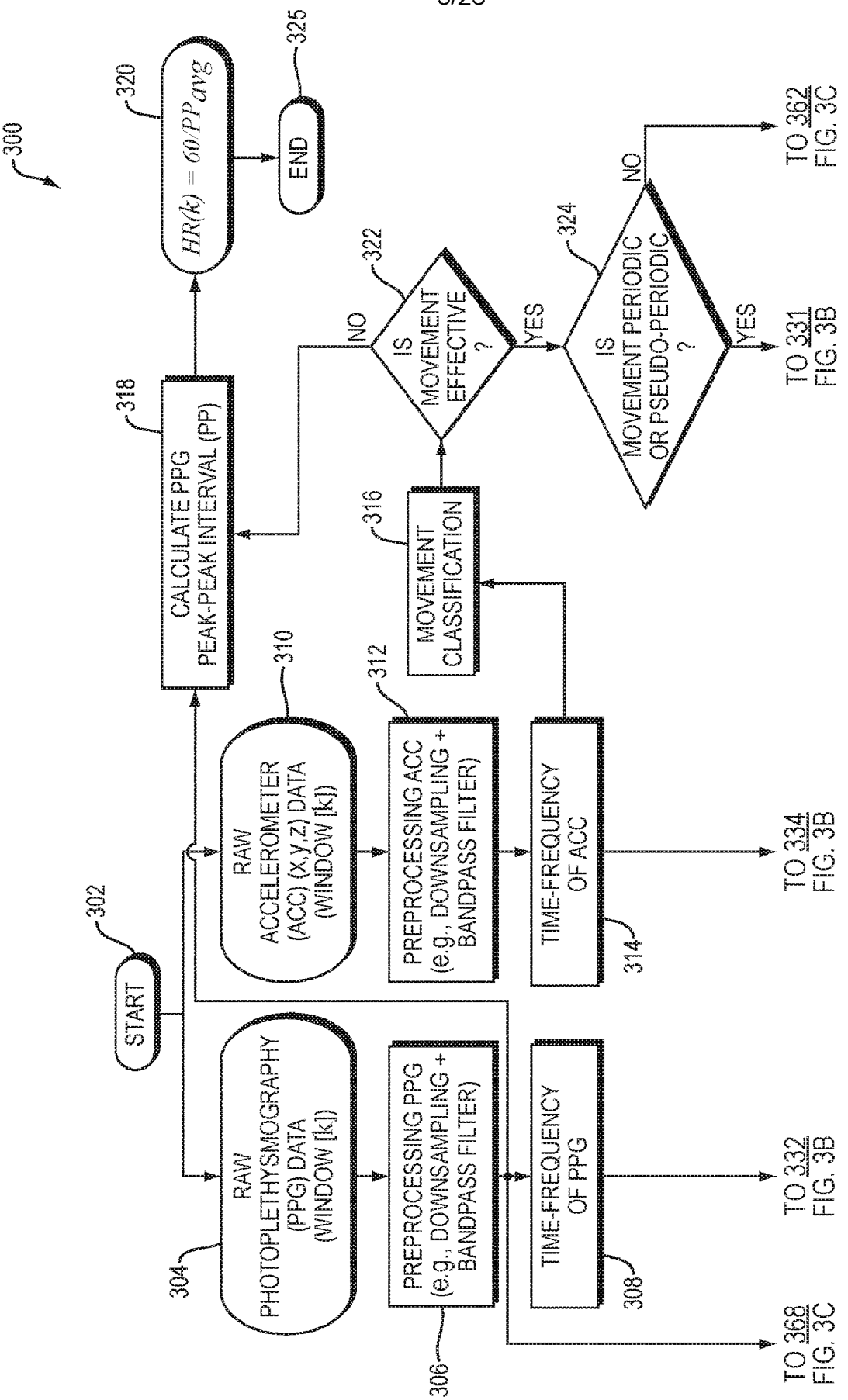


FIG. 3A

Petitioner Ex-1004, 0654

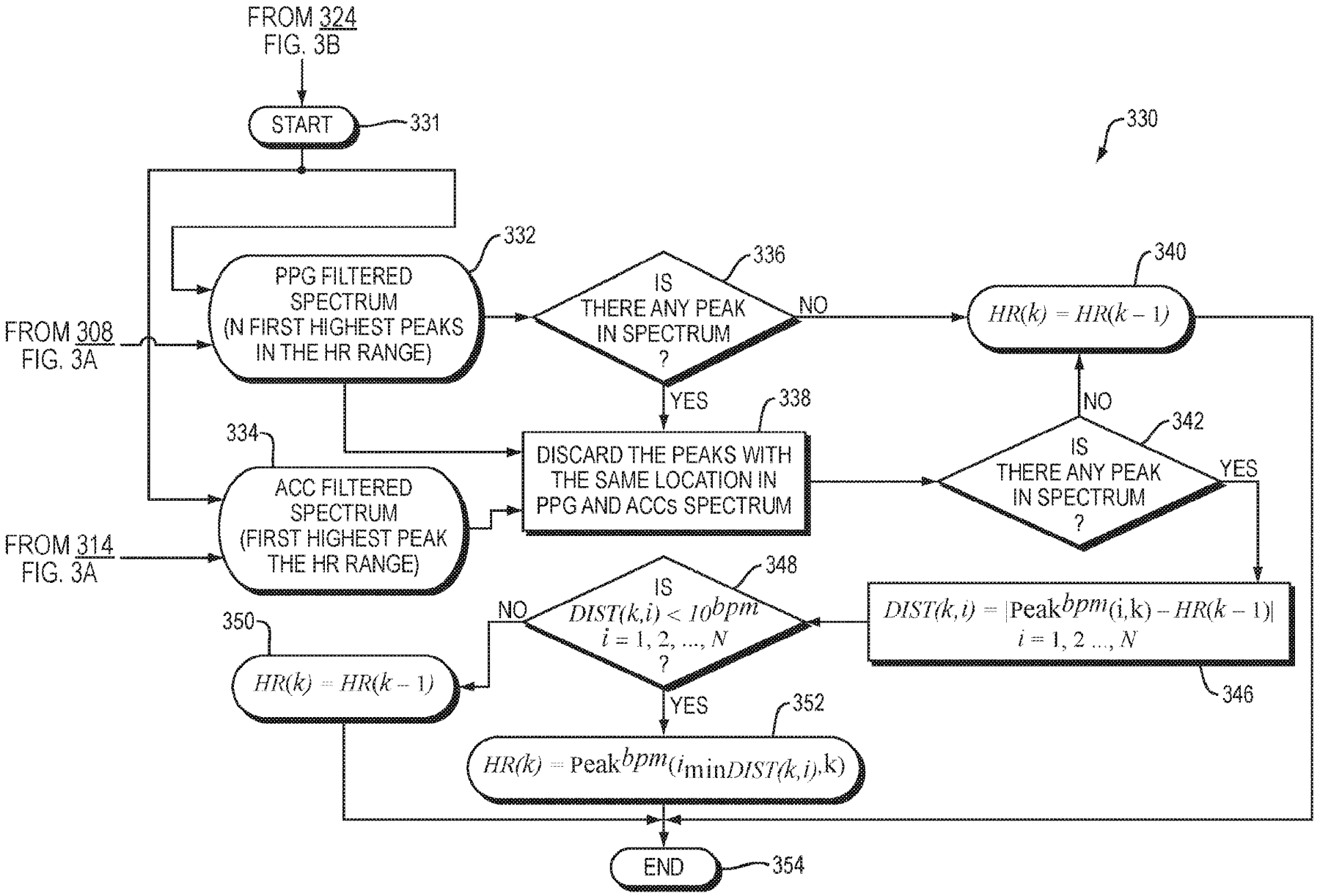

FROM 324
FIG. 3B
START
331
330
PPG FILTERED SPECTRUM (N FIRST HIGHEST PEAKS IN THE HR RANGE)
332
FROM 308
FIG. 3A
IS THERE ANY PEAK IN SPECTRUM ?
336
NO
YES
HR(k) = HR(k – 1)
340
NO
IS THERE ANY PEAK IN SPECTRUM ?
342
YES
DISCARD THE PEAKS WITH THE SAME LOCATION IN PPG AND ACCs SPECTRUM
338
334
ACC FILTERED SPECTRUM (FIRST HIGHEST PEAK THE HR RANGE)
FROM 314
FIG. 3A
IS DIST(k,i) < 10^bpm i = 1, 2, ..., N ?
348
NO
YES
DIST(k,i) = |Peak^bpm(i,k) – HR(k – 1)| i = 1, 2 ..., N
346
350
HR(k) = HR(k – 1)
HR(k) = Peak^bpm(i_minDIST(k,i),k)
352
END
354

FIG. 3B

Petitioner Ex-1004, 0656

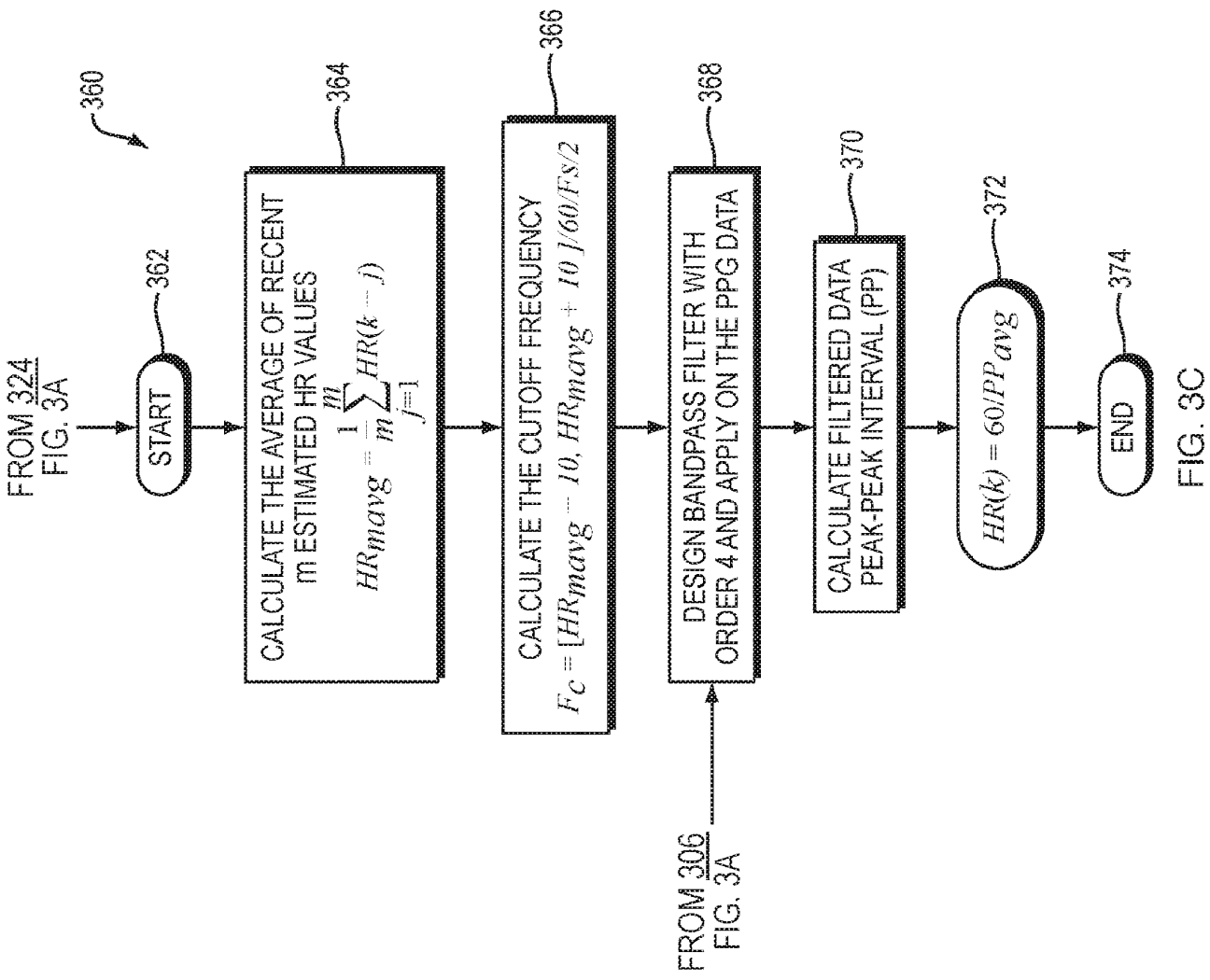


FIG. 3C

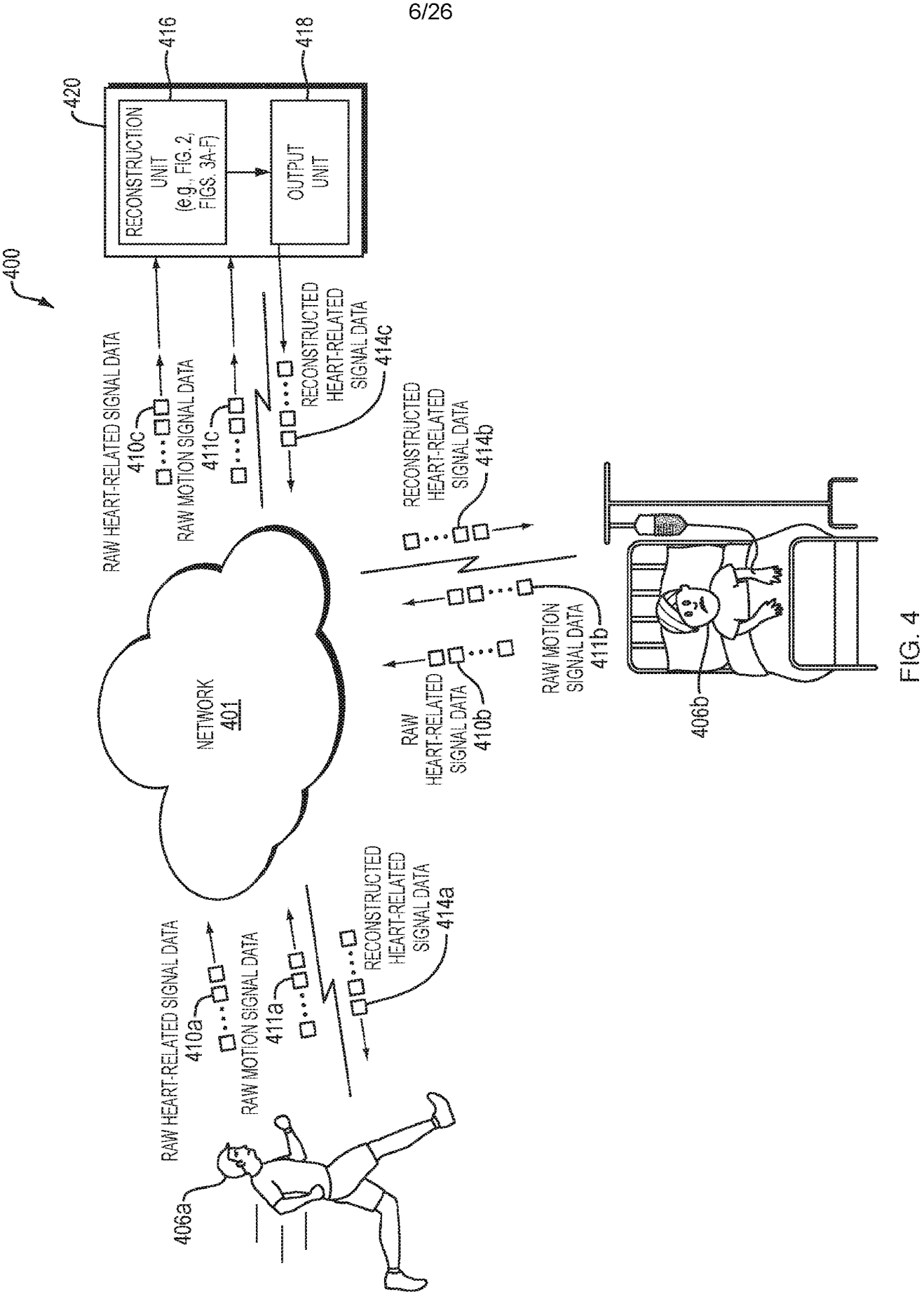


FIG. 4

Petitioner Ex-1004, 0657

Petitioner Ex-1004, 0658

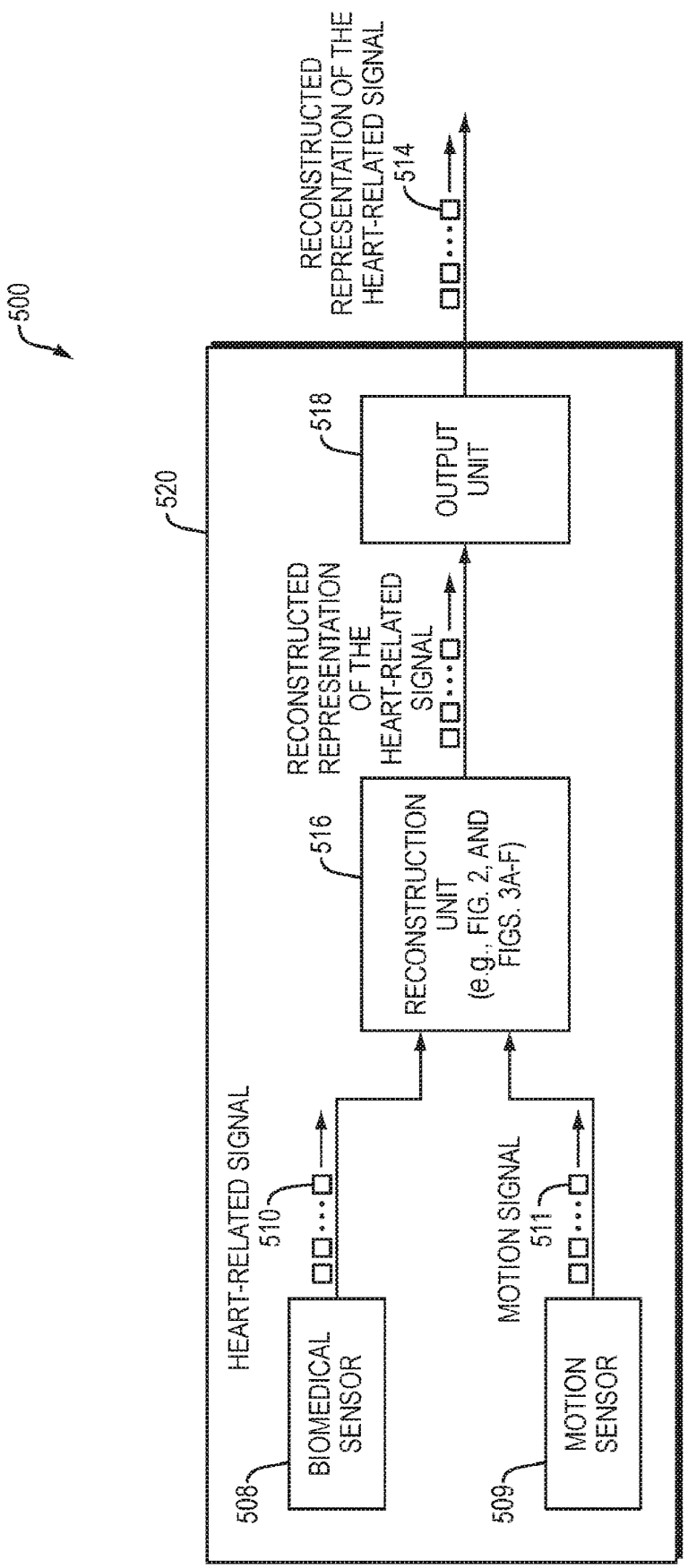


FIG. 5

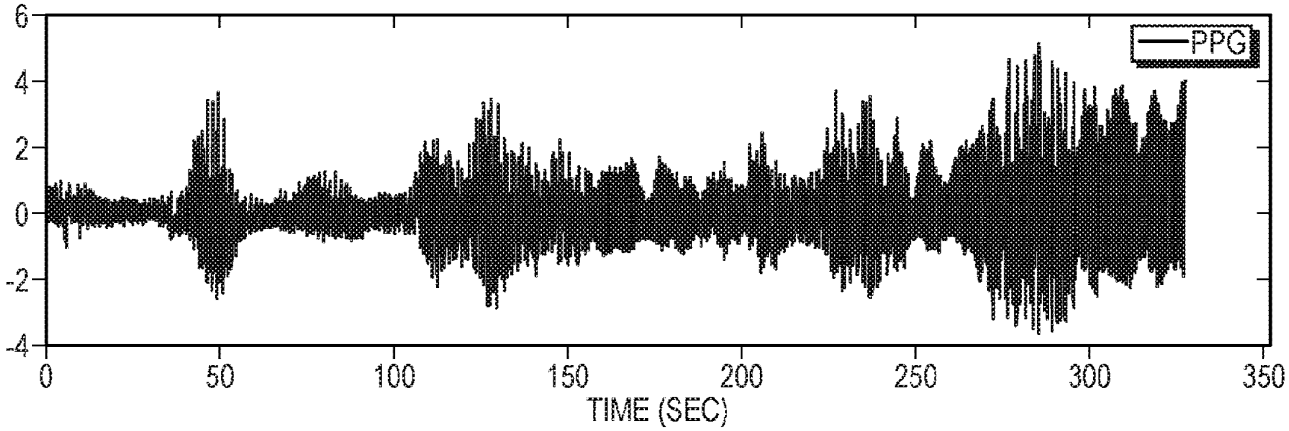


FIG. 6A

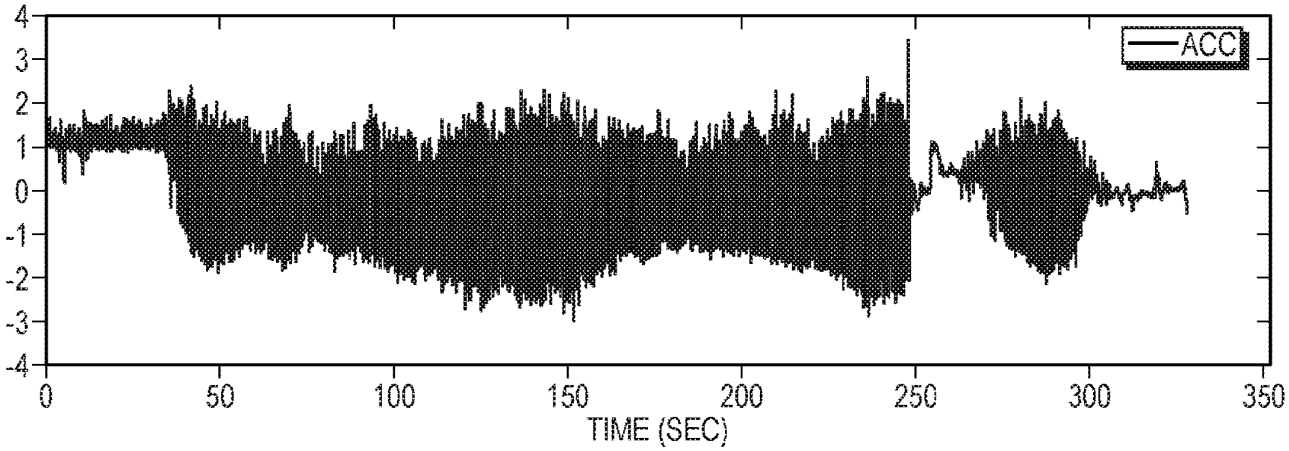


FIG. 6B

Petitioner Ex-1004, 0659

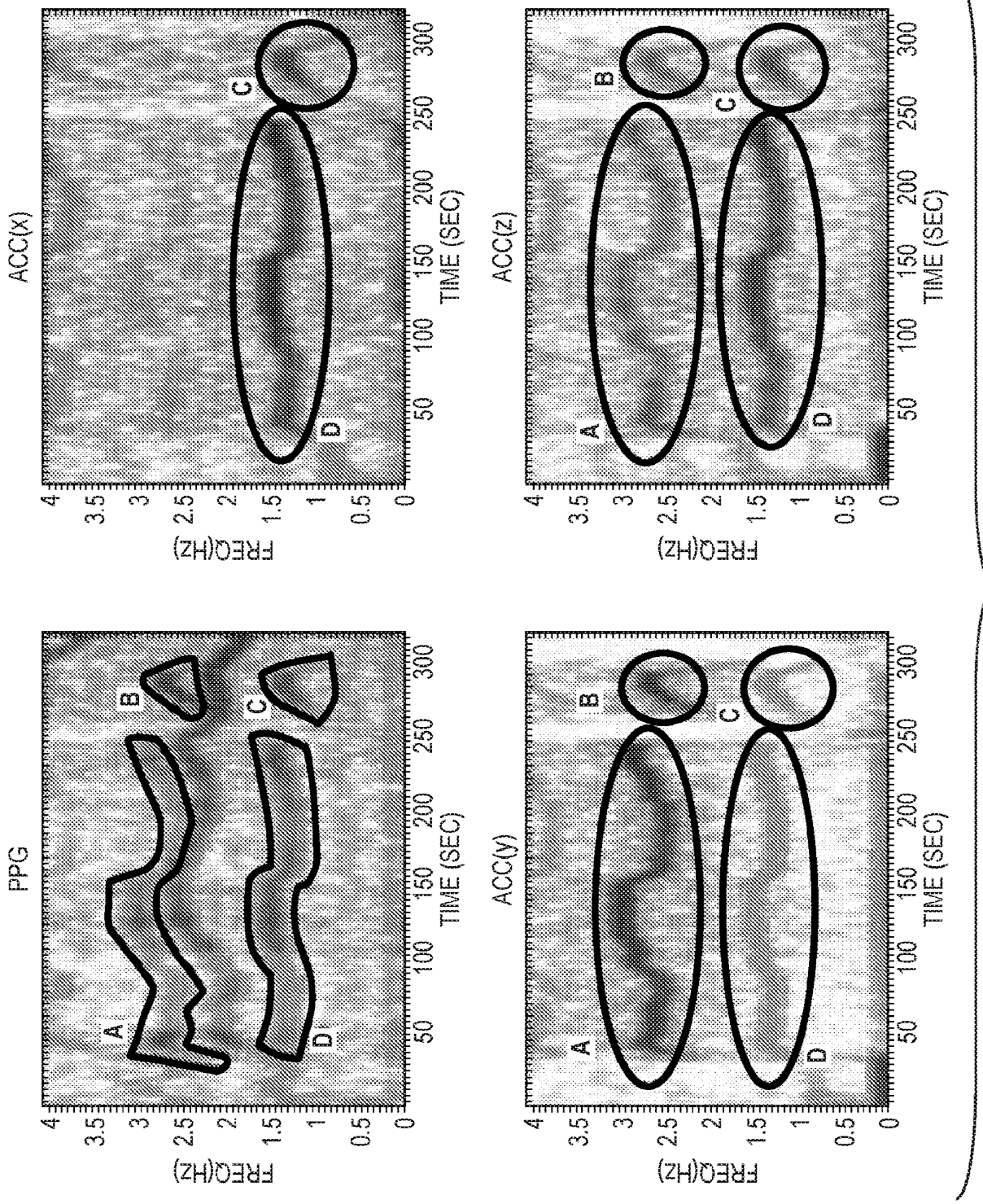


FIG. 6C

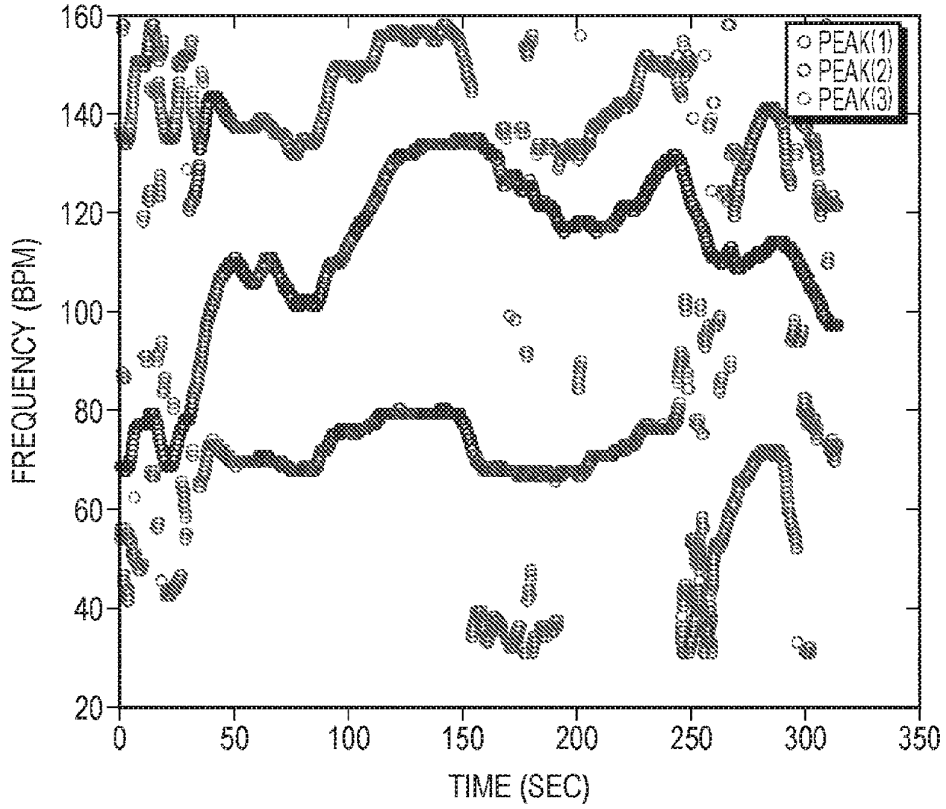

160
140
120
100
80
60
40
20
FREQUENCY (BPM)
0
50
100
150
200
250
300
350
TIME (SEC)
PEAK(1)
PEAK(2)
PEAK(3)

FIG. 7

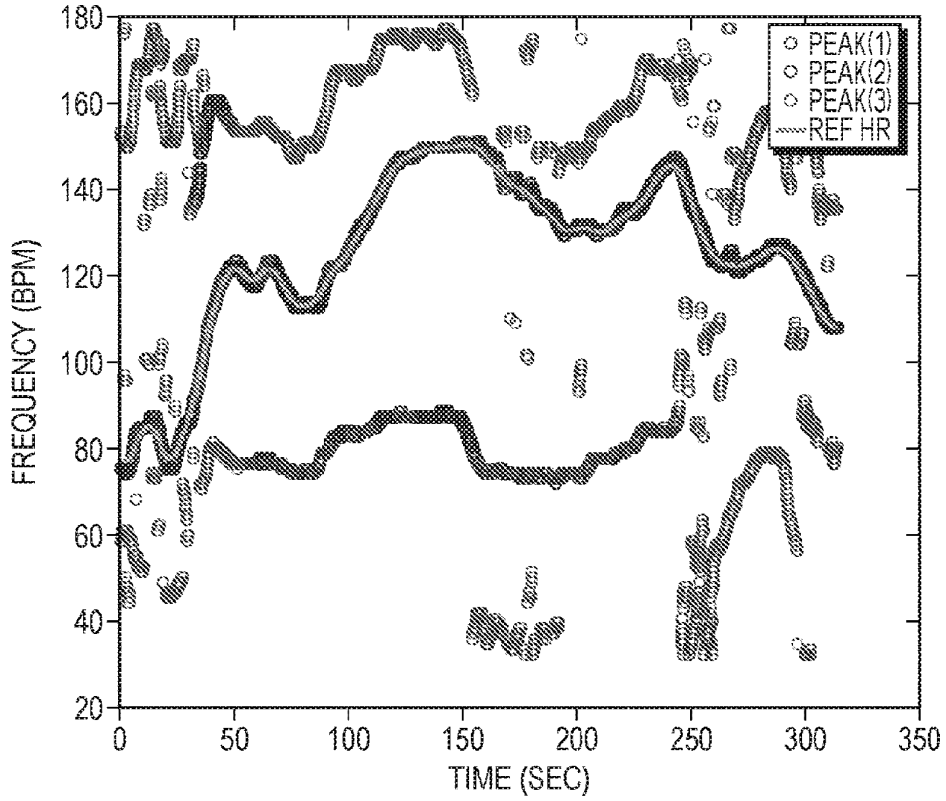

PEAK(1)
PEAK(2)
PEAK(3)
REF HR
FREQUENCY (BPM)
TIME (SEC)
180
160
140
120
100
80
60
40
20
0
50
100
150
200
250
300
350

FIG. 8A

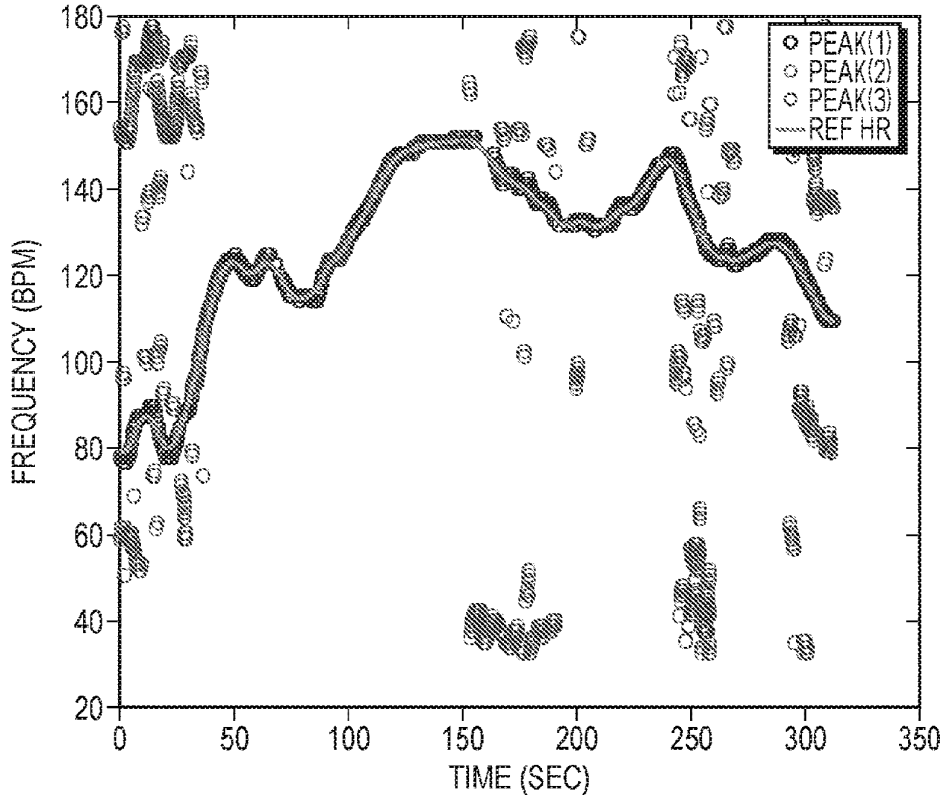

PEAK(1)
PEAK(2)
PEAK(3)
REF HR
FREQUENCY (BPM)
TIME (SEC)
180
160
140
120
100
80
60
40
20
0
50
100
150
200
250
300
350

FIG. 8B

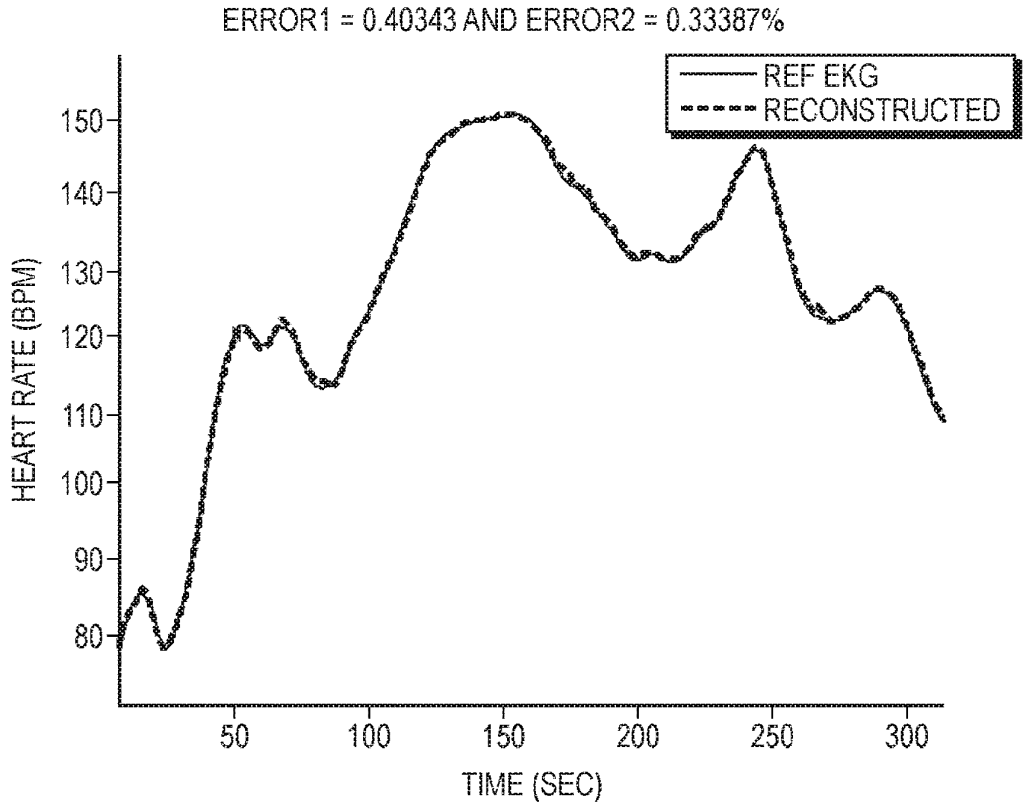


FIG. 9

Petitioner Ex-1004, 0663

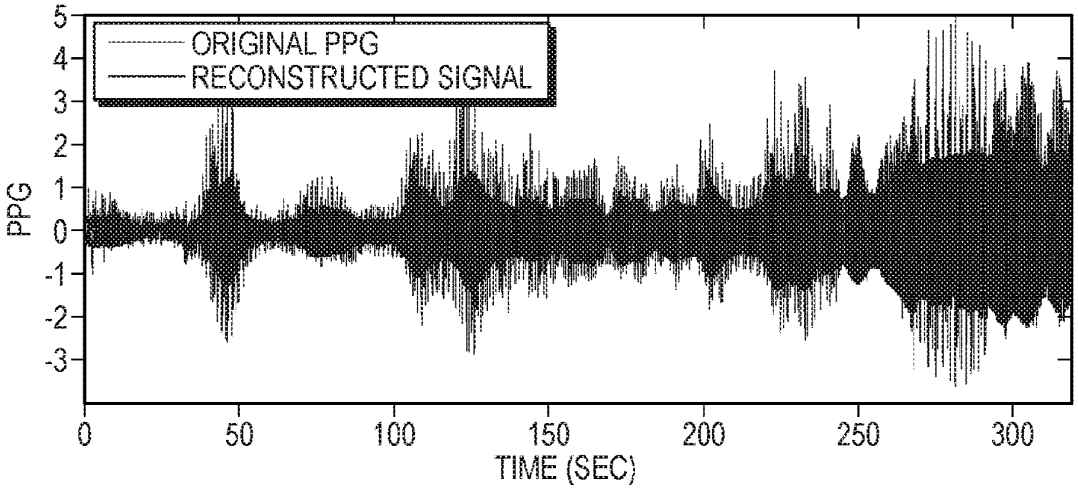


FIG. 10A

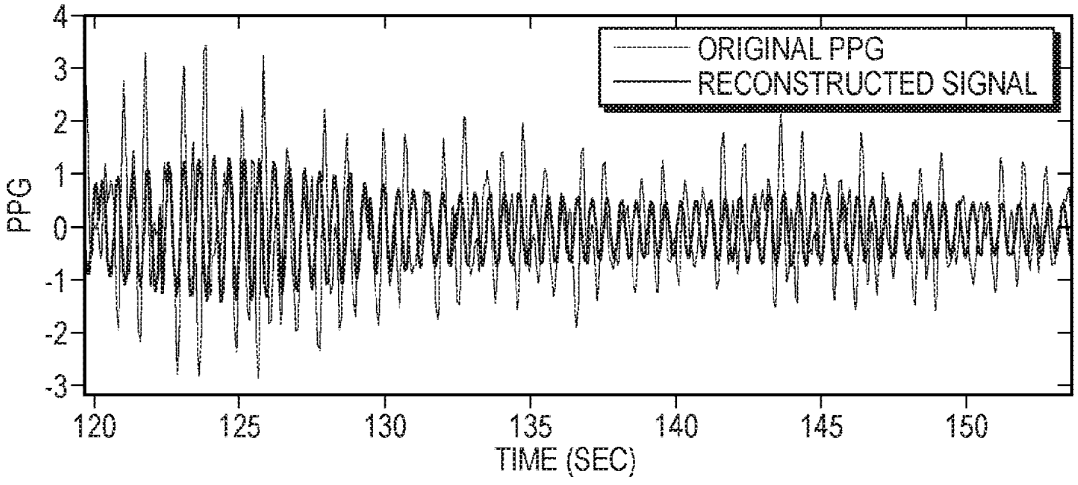


FIG. 10B

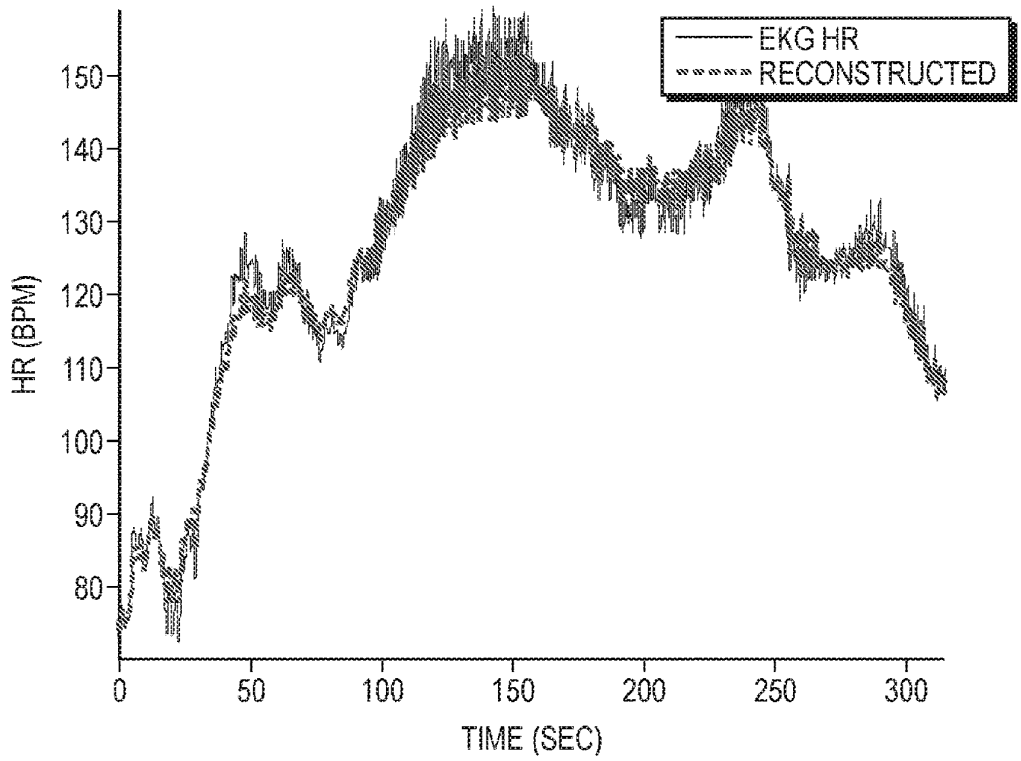


FIG. 11A

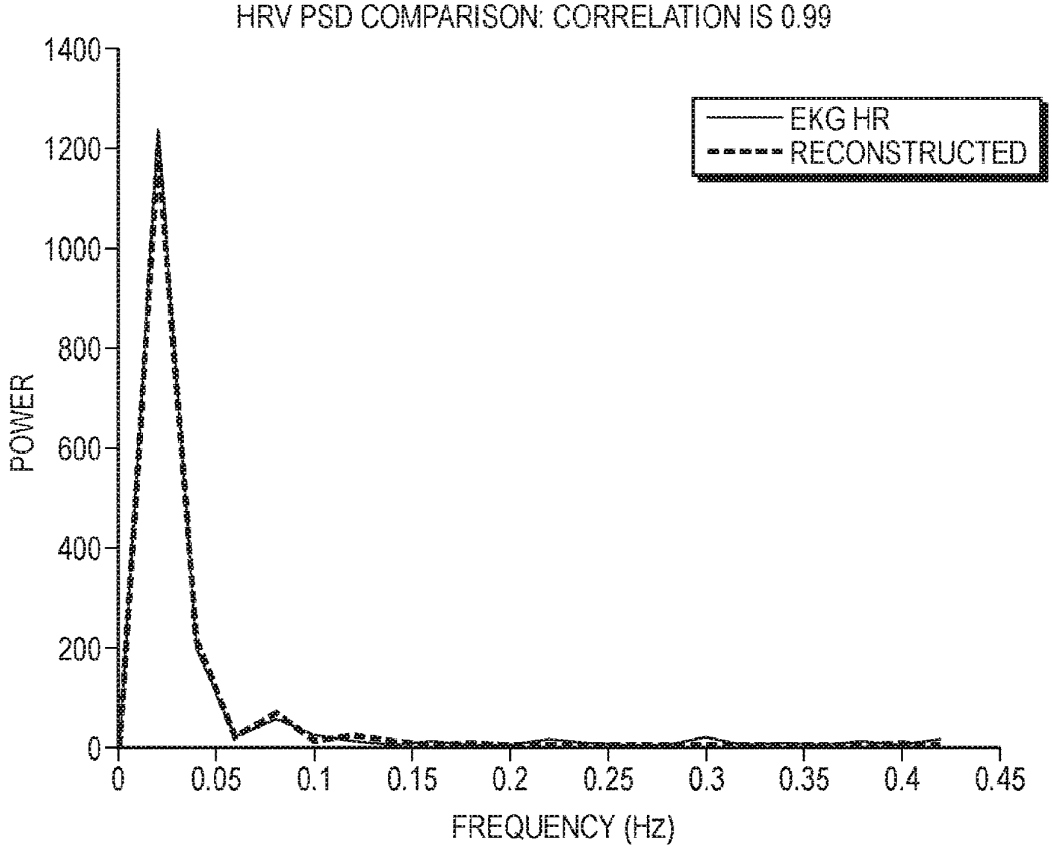


FIG. 11B

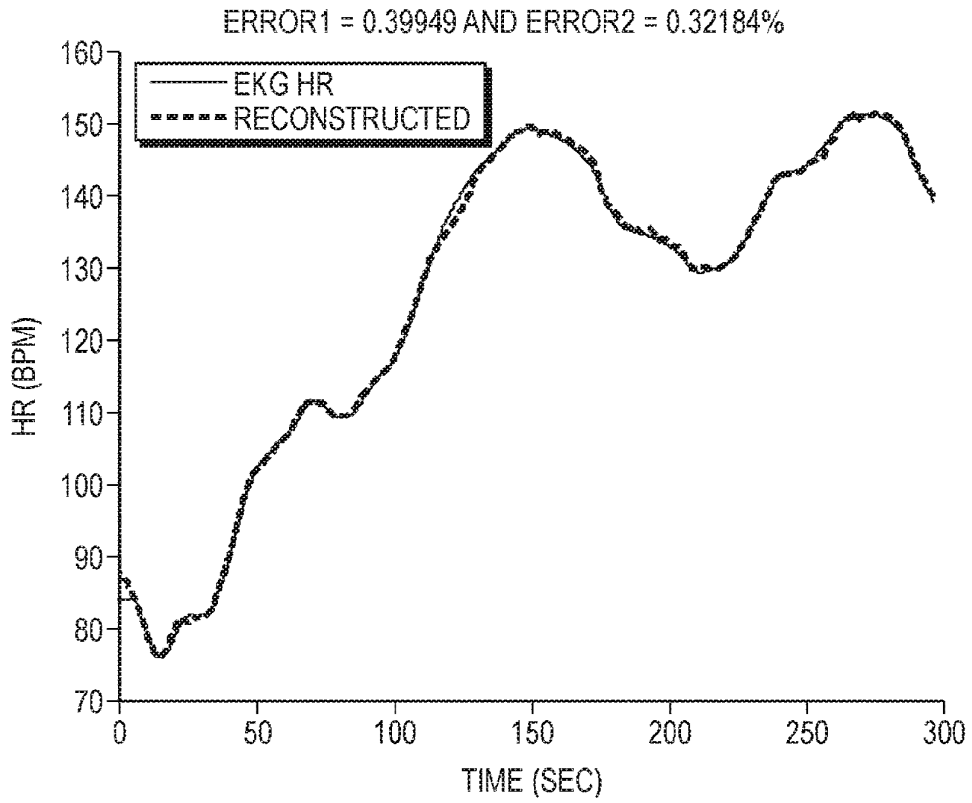


FIG. 12A

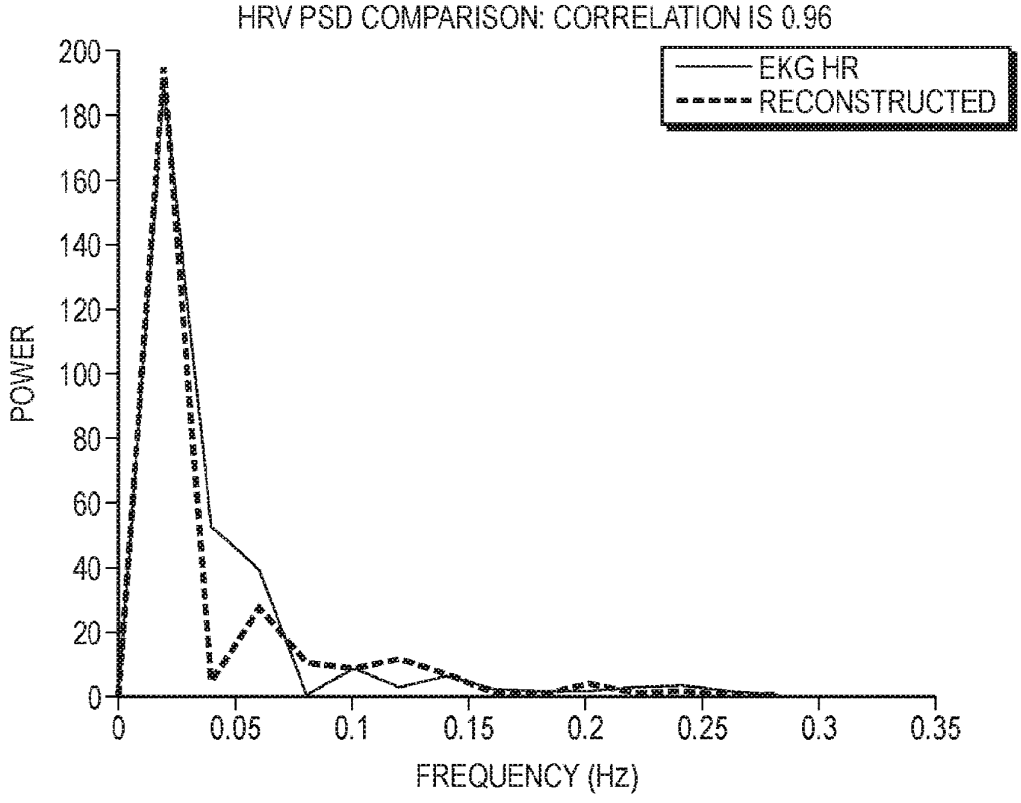


FIG. 12B

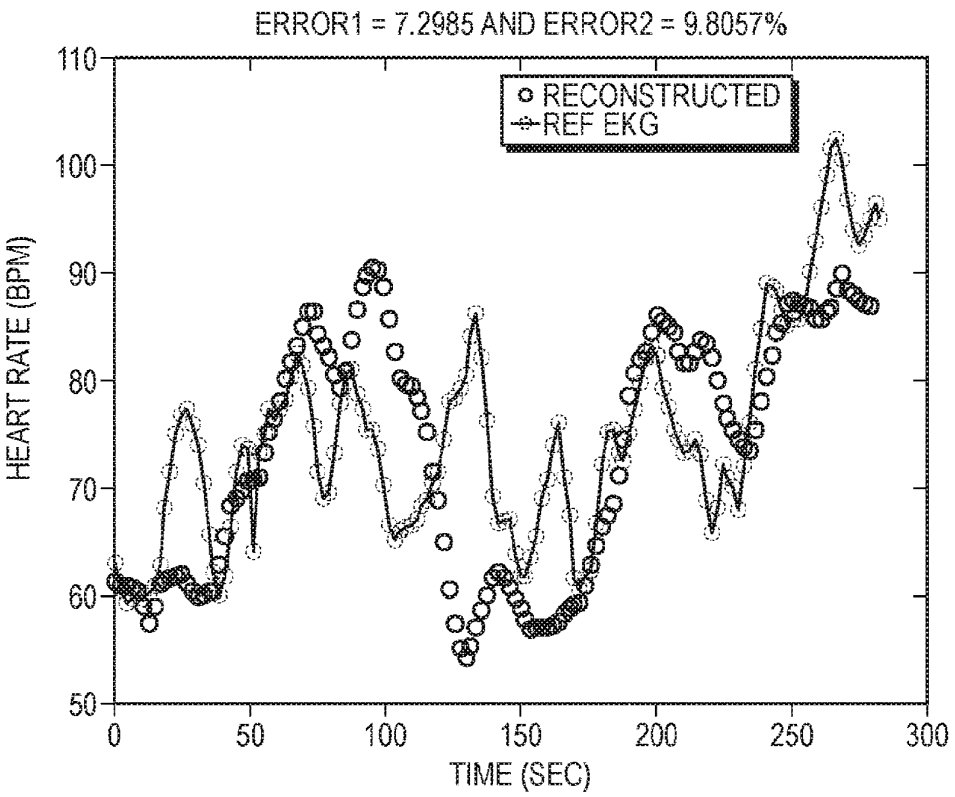


FIG. 13A

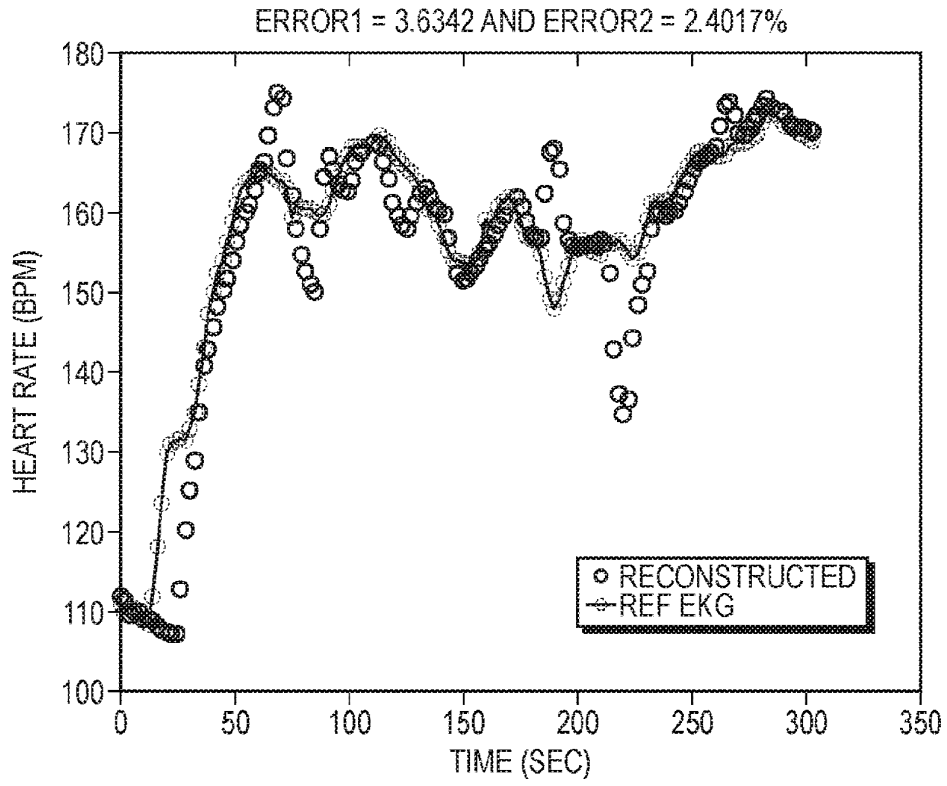


FIG. 13B

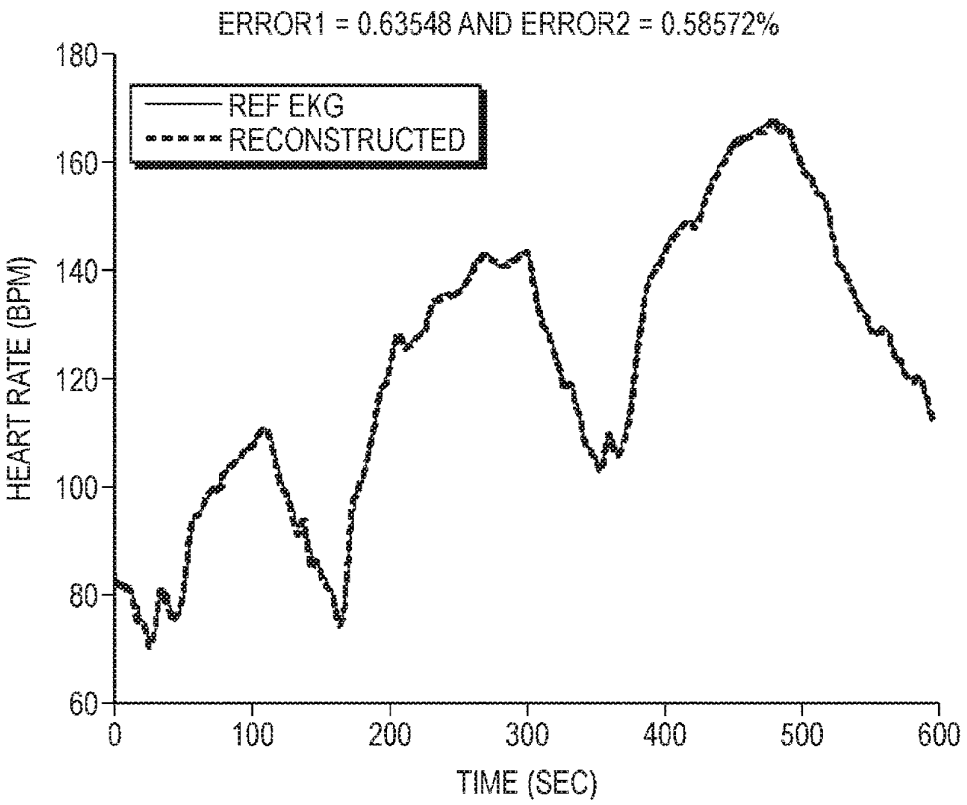


FIG. 14A

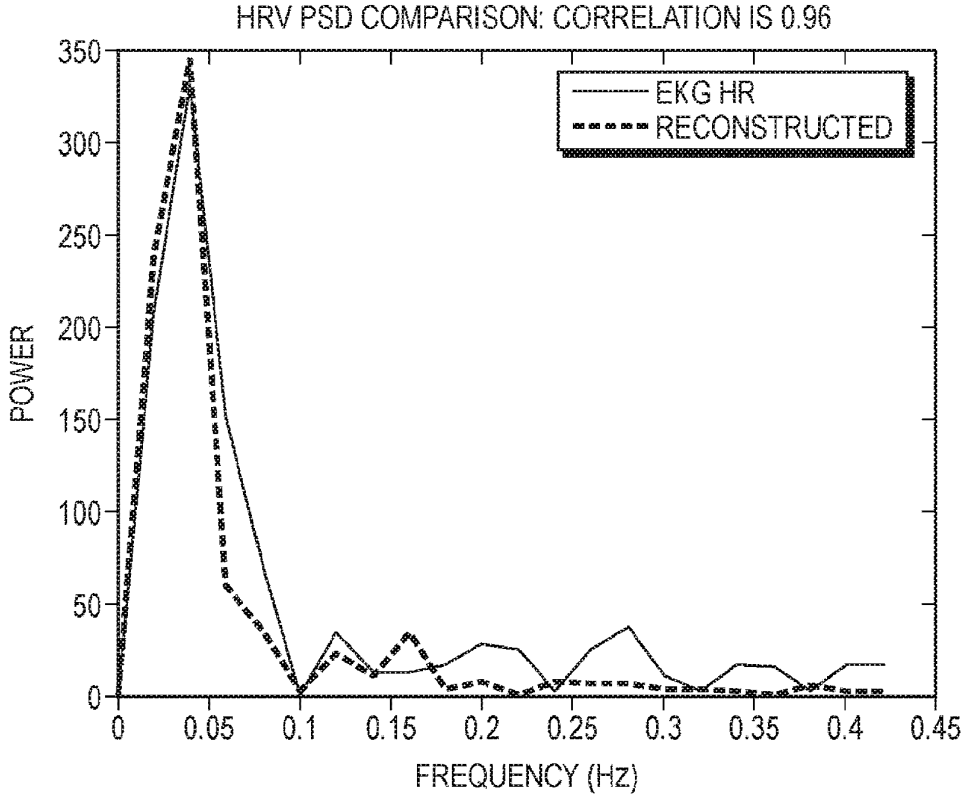


FIG. 14B

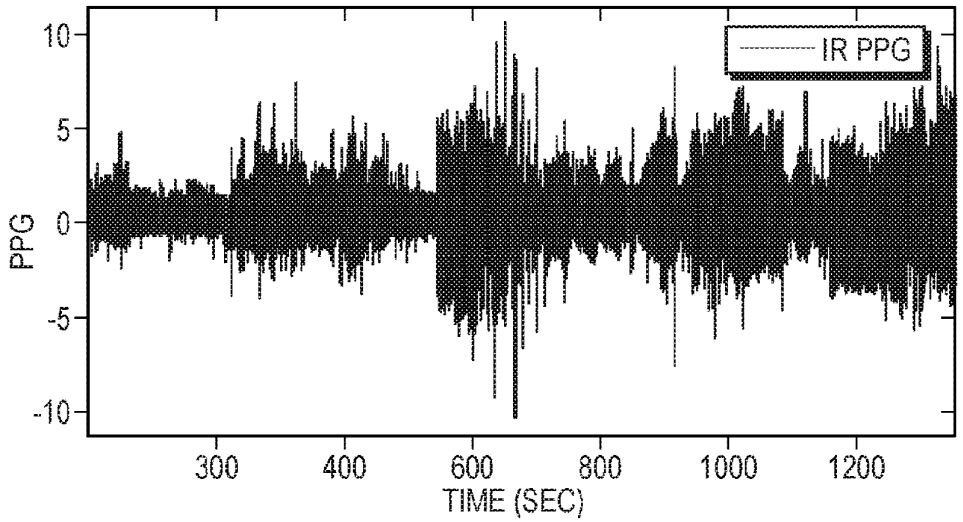


FIG. 15A

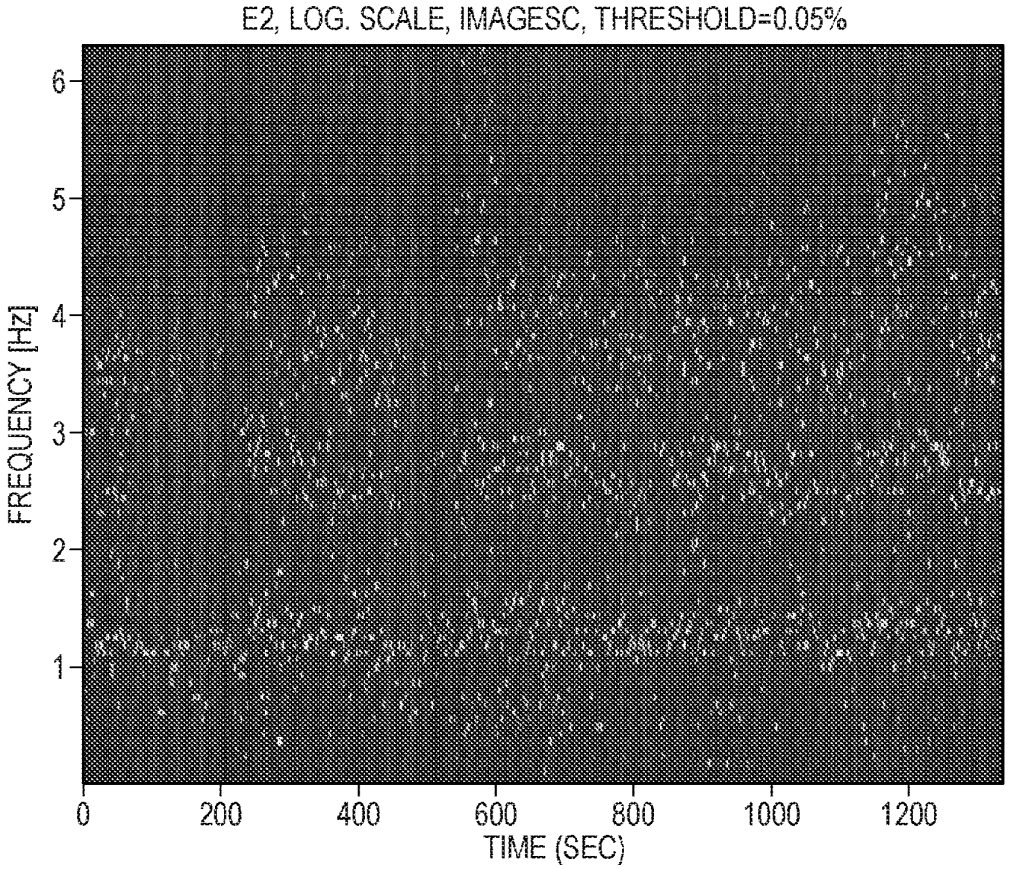


FIG. 15B

Petitioner Ex-1004, 0669

Petitioner Ex-1004, 0670

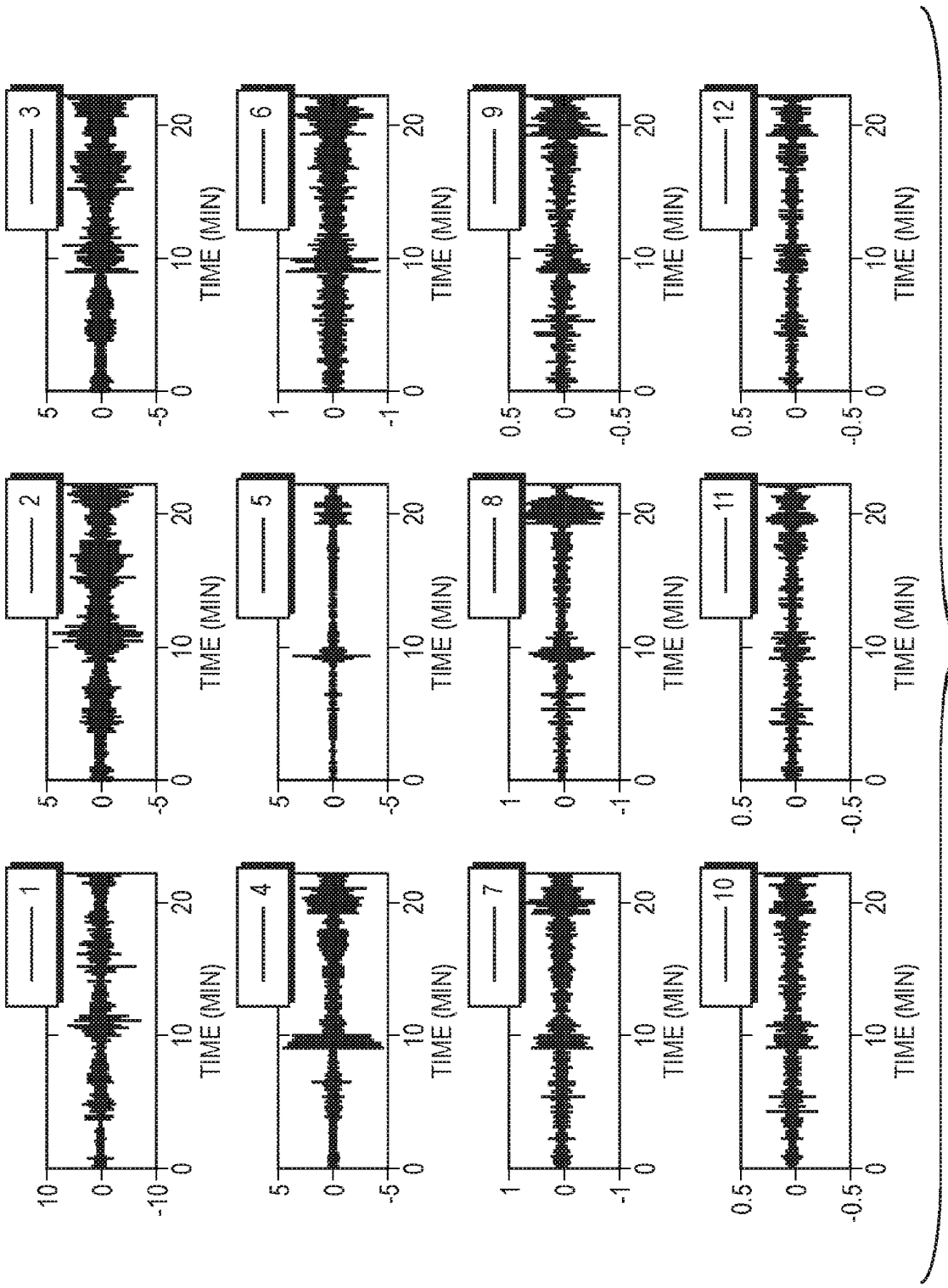


FIG. 16

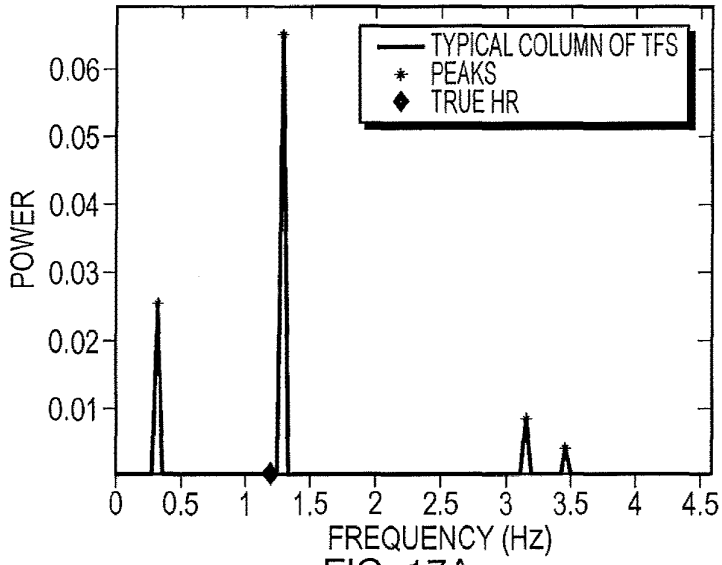


FIG. 17A

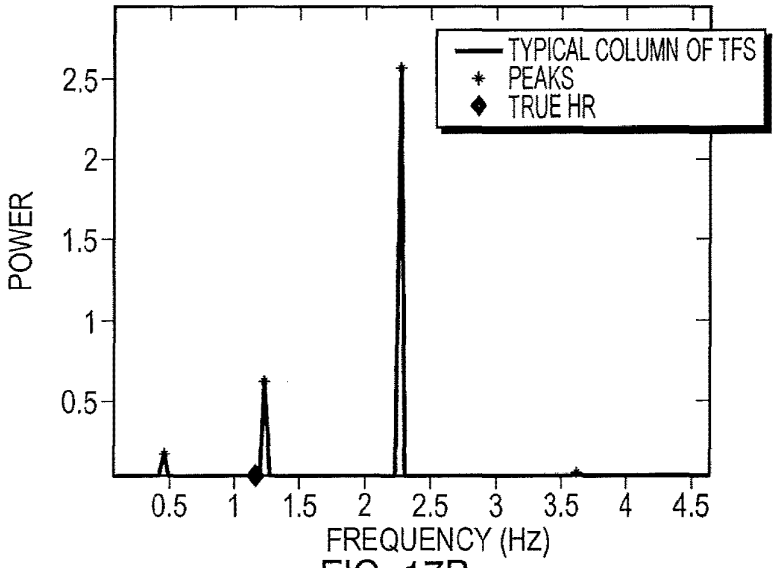


FIG. 17B

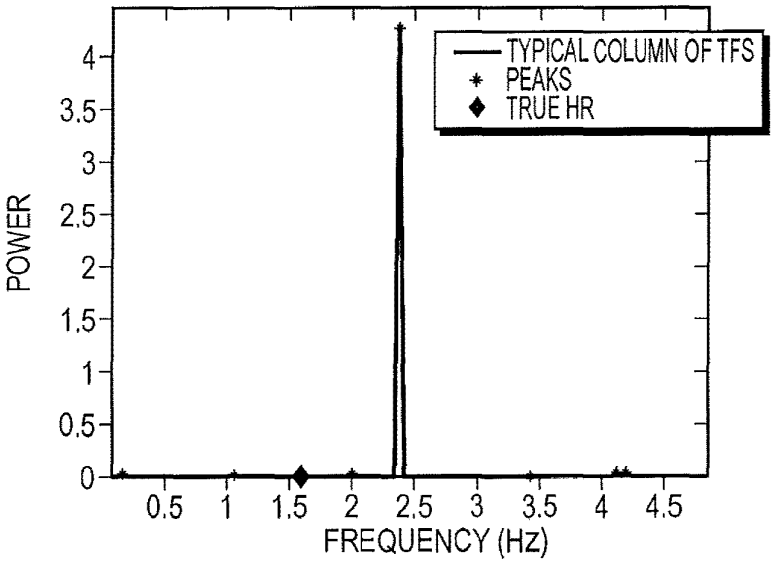


FIG. 17C

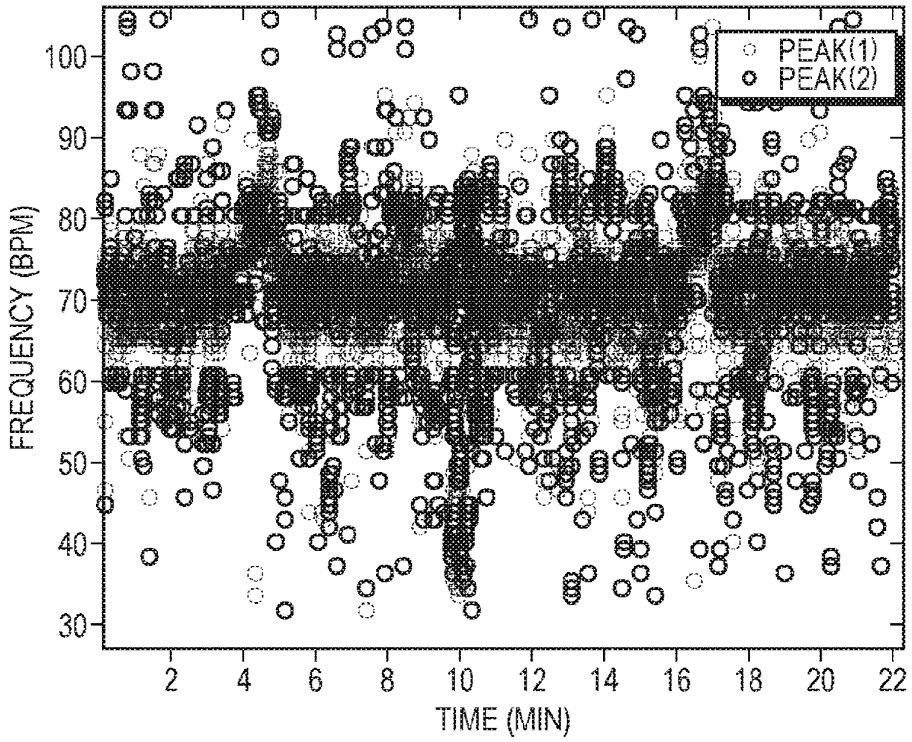


FIG. 18A

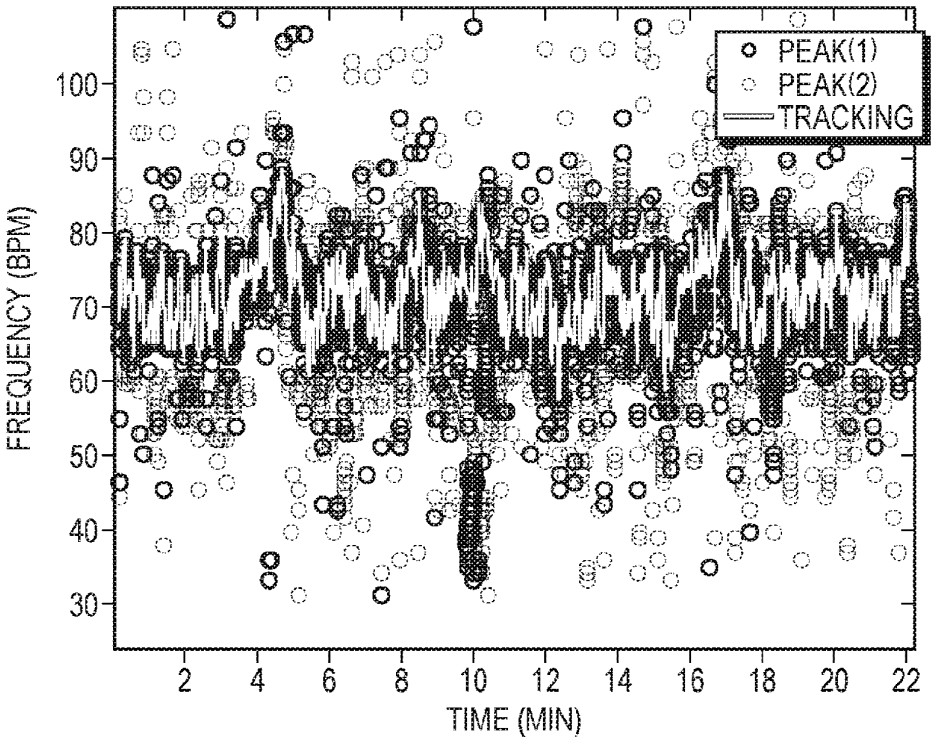


FIG. 18B

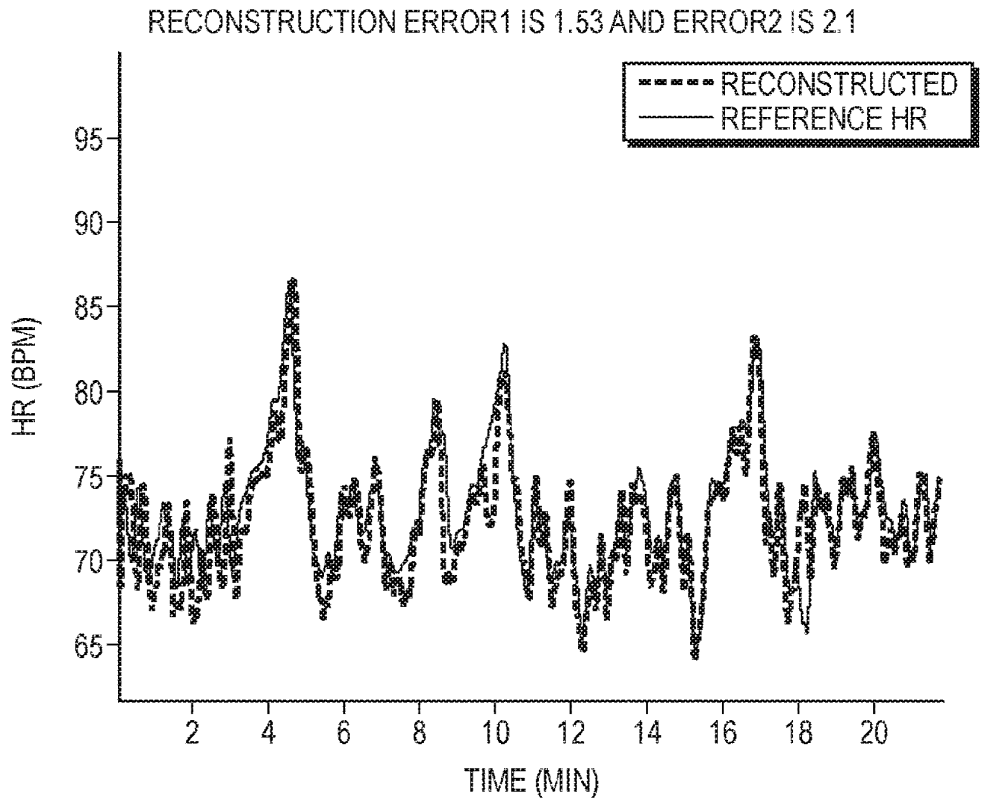


FIG. 19A

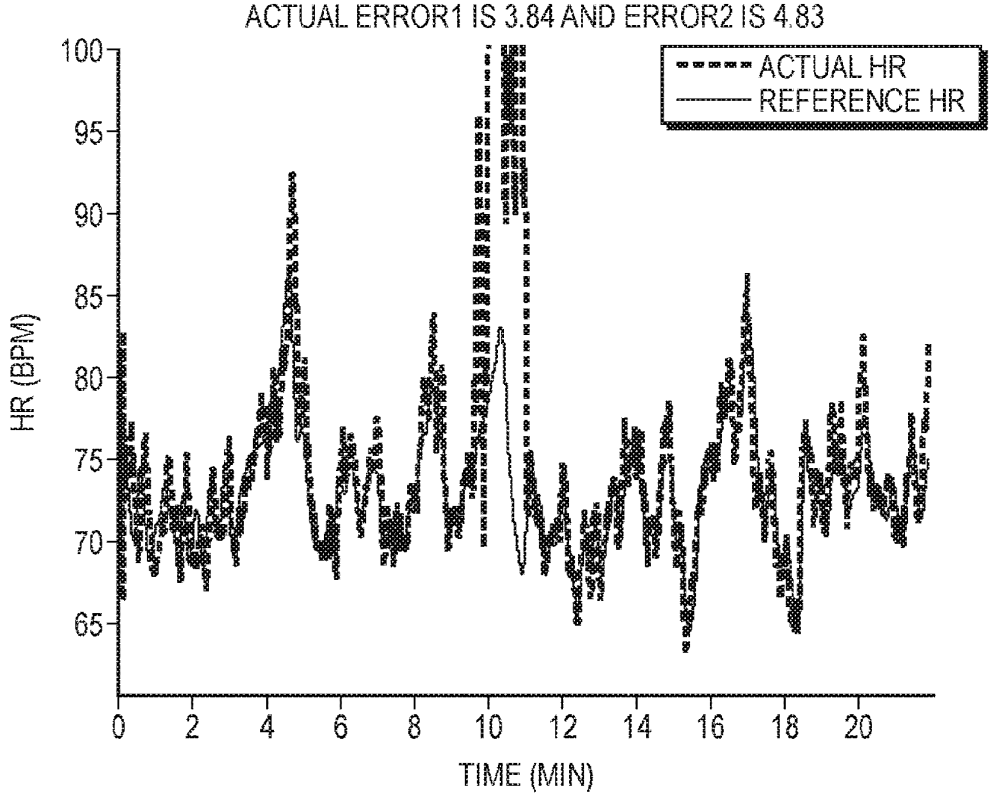


FIG. 19B

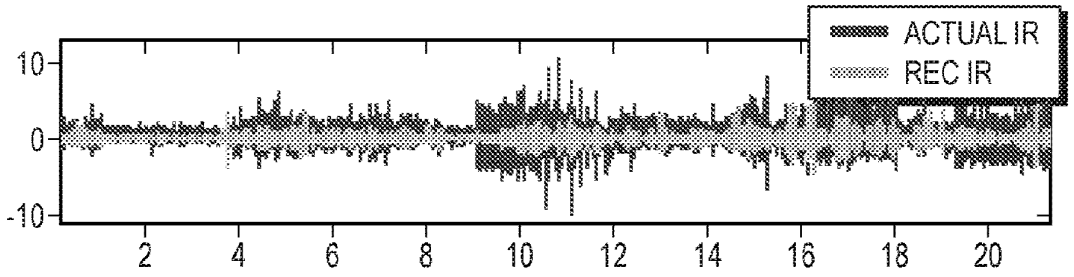


FIG. 20A

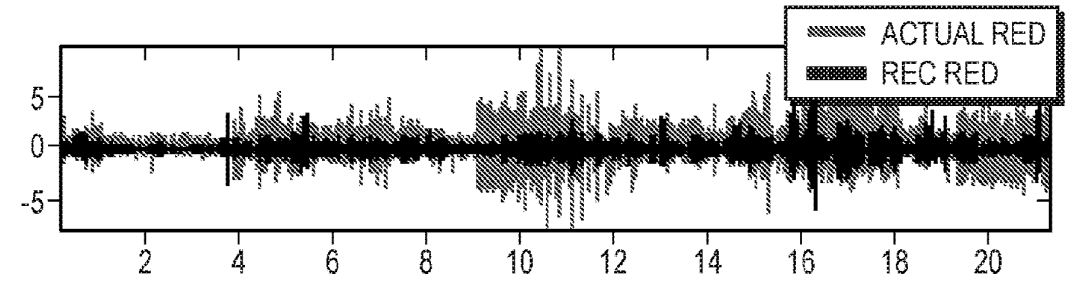


FIG. 20B

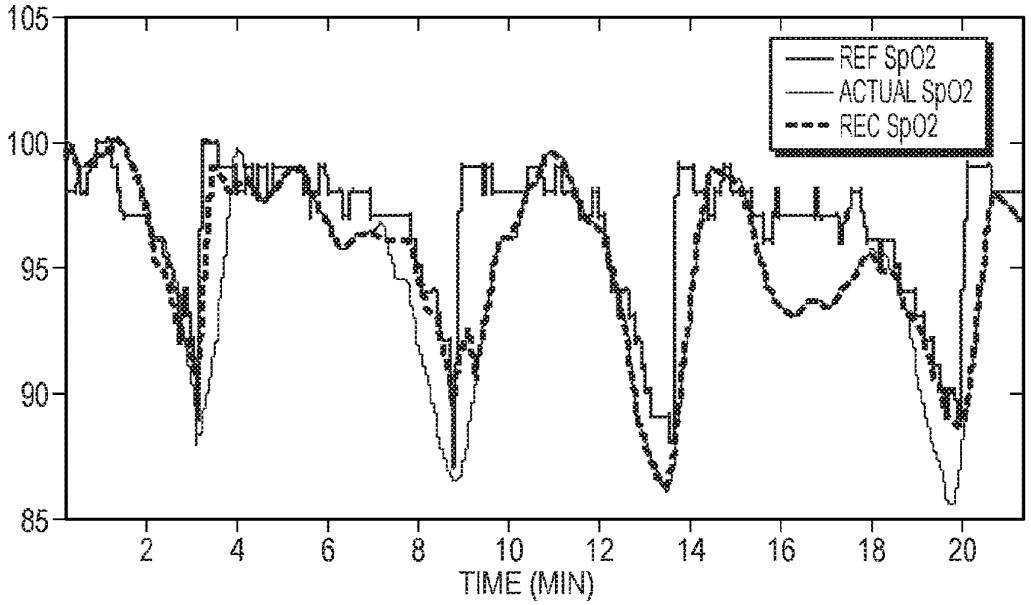


FIG. 20C

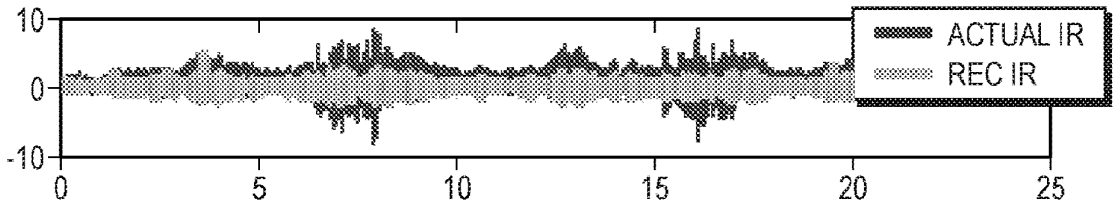


FIG. 21A

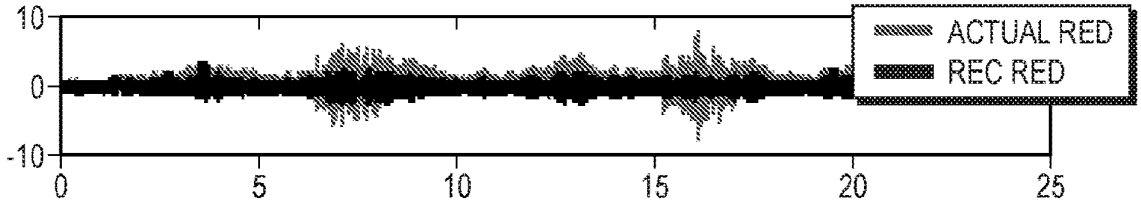


FIG. 21B

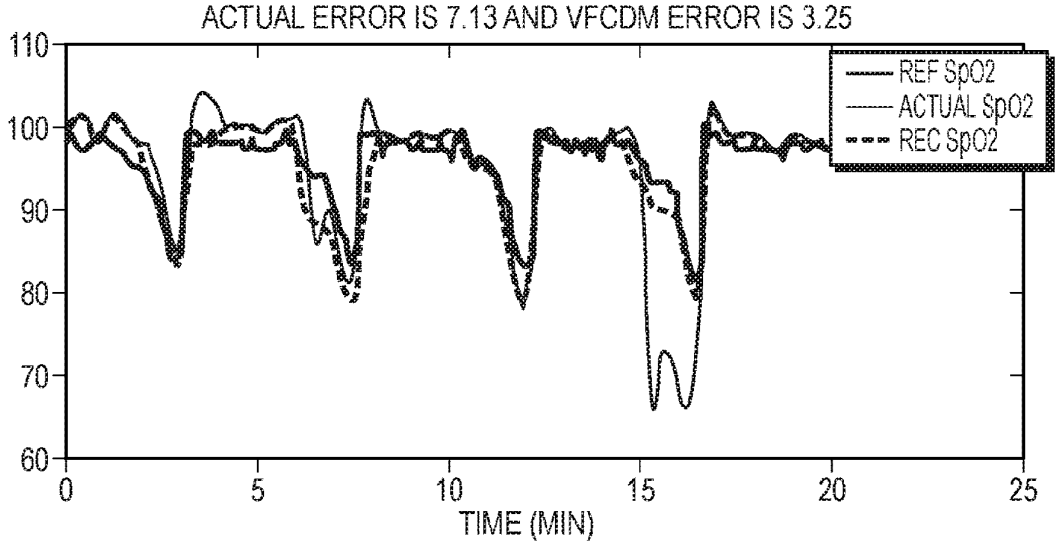


FIG. 21C

Petitioner Ex-1004, 0675

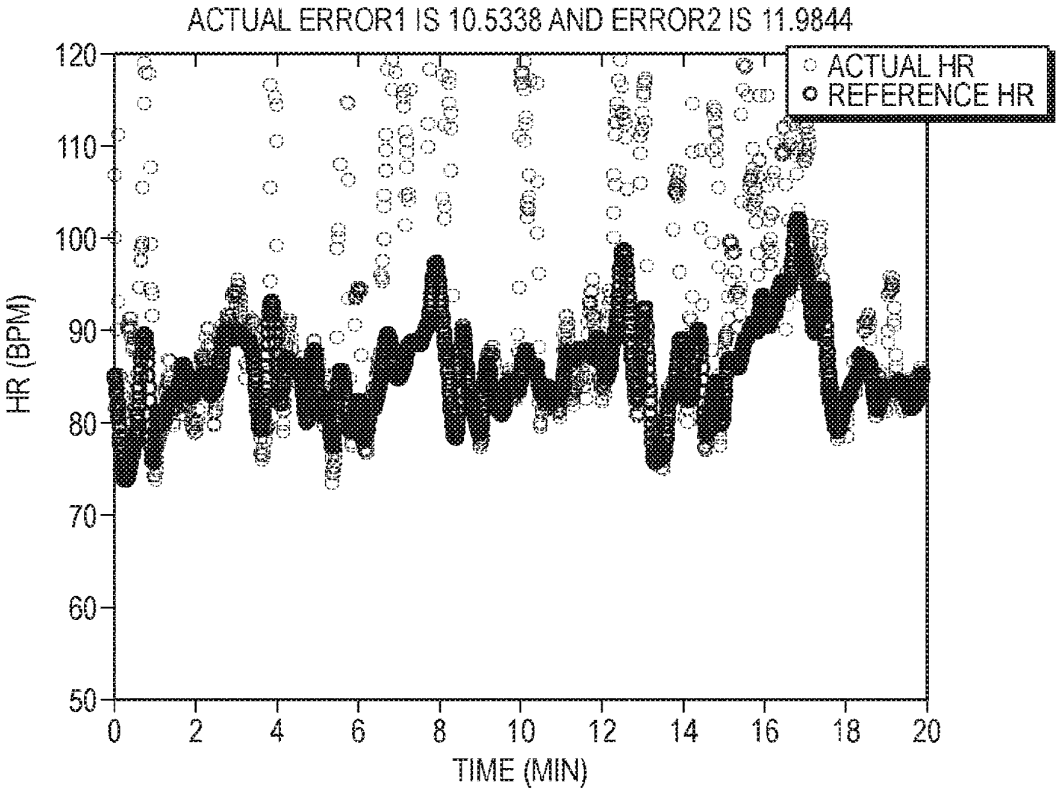


FIG. 22A

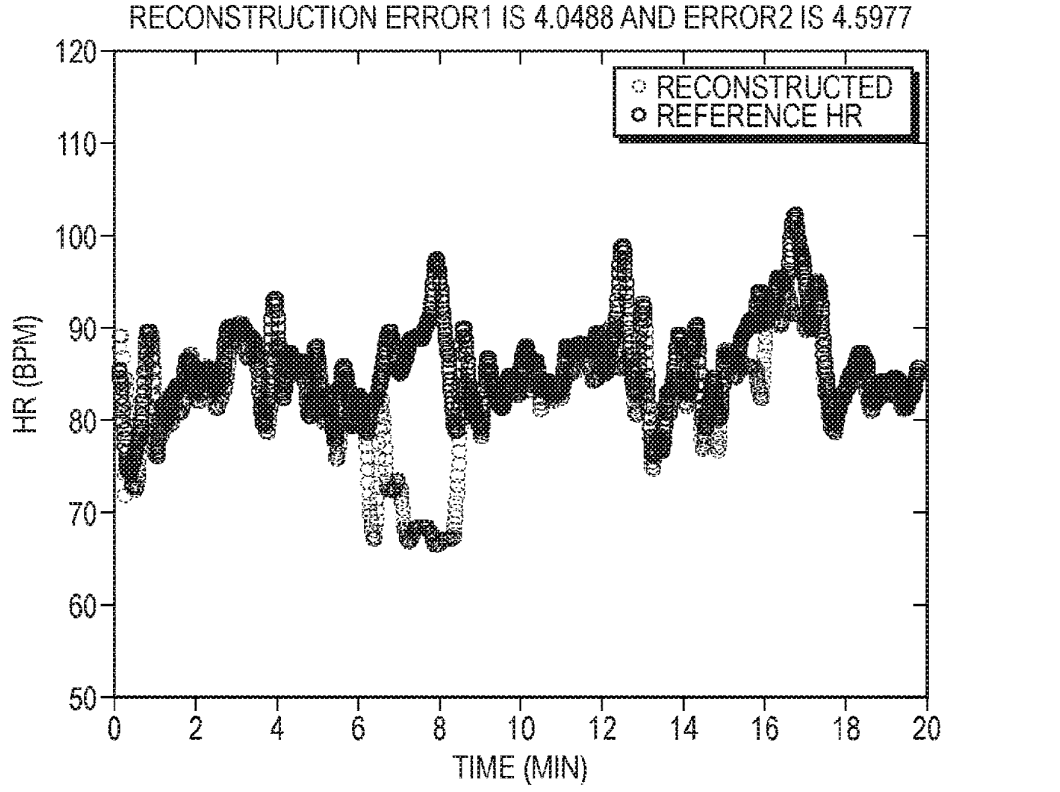


FIG. 22B

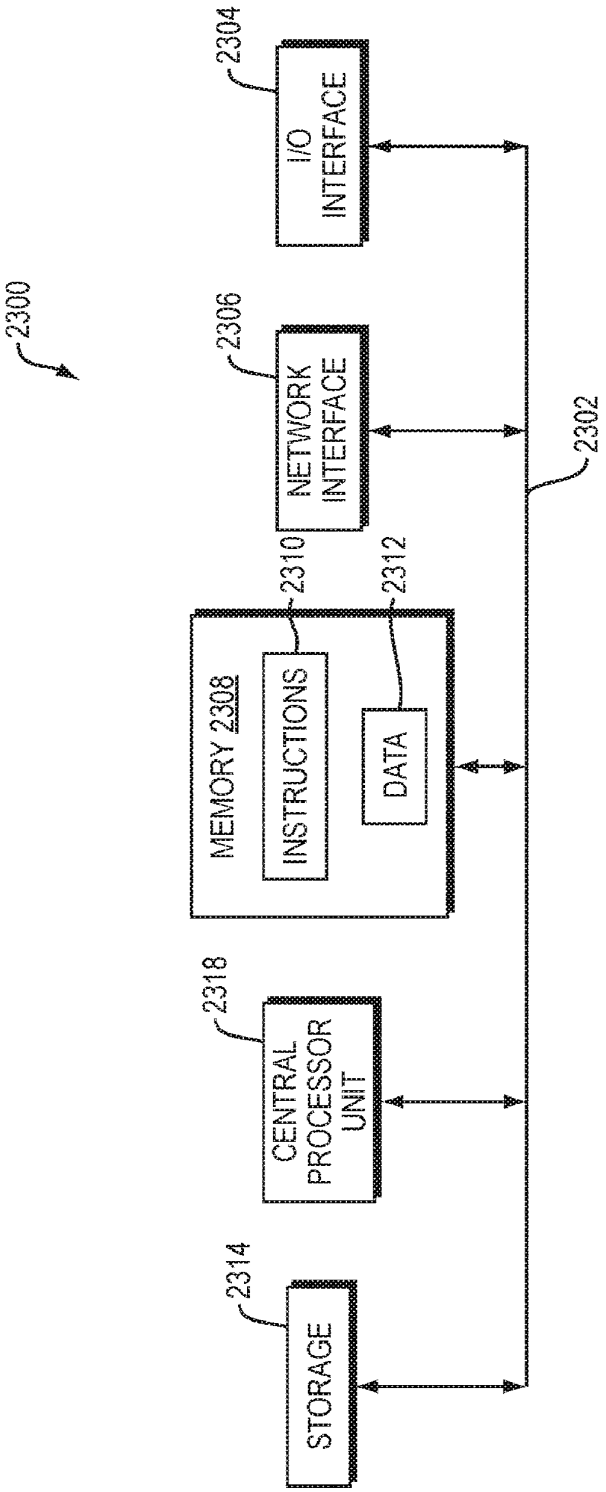


FIG. 23

Petitioner Ex-1004, 0677

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
15/178,089	06/09/2016	Seyed M. A. Salehizadeh	4147.1020-002 (15-089)	7605

21005 7590 05/02/2017

HAMILTON, BROOK, SMITH & REYNOLDS, P.C.
530 VIRGINIA ROAD
P.O. BOX 9133
CONCORD, MA 01742-9133

EXAMINER
THOMSON, WILLIAM D

ART UNIT	PAPER NUMBER
3769	

NOTIFICATION DATE	DELIVERY MODE
05/02/2017	ELECTRONIC

Please find below and/or attached an Office communication concerning this application or proceeding.

The time period for reply, if any, is set in the attached communication.

Notice of the Office communication was sent electronically on above-indicated "Notification Date" to the following e-mail address(es):

docketing.department@hbsr.com
helpdesk@hbsr.com

UNITED STATES DEPARTMENT OF COMMERCE
U.S. Patent and Trademark Office
Address : COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450

APPLICATION NO./ CONTROL NO.	FILING DATE	FIRST NAMED INVENTOR / PATENT IN REEXAMINATION	ATTORNEY DOCKET NO.
15/178,089	09 June, 2016	SALEHIZADEH ET AL.	4147.1020-002 (15-089)

HAMILTON, BROOK, SMITH & REYNOLDS, P.C.
530 VIRGINIA ROAD
P.O. BOX 9133
CONCORD, MA 01742-9133

EXAMINER	
William Thomson	
ART UNIT	PAPER
3769	20170426

DATE MAILED:

Please find below and/or attached an Office communication concerning this application or proceeding.

Commissioner for Patents

This is a decision on the petition under 37 C.F.R. 1.84(a)(2), filed 9 June 2016, requesting acceptance of color drawings. The petition requests that the drawings for Figures 6a-22b, which are in color, be accepted in lieu of black and white drawings.

A grantable petition under 37 C.F.R. 1.84(a)(2) must be accompanied by a fee set forth under 37 C.F.R. 1.17(h), one set of color drawings or color photographs, as appropriate, if submitted via EFS-Web or three sets of color drawings or color photographs, as appropriate, if not submitted via EFS-Web, and, unless already present, an amendment to include the following language as the first paragraph of the brief description of the drawings section of the specification:

"The patent or application file contains at least one drawing executed in color. Copies of this patent or patent application publication with color drawing(s) will be provided by the Office upon request and payment of the necessary fee."

A set of color drawings was filed on 30 August 2016 via EFS-Web. The specification as originally filed included the required notification. The fee was charged in conjunction with filing of the petition. Therefore, the record indicates that all requirements for acceptance of the petition have been met.

The petition is GRANTED.

/David C Eastwood/
Primary Examiner, TC 3700 (for SPE William Thompson)

PTO-90C (Rev.04-03)

Technology Center Petition Count Sheet

Application No.	Applicant(s)	
15/178,089	SALEHIZADEH ET AL.	

Petition Code	Petition Type
☐ 601	Petition to Make Special, Age or Health (37 CFR 1.102, MPEP § 708.02)
☐ 604	Petition to Make Special, Accelerated Examination (37 CFR 1.102, MPEP § 708.02)
☐ 607	Petition to Make Special, For Reasons not Provided in 601-606 and 639-640 (37 CFR 1.102, MPEP § 708.02)
☐ 608	Petition to Reopen After a Board Decision (37 CFR 1.198)
☐ 609	Petition for Review of Final Restriction Requirement (37 CFR 1.144)
☐ 610	Petition Invoking Authority of Commissioner under 37 CFR 1.181 Not Specified in Codes 611-617
☐ 611	Petition Relating to Prematureness of Final Rejection (37 CFR 1.181, MPEP § 706.07)
☐ 612	Petition Relating to Refusal to Enter an Amendment (37 CFR 1.181 and 1.127, MPEP § 714.09)
☐ 613	Petition Relating to Withdraw of holding of Abandonment (37 CFR 1.137, MPEP § 711.03)
☐ 614	Petition Relating to Withdraw of holding of Abandonment (37 CFR 1.137, MPEP § 7.14.19)
☐ 615	Petition Relating to Formal Sufficiency / Propriety of Affidavits (37 CFR 1.131, 1.132, 1.608, MPEP § 608.04(C)
☐ 617	Petition Relating to Refusal to Enter an Amendment (37 CFR 1.312)
☐ 620	Petition for Extension of Time (37 CFR 1.136 (b))
☐ 622	Petition Concerning Appeal Application before Transfer of Jurisdiction to Board of Appeals (MPEP § 1206)
☐ 623	Petition for Second or Subsequent Suspension of Action (37 CFR 1.103, MPEP § 709)
☐ 634	Petition to Correct Inventorship in a Patent not in Interference (37 CFR 1.324, MPEP § 1481)
☐ 635	Petition to Correct Inventorship in a Patent Application (37 CFR 1.48)
☐ 636	Petition to Change Inventorship in a Patent (37 CFR 1.324)
☐ 637	Petition to Withdraw from Issue, before Payment of an Issue Fee (37 CFR 1.313(a))
☐ 639	Petition for Make Special Prospective Manufacture (37 CFR 1.102, MPEP § 708.02)
☐ 646	Petition for Make Special Accelerated Examination
☒ 690	Petition Related Color Drawings of Photographs
☐ 699	Petition for Matters Before Technology Center

Information Required for OPESS Processing

☒ GRANTED ☐ GRANTED-IN-PART ☐ DENIED ☐ DISMISSED

☒ Mail Decision and Enter Decision in Petition Database/PALM
☐ Copy Decision, Send to Scanning
☐ Fees Need to be Charged
☐

Substitute for form 1449B/PTO	ATTORNEY DOCKET NO.	APPLICATION NO.	
SUPPLEMENTAL INFORMATION DISCLOSURE STATEMENT IN AN APPLICATION	4147.1020-002 (15-089)	15/178,089	
	FIRST NAMED INVENTOR	FILING DATE	
LISTING OF REFERENCES	Seyed M. A. Salehizadeh	June 9, 2016	
May 5, 2017 (Use several sheets if necessary)	EXAMINER	CONFIRMATION NO. 7605	GROUP 3766

U.S. PATENT DOCUMENTS

Examiner's Initials	Cite No.	DOCUMENT NUMBER Number-Kind Code (if known)	ISSUE DATE / PUBLICATION DATE MM-DD-YYYY	NAME OF PATENTEE OR APPLICANT OF CITED DOCUMENT
	1.	2008/167564 A1	07-10-2008	Hete, *et al.*
	2.	2014/275854 A1	09-18-2014	Venkatraman, *et al.*
	3.	2014/275852 A1	09-18-2014	Hong, *et al.*

Copies of issued U.S. Patents and Published U.S. Applications are not required and are not being provided. We are not listing separately prior U.S. Patent Office communications regarding the cited documents because the Examiner has access to any such actions through PAIR.

FOREIGN PATENT DOCUMENTS

Examiner's Initials	Cite No.	DOCUMENT NUMBER Country Code-Number-Kind Code (if known)	DATE MM-DD-YYYY	NAME OF PATENTEE OR APPLICANT OF CITED DOCUMENT
	1.	EP 1 297 784 A1	04-02-2003	Csem Ct Suisse Electronique
	2.	EP 1 757 224 A2	02-28-2007	Nihon Kohden Corp
	3.	WO 2011/026669 A1	03-10-2011	Suisse Electronique Microtech
	4.	WO 2012/123828 A1	09-20-2012	Koninkl Philips Electronics
	5.	WO 2017/019184 A2	02-02-2017	University of Connecticut

Examiner's Initials	Cite No.	**OTHER DOCUMENTS** *(Including Author, Title, Date, Pertinent Pages, Etc.)*
	1.	Notification and Transmittal of International Search Report and Written Opinion dated March 16, 2017, for International Appl. No. PCT/US2016/036734, entitled "Method And Apparatus For Removing Motion Artifacts From Biomedical Signals", consisting of 17 pages. (Attorney Docket No: 4147.1020-004).

***Copies of any non-published U.S. Patent Applications are not being provided because the examiner has access to such documents through PAIR. We are not listing separately prior U.S. Patent Office communications regarding the cited documents because the Examiner has access to any such actions through PAIR.**

EXAMINER	DATE CONSIDERED

Petitioner Ex. 1004, 0681

(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 1 297 784 A1

(12) EUROPEAN PATENT APPLICATION

(43) Date of publication:
02.04.2003 Bulletin 2003/14

(51) Int Cl.[7]: **A61B 5/024**

(21) Application number: **01203686.9**

(22) Date of filing: **28.09.2001**

(84) Designated Contracting States:
AT BE CH CY DE DK ES FI FR GB GR IE IT LI LU MC NL PT SE TR
Designated Extension States:
AL LT LV MK RO SI

(71) Applicant: **C.S.E.M. CENTRE SUISSE D'ELECTRONIQUE ET DE MICROTECHNIQUE SA**
2007 Neuchâtel (CH)

(72) Inventors:
- **Vetter, Rolf**
  1400 Yverdon (CH)
- **Philippe, Renevey**
  1005 Lausanne (CH)
- **Gentsch, Roland**
  2068 Hauterive (CH)
- **Krauss, Jens**
  2000 Neuchâtel (CH)
- **Depeursinge Yves**
  1077 Servion (CH)

(54) Method and device for pulse rate detection

(57) There is described a device and a method for detecting the pulse rate. The measuring principle consists of emitting radiant energy at the surface of or through human body tissue (5) by means of a light-emitting source (10), measuring the intensity of the radiant energy after propagation through the human body tissue by means of at least first and second light detectors (21, 22, 23, 24) located at a determined distance from the light-emitting source and providing first and second input signals ($y_1(t)$, $y_2(t)$) representative of this propagation. Simultaneously, a motion detecting device (40), such as a three dimensional accelerometers, provides a motion reference signal ($a_x(t)$, $a_y(t)$, $a_z(t)$) representative of motion of the detecting device on and with respect to the human body tissue (5). The input signals are then processed in order to remove motion-related contributions due to motion of the detecting device (1) on and with respect to the human body tissue (5) and to produce first and second enhanced signals. This processing basically comprises the elaboration of a model of the motion-related contributions based on the motion reference signal and the subtraction of this model from each of the input signals. Pulse rate is then extracted from the enhanced signals using for instance a maximum likelihood histogram clustering technique.

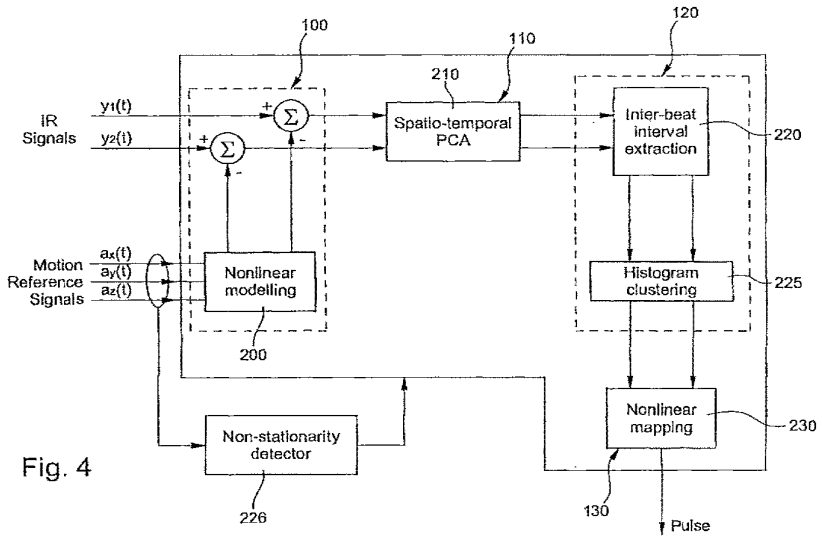


Fig. 4

EP 1 297 784 A1

Printed by Jouve, 75001 PARIS (FR)

Petitioner Ex-1004, 0682

BNSDOCID: <EP_____1297784A1_I_>

Description

[0001] This invention is in the field of signal processing and is more specifically directed to pulse rate detection.

[0002] Portable heart rate monitoring devices are classically composed of a processing device and an external probe (e.g. electronic stethoscope, optical measure at ear lobe, chest belt for electrocardiogram - ECG - based measurement, etc.). The use of an external probe is often considered as a reduction of the user's comfort. ECG-based pulse rate detecting devices using external electrode probes are for instance disclosed in documents US 4,108,166, US 6,018,677, US 6,149,602 and WO 00/51680.

[0003] Various pulse rate detection systems are known in the art. Pulse rate detection devices using pressure sensitive transducers such as piezoelectric elements are for instance disclosed in documents US 3,838,684, US 4,195,642, US 4,331,154, US 5,807,267 and WO 80/00912.

[0004] More recently, measuring techniques based on so-called photoplethysmography (or PPG) have been proposed. PPG is an electro-optic technique of measuring the cardiovascular pulse wave found throughout the human body. This pulse wave is caused by the periodic pulsations of arterial blood volume and is measured by the changing optical absorption of radiant energy which this induces. The measurement system classically consists of a source of radiant energy (usually an infra-red light source), at least one detector for detecting the intensity of the radiant energy after propagation through the human body tissue and a data processing means for extracting bodily parameters such as pulse rate or oxygen concentration in the blood. Infra-red light is predominantly used since it is relatively well absorbed in blood and weakly absorbed in body tissue. Blood volume changes are therefore observed with a reasonable contrast. The principal advantage of PPG measurement resides in the fact that it is entirely non-invasive and can be applied to any blood bearing tissue, typically a finger, nail, ear lobe, nose and, in some instances, wrist.

[0005] Since light is highly scattered in tissue, a detector positioned on the surface of the skin can measure reflections (or transmissions) from a range of depths and those reflections (or transmissions) are variously absorbed depending on whether the light encounters weakly or highly absorbing tissue. Any change in blood volume will be registered by the detector at the surface since increasing (or decreasing) volume will cause more (or less) absorption. The effect will be averaged over many arteries and veins. In the absence of any blood volume changes, the signal level will be determined by the tissue type, skin type, probe positioning, static blood volume content and of course the geometry and sensitivity of the sensor itself.

[0006] PPG systems differentiate between light absorption due to blood volume and that of other fluid and tissue constituents by observation that arterial blood flow pulsates while tissue absorption remains static. As the illuminated blood flow pulsates, it alters the optical path length and therefore modulates the light absorption throughout the cardiac cycle. Non-pulsating fluids and tissues do not modulate the light but have a fixed level of absorption (assuming there is no movement).

[0007] The result of this absorption is that any light reflected from (or transmitted through) the pulsating vascular bed contains an AC component which is proportional to and synchronous with the patients plethysmographic signal. It is this modulated component which is known as the photoplethysmographic signal. This PPG signal is superimposed onto a DC level which represents the difference between incident radiant energy and the constant absorption of the tissue, blood and anything else in the optical path with constant absorption.

[0008] PPG measurement can be achieved by measurement of the intensity of radiant energy transmitted through (transmission mode systems) or reflected by (reflection mode systems) body tissue. A reflection mode system typically has much poorer signal to noise ratio, resulting from the fact that a smaller proportion of the light which is not absorbed will be reflected than transmitted. That is the reason why most of the prior art devices and systems use a detecting arrangement that is placed on the user's finger, nail, ear lobe, nose or part of the body through which light can easily be transmitted.

[0009] PPG has widely been used for measuring arterial oxygen saturation known as pulse oximetry. The technique relies on the knowledge that haemoglobin and oxyhaemoglobin absorb light to varying degrees as a function of wavelength. In particular, the absorption characteristics of red and near infrared light are inverted for the two species. It is thus possible to derive the proportion of oxyhaemoglobin and therefore the arterial oxygen saturation from a knowledge of the absorption characteristics of the arterial blood at these two wavelengths. PPG-based oximetry sensing devices employing sensors which are typically in contact with the user's finger or nail are for instance disclosed in documents US 5,237,994, US 5,645,060, US 5,662,106, US 5,934,277, US 6,018,673, WO 99/52420, WO 99/62399 and WO 01/25802. PPG-based oximetry and heart rate detecting devices intended to be worn on or around other parts of the human body such as the wrist or ear, are also known, for instance from documents US 5,807,267 and WO 97/14357.

[0010] One of the main problems of PPG measurement is corruption of the useful signal by ambient light and other electromagnetic radiations (so-called light artefacts) and by voluntary or involuntary subject movement (so-called motion artefacts). These artefacts lead to erroneous interpretation of PPG signals and degrade the accuracy and reliability of PPG-based algorithms for the estimation of cardiovascular parameters.

[0011] Processing of ambient light artefacts is not critical because the influence of ambient light can be measured

Petitioner Ex-1004, 0683

BNSDOCID: <EP_____1297784A1_I_>

using multiplexing techniques and the PPG signal can be restored using subtractive-type techniques. Reference can here be made to the article "Effect of motion, ambient light, and hypoperfusion on pulse oximeter function", Trivedi N. et al., Journal of Clinical Anaesthesia, vol 9, pp. 179-183, 1997, for a description of these problems. In contrast, processing of motion artefacts is a tough task since its contribution often exceed that of the useful pulse-related signal by an order of magnitude. It is essentially caused by mechanical forces that induces changes in the optical coupling and the optical properties of the tissue. Motion artefacts are a particularly critical problem for the design of a wrist-located pulse detecting device.

[0012] Several methods have been proposed to reduce motion artefacts in PPG signals. Feature-based algorithms have been proposed to discard the corrupted segments from the signals for instance in document WO 94/22360 (corresponding to US 5,368,026). This kind of approach allows one to reduce the occurrence of false alarms in clinical environments, but it often degrades the signals with small motion artefacts contributions. This could lead to erroneous estimation of cardiovascular parameters.

[0013] In order to circumvent this drawback, model-based noise cancelling techniques have been applied more recently for the enhancement of optical signals. Examples are for instance described in documents US 5,490,505, WO 94/03102 and in articles "Simple photon diffusion analysis of the effects of multiple scattering on pulse oximetry", Schmitt J., IEEE Transactions on Biomedical Engineering, vol. 38, pp. 1194-2002, December 1991, and "Noise-resistant oximetry using a synthetic reference signal", Coetzee F. M. et al., IEEE Transactions on Biomedical Engineering, vol. 47, pp. 1018-1026, August 2000. In such approaches a reference signal of motion is recorded and a parametric model is used subsequently to retrieve motion related influences in the optical signals. Nevertheless, motion references are classically obtained by piezo-sensors or optical measures and convey therefore only incomplete or local information of motion. This degrades the performance of model-based noise cancelling techniques since they require complete and low-noise motion reference signals.

[0014] It is thus a principal object of the present invention to provide a device and method for accurately monitoring and detecting heart rate based on photoplethysmography, even under intense physical activity.

[0015] More particularly, an object of the present invention is to provide a solution that allows for adequate removal of ambient light and motion contributions in the optical signals.

[0016] Another object of the invention is to provide a solution that is suitable for enabling measurement and detection to happen at the wrist level.

[0017] Accordingly there is provided a portable pulse rate detecting device the features of which are recited in claim 1.

[0018] There is also provided a method for detecting pulse rate the features of which are recited in claim 17.

[0019] Other advantageous embodiments of the invention are the object of the dependent claims.

[0020] According to the present invention, an accurate motion detecting device is used to provide a reliable motion reference signal. This motion detecting device is preferably a fully integrated three dimensional accelerometer which exhibits a high accuracy and very low noise.

[0021] In order to achieve efficient removal of motion related artefacts in the optical signals, nonlinear model-based techniques are applied. This nonlinear modelling preferably consists in a polynomial expansion model using a moving average and an associated model selection based on the Minimum Description Length (MDL) criterion.

[0022] Furthermore, in order to grasp the spatial diversity of the optical characteristics of the tissue, at least two optical sensors are used. This two-channel arrangement, associated with an adequate noise reduction algorithm (preferably an algorithm based on so-called spatio-temporal Principal Component Analysis or PCA), allows one to remove measurement noise and non-modelled stochastic signal contributions as well as reduce artefacts related to finger movements which are generally not recorded by the accelerometer and therefore not initially cancelled.

[0023] Eventually, the heart rate is estimated from the enhanced signals using inter-beat extraction based on physiological properties of cardiac cells and maximum likelihood histogram clustering of the resulting time series.

[0024] An assessment of the performance of the proposed solution according to the invention has shown its high robustness and accuracy. It has to be pointed out that the application of nonlinear instead of linear modelling decreases the standard deviation of the detected heart rate of about one to two percent. This is mainly due to the inclusion of the parsimonious MDL-based model selection, which avoids an overfitting of the time series. Indeed, the full nonlinear model would retain pulse related components in the estimate of the motion artefacts. Since these components are subtracted from the optical signals, the quality of the enhanced signal and consequently the reliability of the estimated pulse are reduced. In contrast, MDL selects only movement related parameters in the model, which yields higher enhancement performance and a more accurate pulse estimation in adverse noisy environments.

[0025] Other aspects, features and advantages of the present invention will be apparent upon reading the following detailed description of non-limiting examples and embodiments made with reference to the accompanying drawings, in which :

- Figure 1 is a schematic view of the bottom side (intended to come into contact with the body tissue) of a portable pulse rate detecting device according to the invention which is adapted to be worn on the wrist and comprising a

Petitioner Ex-1004, 0684

BNSDOCID: <EP_____1297784A1_I_>

light source and two pairs of light detectors arranged at the bottom side ;

- Figure 2 is a schematic side view of the device of Figure 1 further illustrating the arrangement of the accelerometer;
- Figure 3 is a flow chart of the preferred method for pulse rate detection according to the invention ;
- Figure 4 is a block diagram illustrating a dual channel pulse detection algorithm according to the present invention which is based on nonlinear model-based motion artefact cancelling, coherence-based reduction of measurement noise and stochastic signal contributions, and a pulse detection using maximum likelihood histogram clustering ; and
- Figures 5a to 5e are diagrams respectively illustrating the evolution, as a function of time, (a) of optical signals provided by two light detectors, (b) of acceleration signals detected by the accelerometer along three measurement axes, (c) of the two optical signals after removal of the motion artefacts, (d) of the two optical signals after measurement noise removal (using PCA) and (e) a corresponding ECG electrocardiogram.

[0026] Figures 1 and 2 schematically show a top view of the bottom side and a side view of a wrist-located pulse rate detecting device, indicated globally by reference numeral 1, according to a preferred embodiment of the present invention.

[0027] While the invention will be described hereinbelow with respect to a portable device which is adapted to be worn on the wrist and which is based on the measurement of light reflected in the body tissue, it will be appreciated that the detecting device according to the present invention could be designed to be worn on other parts of the human body such as a patient's finger, nail, ear lobe or any other suitable member or part of the human body. In addition, the same principles could be applied to a detecting device based on the measurement of light transmitted through the body tissue (such as those typically used in pulse oximetry) where the signal to noise ratio is higher. In addition, these principles could be applied for pulse oximetry on the red and IR signals.

[0028] As shown in Figures 1 and 2, detecting device 1 comprises a housing 2 and a strap 3 for attaching detecting device 1 on the patient's wrist. Housing 2 comprises, located in a bottom side 2a of the device in contact with the skin, a light source 10 for emitting radiant energy at the surface of (or through) the human body tissue, designated by reference numeral 5. Light source 10 is preferably an infrared light emitting device (LED).

[0029] According to the preferred embodiment, housing 2 further includes two pairs of light detectors 21, 22 and 23, 24 for detecting the intensity of the radiant energy after propagation through the human body tissue. Such light detectors may conveniently be photodiodes. Preferably, the pairs 21, 22 and 23, 24 of light detectors are respectively disposed along first and second axes, indicated by references A and B, which are substantially perpendicular and parallel to the longitudinal axis of the strap, respectively. More specifically, light source 10 is located in a substantially central part of bottom side 2a and light detectors 21 to 24 are disposed around and at a determined distance from light source 10. In this example, this distance is advantageously selected to be approximately equal to 10 mm.

[0030] According to the invention, it will be appreciated that at least two light detectors are required for a proper detection of the heart rate. The detecting device of Figures 1 and 2 could thus be designed to have only one pair, three or even more than four light detectors. The number and spatial arrangement of these light detectors should however be selected in an adequate manner to provide sufficient spatial diversity for removing light-related artefacts and, as this will be seen hereinafter, to remove other contributions which cannot be detected by the accelerometer, such as reciprocal contributions due to finger movements. In that regard, the two-axes arrangement illustrated in Figures 1 and 2 has the advantage of allowing a good detection of such finger-related reciprocal contributions.

[0031] Referring again to Figures 1 and 2, housing 2 further comprises a motion detecting device 40 which is for example disposed in an upper part 2b of housing 2. This motion detecting device 40 is preferably a three dimensional accelerometer, that is, in effect, three accelerometers disposed along three orthogonal measurement axes and providing three dimensional acceleration data representative of the acceleration to which the device is subjected. This accelerometer is preferably and advantageously an accelerometer of the type manufactured by the company Colibrys S.A. under reference MS 6100. It will however be appreciated that other types of accelerometers or motion detecting devices could be used provided they deliver a reliable measure of motion of the pulse rate detecting device on and with respect to the human body tissue.

[0032] Processing of the signals can either be done by an external processing unit linked to the portable device (by means of a direct or wireless connection) or preferably by an adequately programmed digital signal processor or DSP (indicated schematically by reference numeral 50 in Figure 2) housed within the device.

[0033] Optionally, the portable pulse rate detecting device according to the invention may further comprise means for outputting an indication of the detected pulse rate in the form of an optical, audible signal, or other sensorial signal. Such means could be a display, a buzzer, a vibrating device or any other suitable device adapted for transmitting information representative of the pulse rate measurement to the user. Additionally, the detecting device may also comprise alarm means for generating an alarm when the detected pulse rate reaches a determined threshold, which could be either a low or high threshold or both.

[0034] The basic principle of the invention resides in emitting an optical infrared (IR) signal at the surface of the

Petitioner Ex-1004, 0685

BNSDOCID: <EP_____1297784A1_I_>

human body tissue (or alternatively through the body tissue). This signal is then propagated through the tissue where it is submitted to modifications due to reflection, refraction, scattering and absorption. The resulting signal, after propagation through the tissue is grasped by the light detectors. Since variations of optical tissue characteristics are related to variations in the subcutaneous blood flow, the received signal can be used for the estimation of the heart rate.

[0035] When light is transmitted through biological tissue, several mechanisms are involved in the interaction between the light and the tissue. These interactions are reflection, refraction, scattering and absorption. Reflection and refraction occur at the interfaces between the probe and the subject. Scattering is due to the microscopic variations of the dielectric properties of the tissue. These variations are due to the cell membranes and the sub-cellular components (e.g. mitochondria and nuclei). For infra-red light, the absorption is mainly due to chromophores such as haemoglobin, myoglobin, cytochrome, melanin, lipid, bilirubin, and water. The relative importance depends on the wavelength considered and their distribution in the tissue.

[0036] Under ideal steady-state condition, the received IR light signal contains both a constant (DC) and a time varying (AC) component. The constant component is generally ascribed to baseline absorption of blood and soft tissue, non expansive tissue such as bone, as well as reflectance loss. The time varying component reflects the modification of the effective path length due to the expansion of the tissues subject to the varying blood pressure.

[0037] For the near IR wavelength, the light propagation into the tissue is governed by scattering and absorption. The so-called Beer-Lambert equation is generally used to describe the phenomenon of light absorption in biological tissue :

$$I_o(t) = I_i(t) \cdot \exp\left(- \sum_{j=1}^{n} \varepsilon_{\lambda,j}\, c_j(t)\, d_j(t) \right) \qquad (1)$$

where $I_i(t)$ and $I_o(t)$ are the input and output light intensity, λ is the wavelength of light and $c_j(t)$, $d_j(t)$ and $\varepsilon_{\lambda,j}$ represent, respectively, the concentrations, the spanning path length and the absorption coefficient of the different components. For further information about this subject, reference can be made to the articles "Noise-resistant oximetry using a synthetic reference signal", Coetzee F. M. et al., IEEE Transactions on Biomedical Engineering, vol. 47, pp. 1018-1026, August 2000, and "A review of the optical properties of biological tissues", Cheong W.-F. et al., IEEE Journal of Quantum Electronic, vol. 26, pp. 2166-2185, 1990.

[0038] As briefly mentioned in the preamble part of the description, voluntary or involuntary movements corrupt the PPG signal and create motion-related artefacts. It is generally accepted that motion artefacts are mainly due to modification of the optical properties of the tissue (modification of blood pressure, modification of the optical path, etc.). These modifications affect the corresponding components of the Beer-Lambert equation. Therefore, in presence of motion artefacts, the received intensity can be rewritten in function of the major contributions :

$$I_o(t) = I_i(t) \cdot \gamma_{tissue} \cdot \gamma_{pulse}(t) \cdot \gamma_{gravity}(t) \cdot \gamma_{motion}(t) \qquad (2)$$

where γ_{tissue} is the static attenuation due to the tissue, $\gamma_{pulse}(t)$ is due to pulsatile absorption of the blood, $\gamma_{gravity}(t)$ is due to change of position and $\gamma_{motion}(t)$ is due to dynamic changes of the tissue induced by the movement of the arm (assuming the device is worn on the wrist). It is obvious that the different contributions become additive if one takes the logarithm of expression (2) above.

[0039] When the subject is static, only the contributions of $\gamma_{pulse}(t)$ changes with time and it is then straightforward to remove the other contributions using a high-pass filtering. When the subject is moving, however, the contribution of the gravity and the modification of the interface between the detecting device and the body tissue are varying with time and they have to be removed from the signals in order to allow an accurate estimation of the heart rate. The contributions of the gravity are at low frequency and can be removed quite easily by an adaptation of the gain. The contributions of the motion is difficult to remove, especially if it is in the same frequency band as the heart rate. Therefore techniques have to be developed in order to remove the motion artefacts to obtain an accurate estimation of the heart rate.

[0040] It has been shown above that IR-signals recorded at the wrist are mainly affected by perturbations, such as tissue modifications, motion and gravity related artefacts. The main issue resides in the estimation of the mean heart rate from short time recordings of IR-signals (e.g. 10 seconds). It is assumed that the tissue properties do not vary over the observed duration and for a dual channel approach, the log-corrected observed IR-signals ($y_1(t)$, $y_2(t)$) given by expression (2) can be written as :

Petitioner Ex-1004, 0686

BNSDOCID: <EP_____1297784A1_I_>

$$y_1(t) = s_1(t) + n_{m1}(t) + n_1(t)$$
$$t = 0, \ldots, N_t - 1 \qquad (3)$$
$$y_2(t) = s_2(t) + n_{m2}(t) + n_2(t)$$

where $s_1(t)$, $s_2(t)$ are pulse pressure related signal contributions, $n_{m1}(t)$, $n_{m2}(t)$ are artefacts due to motion and gravity, $n_1(t)$, $n_2(t)$ include measurement noise and non-modelled stochastic signal contributions and N_t is the number of observed samples.

[0041] In order to obtain a robust pulse detection in a large variety of experimental conditions, namely non-stationary environments, the proposed method according to the present invention works on a frame-to-frame basis with a frame duration of e.g. 3 seconds and it consists of mainly a three step algorithm as shown in Figure 3.

[0042] In a first step 100, the observed optical signals $y_1(t)$, $y_2(t)$ are enhanced using nonlinear, model-based noise cancelling techniques (see for instance "Adaptive Filter Theory", Haykin S., Prentice Hall, 1991). For this to be achieved, according to the present invention, an accurate motion reference signal (i.e. acceleration signals $a_x(t)$, $a_y(t)$ and $a_z(t)$) is provided by the accelerometer. The non-linear modelling essentially consists in a polynomial expansion model and an associated model selection based on the Minimum Description Length (MDL) criterion. Such techniques are already known as such by those skilled in the art. Reference can for instance be made to "Nonlinear Biomedical Signal Processing" Celka P. et al., vol. 2, IEEE Press, 2000, and to the PhD thesis of M. R. Vetter (co-inventor) entitled "Extraction of efficient and characteristic features of multidimensional time series", EPFL Lausanne (Switzerland) 1999, which are both incorporated herein by reference.

[0043] The use of the parsimonious MDL selection criterion avoids an overfitting of the time series and ensures in this way that no pulse pressure related signal contributions are cancelled.

[0044] In a second step 110, measurement noise and non-modelled stochastic signal contributions in the two recorded channels are preferably removed. This is achieved, according to the preferred embodiment of the present invention, by a noise reduction algorithm based on spatio-temporal Principal Component Analysis (PCA). For further information about this PCA algorithm, reference will be made to the article "Blind source separation in highly noisy environments", Vetter R. et al., in First International Workshop on Independent Component Analysis and Signal Separation" (ICA'99), Aussois (France), pp. 491-496, 1999, which is also incorporated herein by reference. This step is not as such compulsory since a pulse rate measurement could be derived from the input signals after removal of the motion-related contributions.

[0045] In addition to the removal of measurement noise and non-modelled signal contributions, spatio-temporal PCA allows one to reduce artefacts related to finger movements, which are generally not cancelled in step 100. Indeed, finger movements do not necessarily imply a global displacement of the forearm and are therefore not grasped by the accelerometer. Finger movements, often imply tiny, reciprocal tendon related displacement of the forearm tissue, which yields reciprocal artefact contributions in the two channels. Due to the reciprocity of these signal contributions, they can efficiently be cancelled by a spatio-temporal PCA.

[0046] In a third step 120, the pulse rate is extracted from the enhanced IR-signals. This extraction essentially consists of an inter-beat interval extraction achieved through a classical maximum detection procedure, preferably with inhibition of peak detection during the refractory period of cardiac cells. In addition, a maximum likelihood histogram clustering of the resulting inter-beat intervals is performed (cf. "Vector Quantization and Signal Compression", Gersho A. et al., Kluwer Academic Publishers, 1992).

[0047] Eventually, in a fourth step 130, the most reliable candidate can be selected. A robust and reliable estimate of the pulse rate can be obtained through a nonlinear mapping of the two candidate values in function of their reliability measures. This nonlinear mapping is advantageously achieved by Multiple Layer Perceptron (MLP), which has been trained on data of various experimental setups as described in "Neural Networks", Haykin S., Macmillan College Publishing Company Inc., 1994.

[0048] A more detailed description of the preferred embodiment of the present invention will now be described in reference to the diagrams of Figure 4 and Figures 5a to 5e. Figure 4 shows a diagram illustrating the preferred algorithm according to the invention where block 200 refers to the nonlinear modelling based on the motion reference signal ($a_x(t)$, $a_y(t)$, $a_z(t)$), block 210 refers to the measurement noise and non-modelled contributions cancellation using PCA, block 220 refers to the inter-beat interval extraction on the two enhanced signals, block 225 refers to the maximum likelihood histogram clustering, block 226 refers to the detection of the non-stationary signal segments, and block 230 refers to the final selection of the most reliable candidate using a nonlinear mapping technique.

[0049] One of the key element in the proposed algorithm is the nonlinear model, which provides an estimation of the motion related contributions in the observed IR-signals (block 200 in Figure 4). The relationship between time varying

Petitioner Ex-1004, 0687

BNSDOCID: <EP_____1297784A1_I_>

optical characteristics and its influence on IR-signals is globally described by the Beer-Lambert law hereinabove. Even though one can obtain linear characteristics of these variations of the optical characteristics by a logarithmic transformation, their relationship to a global motion reference signal, such as the one grasped by the accelerometers is complex and may be nonlinear. In order to take into account these potential nonlinear contributions, a third order polynomial moving average model NMA is preferably applied (such an NMA model is described in "Nonlinear Biomedical Signal Processing" to Celka P. et al., and "Extraction of efficient and characteristic features of multidimensional time series", to Vetter R. already mentioned hereinabove).

[0050] Moreover, since this model includes a parsimonious selection criterion (that is the MDL criterion) together with an efficient search algorithm, linear terms are first tested and nonlinear higher order polynomial terms are only included if they are required for an efficient and parsimonious description of the data at disposal. Thus, due to the efficiency of the MDL-based parameter selection, overfitting of the time series is avoided and high model-based noise reduction can be achieved.

[0051] Noise reduction based on PCA (block 210 in Figure 4) has been shown to provide high enhancement performance in various applications (cf. "A signal subspace approach for speech enhancement", Ephraim Y. et al., IEEE Transactions on Speech and Audio Processing, vol. 3, pp. 251-266, 1995 and "Observer of autonomic cardiac outflow based on blind source separation of ECG parameters", Vetter R. et al., IEEE Transactions on Biomedical Engineering, vol. 47, pp. 578-582, 2000).

[0052] In order to take simultaneously advantage of the spatial and temporal correlations existing between and within the observed noisy signals, spatio-temporal PCA has been applied. The basic idea behind PCA-based noise reduction is to observe the noisy data in a large m-dimensional space of delayed coordinates. Since noise is assumed to be random, it extends approximately in a uniform manner in all directions of this space. In contrast, the dynamics of the deterministic system underlying the data confine the trajectories of the useful signal to a lower-dimensional subspace of dimension $p < m$. As a consequence, the eigenspace of the noisy mixtures is partitioned into a noise subspace and a signal-plus-noise subspace. Enhancement (i.e. noise reduction) is performed by projecting the noisy mixtures onto the signal-plus-noise subspace.

[0053] The main problem in PCA-based noise reduction algorithms is the optimal choice of the parameters p and m. For the selection of the optimal PCA dimension m, one can benefit from the fact that, in the given biomedical application, one deals with signals containing quasi-periodic contributions. The embedding dimension can therefore be estimated from the bandwidth of these quasi-periodic contributions. On the other hand, the choice of p is not critical in this application since we are looking mainly for one quasi-periodic contribution which is represented by $p = 2$.

[0054] Model-based noise reduction and artefact cancellation using spatio-temporal PCA described above are not able to cope with highly non-stationary signals such as the one resulting from random irregular movements. Indeed, irregular movement yield burst-like, non-stationary activity signals. Such signal segments constitute outliers from a statistical point of view and they induce large errors in the parameter estimation process. As a result, enhancement performance degrades drastically for random irregular movements.

[0055] In order to avoid this drawback, a method is thus preferably included for determining non-stationary signal segments in the motion reference signals $a_x(t)$, $a_y(t)$, $a_z(t)$ (block 226 in Figure 4). Stationarity detection is achieved as follows :

- firstly, an estimation of the variance of the activity signals $a_x(t)$, $a_y(t)$, $a_z(t)$ is performed on a frame-to-frame basis, with a length of overlapping successive frames of, e.g., 3 seconds ;
- secondly, the relative increment of variance of successive frames is computed ;
- thirdly, non-stationary segments are assessed for relative increments of variance larger than a determined threshold ; and
- finally, signal enhancement and pulse detection are disabled during the detected non-stationary signal segments.

[0056] One can observe that this strategy provides pulse estimation only during stationary signal segments. However, since signal non-stationarity is caused by irregular random movement of short duration, missing probe values can be obtained through methods based on signal prediction. Furthermore, referring to the detecting device of the present invention, it will be appreciated that the light-emitting source (10 in Figure 2), the light detectors (21 to 24 in Figure 2) and/or the processing means (50 in Figure 2) may be disabled when non-stationary signal segments are detected, this being also advantageous in terms of power consumption since processing of the signals is not unnecessarily performed in highly unstable environments. One can indeed obtain an efficient system with lowest power consumption.

[0057] Pulse detection through maximum likelihood histogram clustering (block 225 in Figure 4) mentioned hereinabove, will now briefly be discussed. Estimation of the pulse rate is achieved on a frame-to-frame basis, with a frame duration of approximately 10 seconds (in the above illustrative example). Histogram clustering is performed as follows :

- firstly, inter-beat intervals which are not physiologically plausible are discarded ;

Petitioner Ex-1004, 0688

BNSDOCID: <EP_____1297784A1_I_>

- secondly, for each detected inter-beat interval IBI(n), one looks for all neighbouring inter-beat intervals closer than dIBI(n), where $0 < d < 1$ determines the size of the neighbourhood ;
- thirdly, the centroid of the resulting cluster is evaluated and the number of inter-beat intervals of each cluster is determined to obtain the final histogram ;
- finally, the location of the maximum value of the histogram provides the mean heart rate and the ratio of the maximum value of the histogram with respect to the total number of detected intervals yields the reliability measure.

[0058] Figures 5a to 5d are diagrams respectively illustrating the evolution, as a function of time, (a) of the two optical signals $y_1(t)$, $y_2(t)$ provided by the light detectors, (b) of the measured acceleration signals $a_x(t)$, $a_y(t)$, $a_z(t)$ along the three orthogonal measurement axes, (c) of the two enhanced optical signals after removal of the motion artefacts, and (d) of the two enhanced optical signals after measurement noise removal (using PCA). Figure 5e illustrates the corresponding electrocardiogram ECG.

[0059] For the purpose of illustration, Figures 5a and 5b respectively show an example of two PPG optical signals $y_1(t)$, $y_2(t)$ and associated motion reference signals, i.e. acceleration signals $a_x(t)$, $a_y(t)$ and $a_z(t)$ provided by the three dimensional accelerometer. Figure 5c shows the resulting optical signals after modelling and removal of the motion-related artefact, that is after subtraction of the constructed nonlinear models from both PPG optical signals $y_1(t)$, $y_2(t)$. After model-based artefact cancelling, one can see, in a qualitative manner, that pulse-related peaks are recovered, while motion-related contributions are discarded.

[0060] Figure 5d shows the enhanced optical signals after noise reduction using PCA. Residual noise contributions due to tiny local movements not grasped by the accelerometers, modelling errors, and other stochastic influences are removed by spatio-temporal PCA. Figure 5d also shows an almost perfect matching of the two enhanced optical signals, highlighting the efficiency of the proposed algorithm.

[0061] A thorough analysis of the signals of Figure 5d with regard to the corresponding recorded ECG highlights that the information of inter-beat intervals (schematised by the detected signal peaks indicated by small circles in the Figure) is recovered up to a delay, which can be associated to the applied signal processing techniques.

[0062] Having described the invention with regard to certain specific embodiments, it is to be understood that these embodiments are not meant as limitations of the invention. Indeed, various modifications and/or adaptations may become apparent to those skilled in the art without departing from the scope of the annexed claims. For instance, the invention shall not be meant to be applied only to pulse rate determination at the wrist level. The same principles could be applied with a device adapted to be worn on the user's finger, nail, ear lobe or other adequate part of the human body.

[0063] In addition, the present invention could also be modified to allow measurement of the oxygen saturation in the blood, provided that the device is equipped with separate red and infrared light sources. The above-described enhancing schemes would then be applied for both red and IR signals.

[0064] The proposed algorithm for pulse detection which has been presented hereinabove uses a frame-to-frame signal processing approach. Nevertheless, it has to be pointed out that all the above methods can be implemented in an adaptive form (see "Adaptive Filter Theory", Haykin S., Prentice Hall, 1991). The advantage of the proposed implementation resides mainly in a much lower computational load, which is a key element in the design of a portable unit.

[0065] Finally, as already mentioned hereinabove, the detecting device of the invention could be designed as a device adapted to fit around the user's ear, the light source and light detectors being conveniently disposed to emit and detect propagation of light through the ear lobe. An example of such a device is disclosed in document WO 97/14357 which has already been cited in the preamble part of the description. Such an ear-mounted device could be provided with means for generating an audible signal indicative of the detected pulse rate or of an alarm when a determined threshold is reached.

Claims

1. Portable pulse rate detecting device (1) intended to be worn on and in contact with the human body tissue (5), comprising

   a light-emitting source (10) for emitting radiant energy at the surface of or through the human body tissue (5);
   at least first and second light detectors (21, 22, 23, 24) for detecting the intensity of said radiant energy after propagation through the human body tissue (5) and for providing first and second input signals ($y_1(t)$, $y_2(t)$) representative of said propagation ;
   a device (40) for measuring motion of the detecting device (1) on and with respect to the human body tissue (5) and for providing a motion reference signal ($a_x(t)$, $a_y(t)$, $a_z(t)$) representative of said motion ; and
   processing means (50) for removing, from said first and second input signals ($y_1(t)$, $y_2(t)$), motion-related contributions due to movement of the detecting device (1) on and with respect to the human body tissue and

Petitioner Ex-1004, 0689

BNSDOCID: <EP_____1297784A1_I_>

producing first and second enhanced signals,
said processing means being arranged to elaborate a model of said motion-related contributions based on said motion reference signal ($a_x(t)$, $a_y(t)$, $a_z(t)$) and to subtract this model from each of said first and second input signals ($y_1(t)$, $y_2(t)$).

2. Portable pulse rate detecting device (1) according to claim 1, wherein said model is a nonlinear model such as a third order polynomial moving average model.

3. Portable pulse rate detecting device (1) according to claim 2, wherein the model is selected using a Minimum Description Length (MDL) criterion.

4. Portable pulse rate detecting device (1) according to any one of claims 1 to 3, wherein said processing means (50) are further arranged to remove measurement noise and residual non-modelled contributions from said first and second enhanced signals using a noise reduction algorithm.

5. Portable pulse rate detecting device (1) according to claim 4, wherein said noise reduction algorithm is based on Principal Component Analysis (PCA).

6. Portable pulse rate detecting device (1) according to any one of the preceding claims, wherein said processing means (50) are arranged to detect peaks in said first and second enhanced signals and to extract inter-beat intervals from said detected peaks to provide a pulse rate measurement, the detection of said peaks being inhibited during the refractory period of cardiac cells.

7. Portable pulse rate detecting device (1) according to any one of the preceding claims, wherein said detecting device comprises a strap (3) for being worn around the wrist, said light-emitting source (10) and said light detectors (21, 22, 23, 24) being disposed on a bottom side (2a) of said detecting device in contact with the human body tissue (5).

8. Portable pulse rate detecting device (1) according to any one of the preceding claims, wherein said first and second light detectors (21, 22) are located on each side of the light-emitting source (10) along a first axis (A), this detecting device further comprising third and fourth light detectors (23, 24) located on each side of the light-emitting source (10) along a second axis (B) substantially perpendicular to the first axis (A).

9. Portable pulse rate detecting device (1) according to claims 7 and 8, wherein said first and second axes (A, B) are respectively perpendicular and parallel to a longitudinal direction of said strap (3).

10. Portable pulse rate detecting device (1) according to any one of claims 7 to 9, wherein said light-emitting source (10) is located in a substantially central area of the bottom side (2a) of the detecting device and said light detectors (21, 22, 23, 24) are disposed around said light-emitting source (10).

11. Portable pulse rate detecting device according to any one of the preceding claims, wherein the distance between said light-emitting source (10) and said light detectors (21, 22, 23, 24) is approximately 10 mm.

12. Portable pulse rate detecting device according to any one of the preceding claims, wherein said light-emitting source (10) is an infrared light-emitting device and said light detectors (21, 22, 23, 24) are photodiodes.

13. Portable pulse rate detecting device according to any one of the preceding claims, wherein said processing means (50) are in the form of a digital signal processor DSP housed within said detecting device (1).

14. Portable pulse rate detecting device according to any one of the preceding claims, wherein said device (40) for providing the motion reference signal ($a_x(t)$, $a_y(t)$, $a_z(t)$) is a three dimensional accelerometer.

15. Portable pulse rate detecting device according to any one of the preceding claims, further comprising means (226) for detecting non-stationary signal segments in said motion reference signal ($a_x(t)$, $a_y(t)$, $a_z(t)$) and for disabling said light-emitting source (10), said light detectors (21, 22, 23, 24) and/or said processing means (50) when non-stationary signal segments are detected.

16. Portable pulse rate detecting device according to any one of the preceding claims, further comprising means for

Petitioner Ex-1004, 0690

BNSDOCID: <EP_____1297784A1_I_>

outputting an indication of the detected pulse rate in the form of an optical, audible or other sensorial signal and/or for outputting an alarm when the detected pulse rate reaches a determined threshold.

17. Method for detecting a pulse rate comprising the steps of:

a) emitting radiant energy at the surface of or through human body tissue (5) by means of a light-emitting source (10);
b) measuring the intensity of said radiant energy after propagation through the human body tissue (5) by means of at least first and second light detectors (21, 22, 23, 24) located at a determined distance from said light-emitting source (10) and providing first and second input signals ($y_1(t)$, $y_2(t)$) representative of said propagation ;
c) measuring motion of the detecting device (1) on and with respect to the human body tissue (5) during propagation of said radiant energy through the human body tissue (5) by means of a motion detecting device (40) and providing a motion reference signal ($a_x(t)$, $a_y(t)$, $a_z(t)$) representative of said motion ;
d) processing said first and second input signals ($y_1(t)$, $y_2(t)$) to remove motion-related contributions due to motion of the detecting device (1) on and with respect to the human body tissue (5) and producing first and second enhanced signals,

said processing comprising elaborating a model of said motion-related contributions based on said motion reference signal ($a_x(t)$, $a_y(t)$, $a_z(t)$) and subtracting this model from each of said first and second input signals ($y_1(t)$, $y_2(t)$); and
e) extracting the pulse rate from said first and second enhanced signals.

18. Method according to claim 17, wherein said model is a nonlinear model such as a third order polynomial moving average model.

19. Method according to claim 18, wherein said processing step (d) includes selecting the model using a Minimum Description Length (MDL) criterion.

20. Method according to any one of claims 17 to 19, further comprising, after subtracting said model from each of the first and second input signals ($y_1(t)$, $y_2(t)$) :

d1) removing measurement noise and residual non-modelled contributions from said first and second enhanced signals using a noise reduction algorithm.

21. Method according to claim 19, wherein said noise reduction algorithm is based on Principal Component Analysis (PCA).

22. Method according to any one of claims 17 to 21, wherein said extracting step (e) includes detecting peaks in said first and second enhanced signals and extracting inter-beat intervals from said detected peaks to provide a pulse rate measurement, the detection of said peaks being inhibited during the refractory period of cardiac cells.

23. Method according to any one of claim 22, further comprising the step of performing a maximum likelihood histogram clustering of said inter-beat intervals.

24. Method according to claim 23, further comprising the step of determining a reliability measure of the pulse rate measurement of each one of said first and second enhanced signals and performing a nonlinear mapping of the two pulse rate measurements in function of their reliability measures.

Petitioner Ex-1004, 0691

BNSDOCID: <EP_____1297784A1_I_>

Fig.1

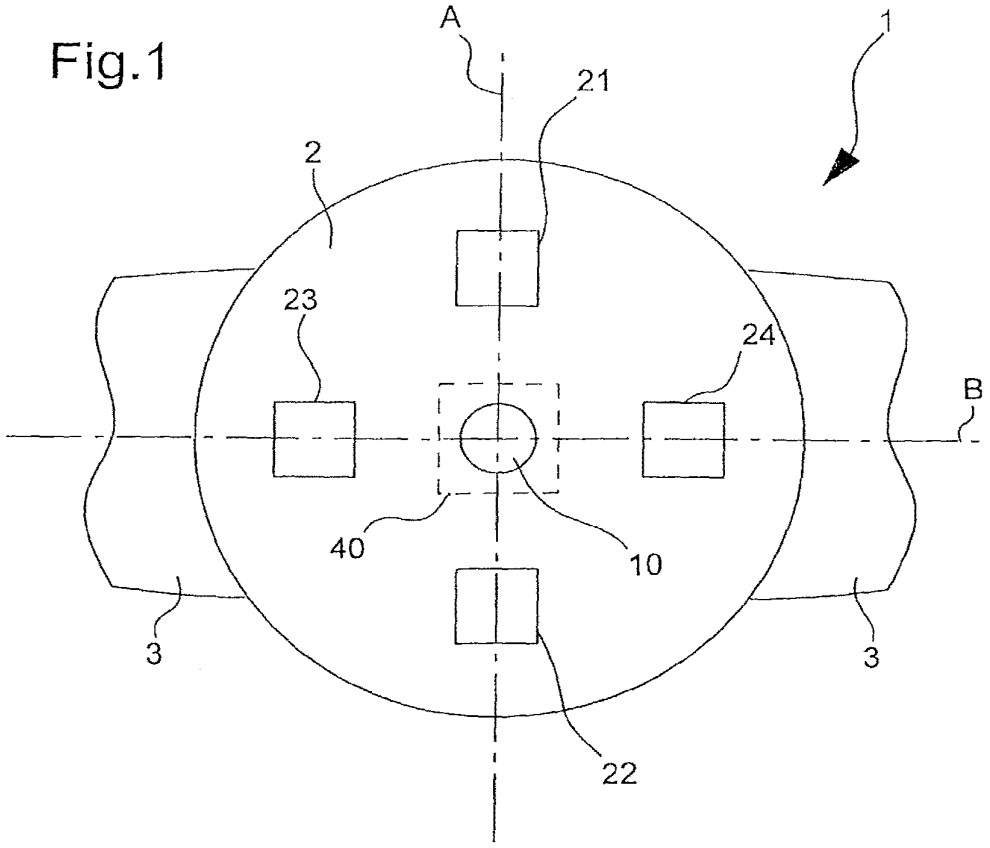
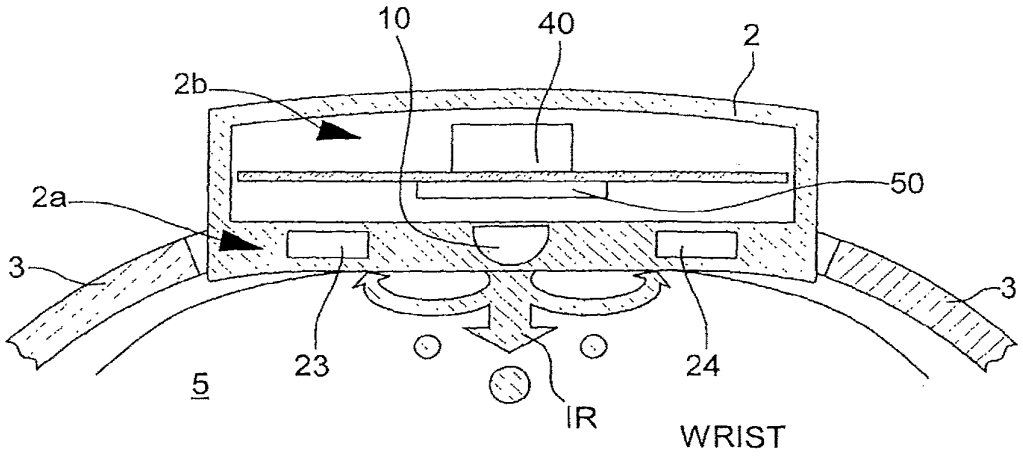


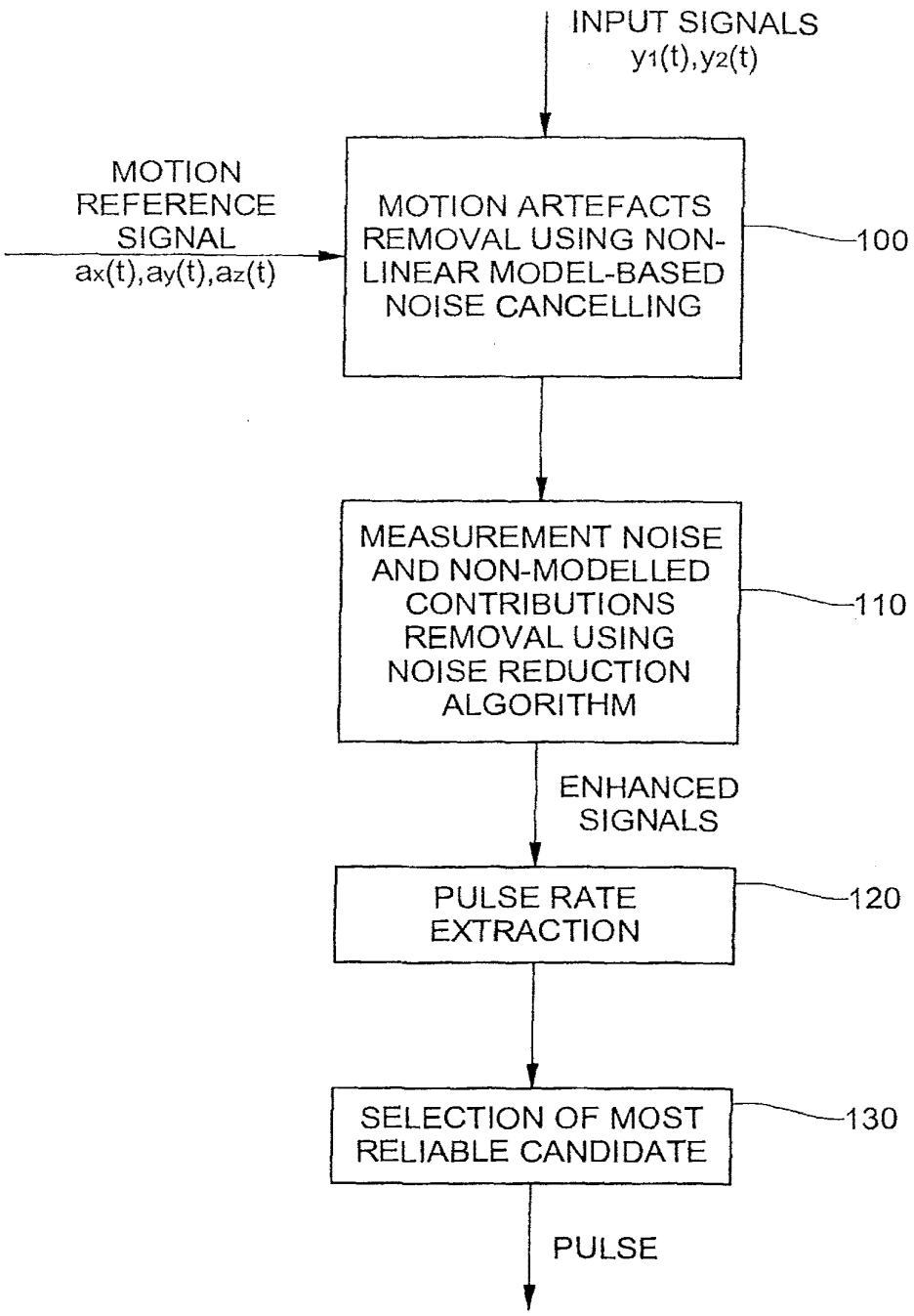
Fig.2



Petitioner Ex-1004, 0692

BNSDOCID: <EP_____1297784A1_I_>

Fig.3



Petitioner Ex-1004, 0693

BNSDOCID: <EP_____1297784A1_I_>

BNSDOCID: <EP 1297784A1_I_>

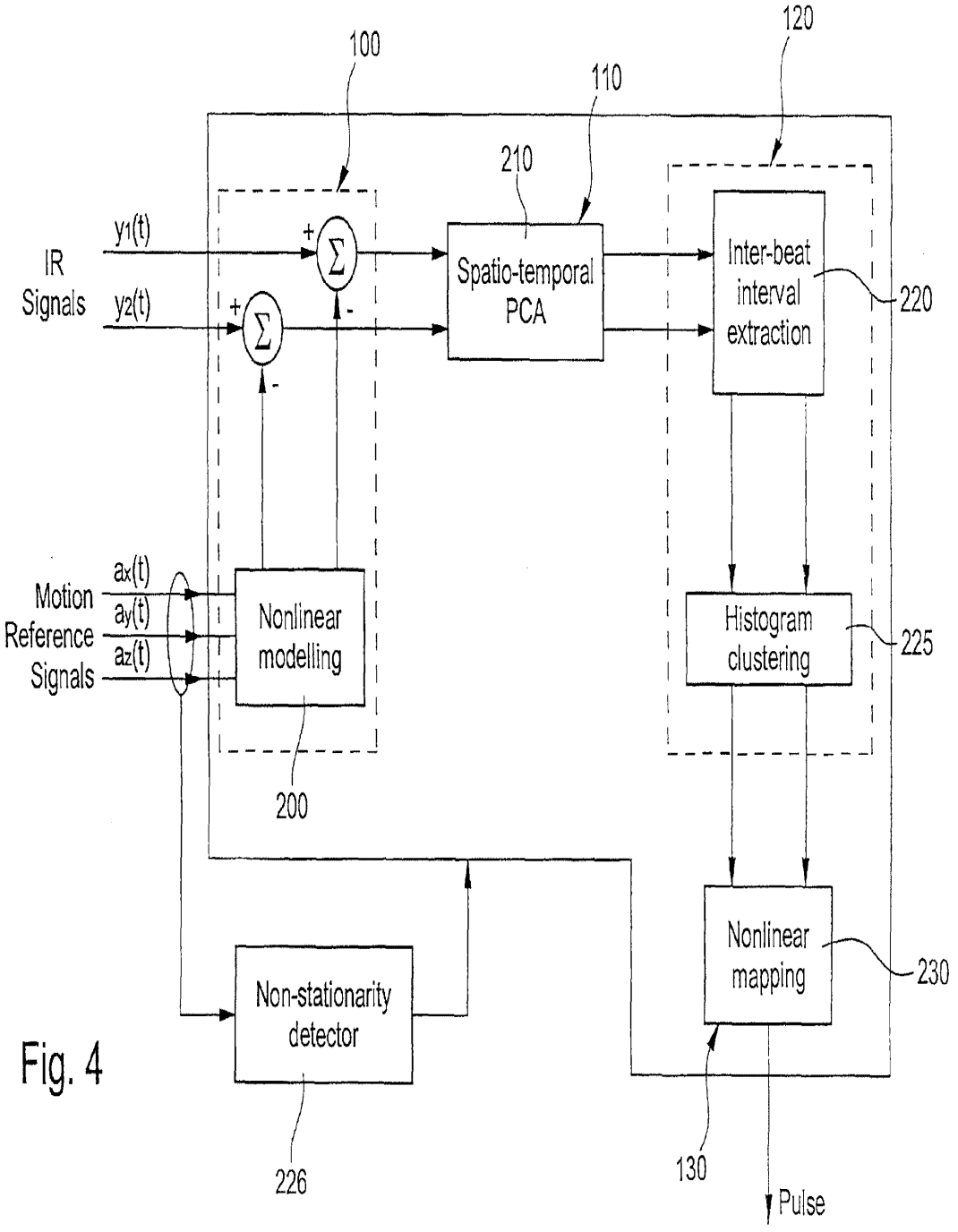


Fig. 4

Petitioner Ex-1004, 0694

Fig. 5a

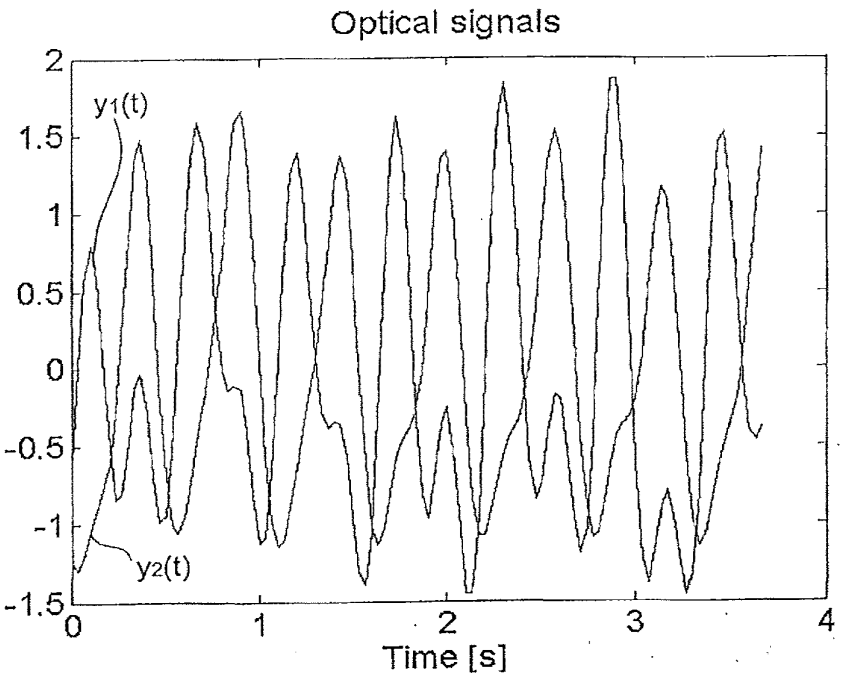
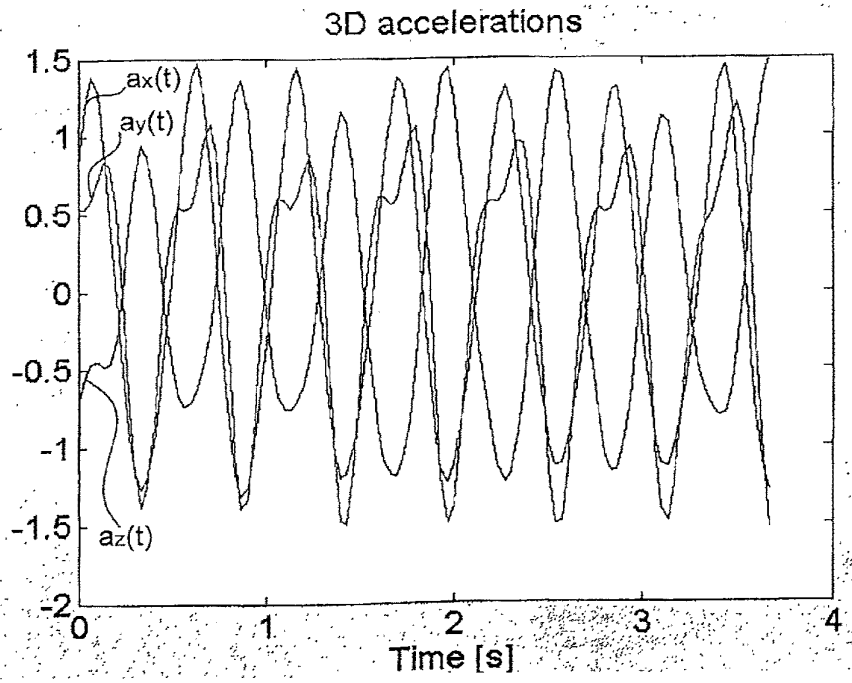


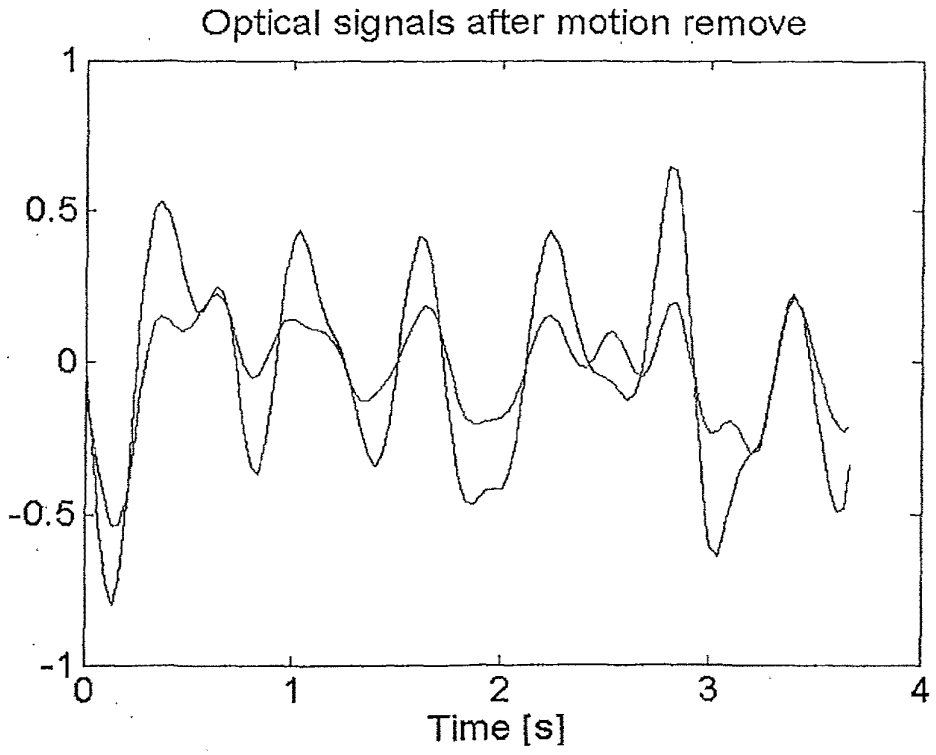
Fig. 5b



Petitioner Ex-1004, 0695

BNSDOCID: <EP_____1297784A1_I_>

Fig. 5c



Petitioner Ex-1004, 0696

BNSDOCID: <EP_____1297784A1_I_>

Fig. 5d

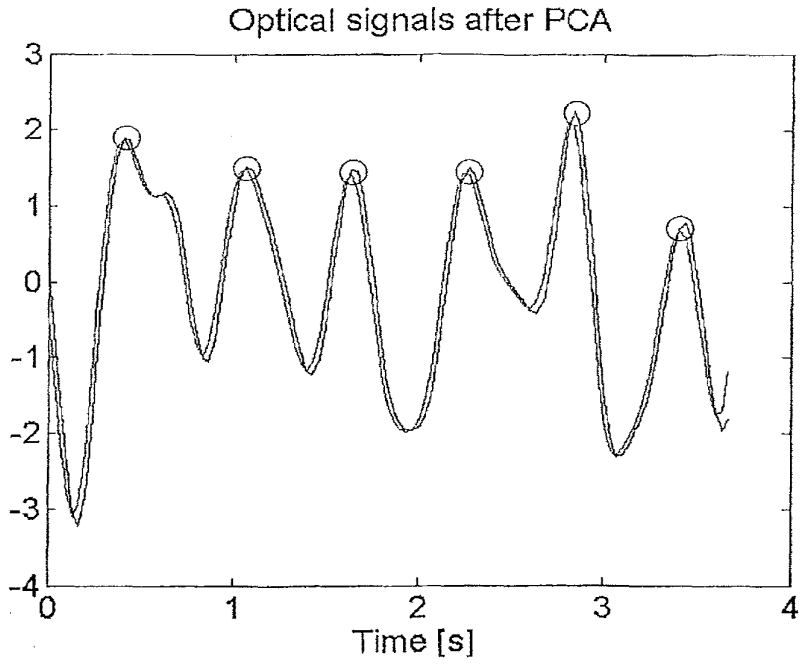
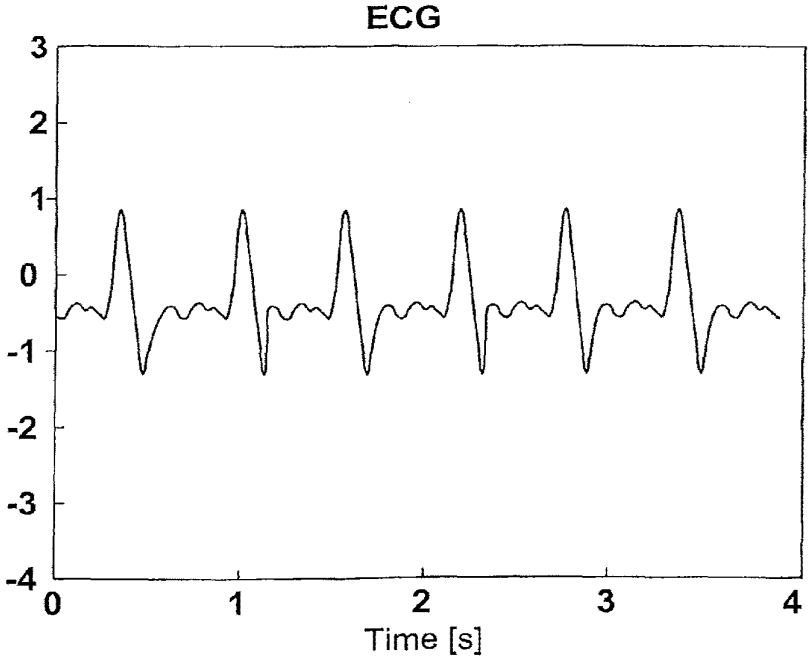


Fig. 5e



Petitioner Ex-1004, 0697

BNSDOCID: <EP_____1297784A1_I_>

European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 01 20 3686

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.7)
X	EP 0 941 694 A (SEIKO EPSON CORP) 15 September 1999 (1999-09-15) * column 3, line 24,25; claims 9,11,12; figure 1 * * column 10, line 1-5 *	1,17	A61B5/024
A	US 6 018 673 A (CHIN RODNEY ET AL) 25 January 2000 (2000-01-25) * claims 1,13; figure 1 *	1,17	
A	EP 0 645 117 A (SEIKO EPSON CORP) 29 March 1995 (1995-03-29) * claim 1; figure 1 *	1,17	
A	US 5 025 791 A (NIWA MINORU) 25 June 1991 (1991-06-25) * claim 1; figure 1 *	1,14,17	
			TECHNICAL FIELDS SEARCHED (Int.Cl.7) A61B

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
BERLIN	2 April 2002	Bernas, Y

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document

EPO FORM 1503 03.82 (P04C01)

Petitioner Ex-1004, 0698

BNSDOCID: <EP_____1297784A1_I_>

ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 01 20 3686

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report. The members are as contained in the European Patent Office EDP file on
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

02-04-2002

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 0941694 A	15-09-1999	EP 0941694 A1	15-09-1999
		US 6198951 B1	06-03-2001
		WO 9912469 A1	18-03-1999
US 6018673 A	25-01-2000	AU 4666397 A	05-05-1998
		EP 0951232 A2	27-10-1999
		JP 2001501847 T	13-02-2001
		WO 9815224 A2	16-04-1998
EP 0645117 A	29-03-1995	JP 7088092 A	04-04-1995
		DE 69429405 D1	24-01-2002
		EP 0645117 A1	29-03-1995
		US 6217523 B1	17-04-2001
		US 6022321 A	08-02-2000
US 5025791 A	25-06-1991	NONE	

EPO FORM P0459

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

Petitioner Ex-1004, 0699

BNSDOCID: <EP_____1297784A1_I_>

(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 1 757 224 A2

(12) EUROPEAN PATENT APPLICATION

(43) Date of publication:
28.02.2007 Bulletin 2007/09

(51) Int Cl.:
A61B 5/00 *(2006.01)*

(21) Application number: **06017637.7**

(22) Date of filing: **24.08.2006**

(84) Designated Contracting States:
AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HU IE IS IT LI LT LU LV MC NL PL PT RO SE SI SK TR
Designated Extension States:
AL BA HR MK YU

(30) Priority: **24.08.2005 JP 2005242574**
28.07.2006 JP 2006205453

(71) Applicant: **Nihon Kohden Corporation**
Shinjuku-ku
Tokyo (JP)

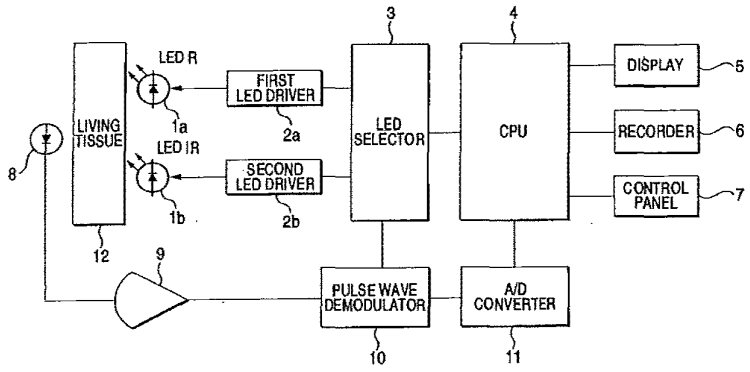
(72) Inventors:
- **Kobayashi, Naoki**
  Shinjuku-ku
  Tokyo (JP)
- **Miyata, Kenji**
  Shinjuku-ku
  Tokyo (JP)
- **Yarita, Masaru**
  Shinjuku-ku
  Tokyo (JP)
- **Ito, Kazumasa**
  Shinjuku-ku
  Tokyo (JP)

(74) Representative: **Grünecker, Kinkeldey,**
Stockmair & Schwanhäusser
Anwaltssozietät
Maximilianstrasse 58
80538 München (DE)

(54) Apparatus and method for measuring oxygen saturation in blood

(57) In an apparatus for measuring an oxygen saturation in blood, a plurality of light emitters are adapted to irradiate a living tissue with a plurality of light beams having different wavelengths. A light receiver is adapted to receive the light beams reflected from or transmitted through the living tissue to generate pulse wave signals in accordance with pulsations of the blood in the living tissue. A separator is operable to separate each of the pulse wave signals into a plurality of amplitude signals each of which is associated with one frequency, thereby generating pairs of amplitude signals each of which is associated with one of a plurality of frequencies. A first processor is operable to calculate a ratio between the amplitude signals in each of the pairs of the amplitude signals. A selector is operable to select one of the pairs of the amplitude signals. A second processor is operable to calculate the oxygen saturation based on the ratio of the selected one of the pairs of the amplitude signals.

FIG. 1



EP 1 757 224 A2

Description

BACKGROUND OF THE INVENTION

[0001] The present invention relates to signal processing in a pulse oximeter used in a patient monitoring or for diagnosing a respiratory system or a circulatory system.

[0002] Various methods have been proposed to separate a signal component and a noise component from two signals substantially simultaneously extracted from a single medium. The methods are usually conducted by performing processing in a frequency region and a time region.

[0003] In medical fields, it is known a pulse photometer including: an apparatus called a photoplethysmograph for measuring a pulse waveform and a pulse rate; and an apparatus for measuring the concentration of a light absorbing material in blood such as an apparatus for measuring an oxygen saturation in blood (SpO_2), an apparatus for measuring the concentration of abnormal hemoglobins such as carboxyhemoglobin and methemoglobin, and an apparatus for measuring the concentration of an injected dye. Particularly, the apparatus for measuring the SpO_2 is called a pulse oximeter.

[0004] The principle of the pulse photometer is to determine the concentration of an object material from a pulse wave signal obtained by causing a living tissue to transmit or reflect light beams, which have a plurality of wavelengths respectively correspond to different absorbances of the object material, and by continuously measuring an intensity of transmitted or reflected light. In a case where noise are superimposed on pulse wave data, calculation of a correct concentration or pulse rate cannot be achieved. Consequently, there is an anxious that an erroneous treatment may be performed.

[0005] There is proposed a method performed in the pulse photometer, in which pulse wave signals are divided into a plurality of frequency bands and a correlation between the signals is examined in each of the divided frequency bands to reduce noises. However, this method has a problem in that analysis is time-consuming.

[0006] Japanese Patent No. 3270917 discloses a method comprising: irradiating light beams respectively having different wavelengths onto a living tissue; drawing a graph in which the longitudinal axis and the transverse axis thereof respectively represent the magnitudes of two signals obtained from transmitted light; and obtaining a regression line to thereby obtain an oxygen saturation or the concentration of a light absorbing material in arterial blood according to the gradient of the regression line.

[0007] However, a large amount of calculation is needed to obtain a regression line and the gradient thereof by using a great amount of sampling-data on each of the pulse wave signals.

[0008] Japanese Patent Publication No. 2003-135434A discloses a method of using frequency analysis, in which the fundamental frequency of a pulse wave signal is obtained instead of conventional extraction of the pulse wave signal itself, and the pulse wave signal is filtered by using a filter employing a higher harmonic wave frequency to enhance accuracy. Japanese Patent Publication Nos. 2005-95581A and 2005-245574A disclose a method for separating noise from a pulse wave signal.

[0009] However, in a case where noise due to a body movement of a patient, whose amplitude is about ten times that of the pulse wave, is superimposed on a pulse wave signal, it is difficult according to any of these methods to compute a pulse rate and an oxygen saturation in arterial blood. Thus, a further improvement in signal processing is desired.

SUMMARY OF THE INVENTION

[0010] It is therefore an object of the invention to provide a signal processing method enabled to alleviate load calculation for extracting a common signal component by processing two signals of a same kind, which are substantially simultaneously extracted from a same medium.

[0011] It is also an object of the invention to measure the oxygen saturation of an object material with high accuracy by applying the signal processing method even when noise due to the body movement of the medium is superimposed on a pulse wave signal, thereby obtaining a pulse rate with high precision.

[0012] In order to achieve the above objects, according to the invention, there is provided an apparatus for measuring an oxygen saturation in blood, comprising:

a plurality of light emitters, adapted to irradiate a living tissue with a plurality of light beams having different wavelengths;

a light receiver, adapted to receive the light beams reflected from or transmitted through the living tissue to generate pulse wave signals in accordance with pulsations of the blood in the living tissue;

a separator, operable to separate each of the pulse wave signals into a plurality of amplitude signals each of which is associated with one frequency, thereby generating pairs of amplitude signals each of which is associated with one of a plurality of frequencies;

Petitioner Ex-1004, 0701

BNSDOCID: <EP_____1757224A2_I_>

a first processor, operable to calculate a ratio between the amplitude signals in each of the pairs of the amplitude signals;
a selector, operable to select one of the pairs of the amplitude signals; and
a second processor, operable to calculate the oxygen saturation based on the ratio of the selected one of the pairs of the amplitude signals.

[0013] The separator may comprise either an FFT processor or a digital filter.

[0014] The selector may be operable to select such a pair of the amplitude signals that have maximum amplitude values.

[0015] The selector may be operable to select such a pair of the amplitude signals that the ratio takes a minimum value.

[0016] The first processor may comprise: a first calculator, operable to define a plurality of frequency bands each of which includes a plurality of amplitude signals obtained from each of the pulse wave signals, and operable to calculate an average value of the amplitude signals in each of the frequency bands, thereby generating pairs of average values each of which is associated with one of the frequency bands; and a second calculator, operable to calculate an average ratio between the average values in each of the pairs of the average values. The selector may be operable to select such a frequency band that the average ratio takes a minimum value.

[0017] The apparatus first processor may comprise: a first calculator, operable to: define a plurality of frequency bands each of which includes a plurality of amplitude signals obtained from each of the pulse wave signals; judge whether there is a maximal point of the amplitude signals in each of the frequency bands; and calculate an average value of the amplitude signals in at least one of the frequency bands which is judged as one including the maximal point, thereby at least one pair of average values each of which is associated with one of the frequency bands; and a second calculator, operable to calculate an average ratio between the average values in each of the at least one pair of the average values. The selector may be operable to select such a frequency band that the average ratio takes a minimum value.

[0018] The first processor may comprise: a first calculator, operable to calculate ratios each of which is a ratio between each of the pairs of the amplitude signals; and a second calculator, operable to define a plurality of frequency bands each of which includes a plurality of amplitude signals obtained from each of the pulse wave signals, and operable to calculate an average value of the ratios in each of the frequency bands, thereby generating a plurality of average values. The selector may be operable to select such a frequency band that the average value takes a minimum value.

[0019] A part of one of the frequency bands may be overlapped with a part of another one of the frequency bands.

[0020] The selector may be operable to select either such a pair of the amplitude signals that have maximum amplitude values or such a pair of the amplitude signals that the ratio takes a minimum value in accordance with a prescribed condition.

[0021] The prescribed condition may include a waveform of the amplitude signals.

[0022] The light beams may include a red light beam and an infrared light beam.

[0023] According to the invention, there is also provided a method for measuring an oxygen saturation in blood, comprising:

irradiating a living tissue with a plurality of light beams having different wavelengths;
receiving the light beams reflected from or transmitted through the living tissue to generate pulse wave signals in accordance with pulsations of the blood in the living tissue;
separating each of the pulse wave signals into a plurality of amplitude signals each of which is associated with one frequency, thereby generating pairs of amplitude signals each of which is associated with one of a plurality of frequencies;
calculating a ratio between the amplitude signals in each of the pairs of the amplitude signals;
selecting one of the pairs of the amplitude signals; and
calculating the oxygen saturation based on the ratio of the selected one of the pairs of the amplitude signals.

[0024] The separating may be performed with either an FFT processing or a digital filtering.

[0025] Such a pair of the amplitude signals that have maximum amplitude values may be selected as the one of the pairs of the amplitude signals.

[0026] Such a pair of the amplitude signals that the ratio takes a minimum value may be selected as the one of the pairs of the amplitude signals.

[0027] The method may further comprise:

defining a plurality of frequency bands each of which includes a plurality of amplitude signals obtained from each of the pulse wave signals;
calculating an average value of the amplitude signals in each of the frequency bands, thereby generating pairs of average values each of which is associated with one of the frequency bands;
calculating an average ratio between the average values in each of the pairs of the average values; and

Petitioner Ex-1004, 0702

BNSDOCID: <EP_____1757224A2_I_>

selecting such a frequency band that the average ratio takes a minimum value.

[0028] The method may further comprise:

defining a plurality of frequency bands each of which includes a plurality of amplitude signals obtained from each of the pulse wave signals;
judging whether there is a maximal point of the amplitude signals in each of the frequency bands;
calculating an average value of the amplitude signals in at least one of the frequency bands which is judged as one including the maximal point, thereby at least one pair of average values each of which is associated with one of the frequency bands;
calculating an average ratio between the average values in each of the at least one pair of the average values; and
selecting such a frequency band that the average ratio takes a minimum value.

[0029] The method may further comprise:

calculating ratios each of which is a ratio between each of the pairs of the amplitude signals;
defining a plurality of frequency bands each of which includes a plurality of amplitude signals obtained from each of the pulse wave signals;
calculating an average value of the ratios in each of the frequency bands, thereby generating a plurality of average values; and
selecting such a frequency band that the average value takes a minimum value.

[0030] A part of one of the frequency bands may be overlapped with a part of another one of the frequency bands.

[0031] Either such a pair of the amplitude signals that have maximum amplitude values or such a pair of the amplitude signals that the ratio takes a minimum value may be selected as the one of the pairs of the amplitude signals in accordance with a prescribed condition.

[0032] The prescribed condition may include a waveform of the amplitude signals.

BRIEF DESCRIPTION OF THE DRAWINGS

[0033] The above objects and advantages of the present invention will become more apparent by describing in detail preferred exemplary embodiments thereof with reference to the accompanying drawings, wherein:

Fig. 1 is a block diagram schematically showing a pulse oximeter;
Fig. 2A is a graph showing attenuation change signals obtained from pulse wave signals measured by the pulse oximeter, in a case where no noise is superimposed;
Fig. 2B is a graph showing amplitude spectra obtained by applying a FFT processing with respect to the pulse wave signals shown in Fig. 2A;
Fig. 2C is a graph showing a ratio between amplitudes of the spectra shown in Fig. 2B;
Fig. 3A is a graph showing attenuation change signals obtained from pulse wave signals pulse wave signals measured by the pulse oximeter, in a case where noise is superimposed thereon;
Fig. 3B is a graph showing amplitude spectra obtained by applying a FFT processing with respect to the pulse wave signals shown in Fig. 3A;
Fig. 3C is a graph showing a ratio between amplitudes of the spectra shown in Fig. 3B, for explaining a signal processing according to a first embodiment of the invention;
Fig. 3D is a graph showing the ratio between amplitudes of the spectra shown in Fig. 3B, for explaining a signal processing according to a second embodiment of the invention;
Fig. 4A is a graph showing attenuation change signals obtained from pulse wave signals measured by the pulse oximeter, in a case where large noise is superimposed;
Fig. 4B is a graph showing amplitude spectra obtained by applying a FFT processing with respect to the pulse wave signals shown in Fig. 4A;
Fig. 4C is a graph showing attenuation change signals obtained from pulse wave signals measured by the pulse oximeter, in a case where a signal separation method is applied;
Fig. 4D is a graph showing amplitude spectra obtained by applying a FFT processing with respect to the pulse wave signals shown in Fig. 4C;
Fig. 4E is a graph showing a ratio between amplitudes of the spectra shown in Fig. 4D;
Fig. 5A is a graph showing attenuation change signals obtained from pulse wave signals measured by the pulse oximeter, in a case where extreme large noise is superimposed;

Petitioner Ex-1004, 0703

BNSDOCID: <EP_____1757224A2_I_>

Fig. 5B is a graph showing amplitude spectra obtained by applying a FFT processing with respect to the pulse wave signals shown in Fig. 5A;
Fig. 5C is a graph showing attenuation change signals obtained from pulse wave signals measured by the pulse oximeter, in a case where a signal separation method is applied;
Fig. 5D is a graph showing amplitude spectra obtained by applying a FFT processing with respect to the pulse wave signals shown in Fig. 5C;
Fig. 5E is a graph showing a ratio between amplitudes of the spectra shown in Fig. 5D;
Fig. 6 is a graph showing an actual measurement example;
Fig. 7A is a diagram showing a blood pulsation model in a case where no body movement is present;
Fig. 7B is a diagram showing the blood pulsation model in a case where a body movement is present;
Fig. 8 is a diagram showing a vector representation of attenuation ratios derived from the model shown in Fig. 78;
Fig. 9 is a diagram showing a correlation between the attenuation ratio and an oxygen saturation in blood;
Fig. 10A is a graph showing attenuation change signals obtained from pulse wave signals pulse wave signals measured by the pulse oximeter, in a case where noise is superimposed thereon;
Fig. 10B is a graph showing amplitude spectra obtained by applying a FFT processing with respect to the pulse wave signals shown in Fig. 10A, for explaining a third embodiment of the invention;
Fig. 10C is a graph showing values each of which is an average value of amplitudes in each of divided frequency bands shown in Fig. 10B; and
Fig. 10D is a graph showing values each of which is a ratio between the average values shown in Fig. 10C in each of the divided frequency bands.

DETAILED DESCRIPTION OF THE EMBODIMENTS

[0034] Embodiments of the invention will be described below in detail with reference to the accompanying drawings.

[0035] As shown in Fig. 1, in a pulse oximeter of the invention, light emitters 1 a (LED R) and 1b (LED IR) are driven by a first LED driver 2a, a second LED driver 2b and an LED selector 3 to alternately emit light.

[0036] Preferably, light emitted from the light emitter 1 a is red light (for example, the wavelength is 660nm), which is highly sensitive to change in the oxygen saturation in arterial blood, and light emitted from the light emitter 1 b is infrared light (for example, the wavelength is 940nm), which is less sensitive to the change in the oxygen saturation in arterial blood.

[0037] Light beams coming from these light emitters 1 a and 1b are transmitted (or reflected) by a living tissue 12 and are subsequently received by a photodiode 8 that converts the received light to photoelectric current. Then, a current-voltage converter 9 converts the photoelectric current to a voltage signal that is outputted to an A/D converter 11 through a pulse wave demodulator 10.

[0038] An LED selection signal is applied from the LED selector 3 to the pulse wave demodulator 10 as a timing signal. Thus, the red light and the infrared light received by the single photodiode 8 are extracted as separate pulse wave signals.

[0039] Pulse wave signals digitalized by the A/D converter 11 are processed by a CPU (adapted to perform computing, processing, and control). The digital pulse wave signals are displayed on a display 5 and are recorded in a recorder 6.

[0040] A control panel 7 is operative to perform the setting for performing processing in the CPU.

[0041] Each of pulse waves respectively corresponding to red light R and infrared light IR is separated into an AC component and a DC component by filtering. In addition, the ratio AC/DC of the magnitude of the AC component to that of the DC component is calculated corresponding to each of the pulse waves R and IR to thereby calculate signals representing attenuation changes ΔA.

[0042] The magnitude of the AC component in the pulse wave for the red light R is denoted as R_AC(t). The magnitude of the DC component in the pulse wave for the red light R is denoted as R_DC(t). The magnitude of the AC component in the pulse wave for the infrared light IR is denoted as IR_AC(t). The magnitude of the DC component in the pulse wave for the infrared light IR is denoted as IR_DC(t).

[0043] Thus, the attenuation change signal for the red light R is expressed by $\Delta Ar(t)$ = R_AC(t) / R_DC(t), and the attenuation change signal for the infrared light IR is expressed by $\Delta Air(t)$ = IR_AC(t) / IR_DC(t). Fig. 2A shows these attenuation change signals.

[0044] Fig. 2B shows amplitude spectra obtained after FFT processing is performed on the pulse waves shown in Fig. 2A. The amplitude spectrum corresponding to $\Delta Ar(t)$ is denoted as R_F, FT(f) and the amplitude spectrum corresponding to $\Delta Air(t)$ is denoted as IR_FFT(f). Because no noise are superimposed on the pulse waves, each of the amplitude spectra shows a maximum value at a frequency of the pulse wave.

[0045] Fig. 2C shows a ratio between the amplitudes of the spectra shown in Fig. 2B (R_FFT(f) / IR_FFT(f)). This ratio represents an attenuation ratio Φ at each frequency of the spectra. Thus, the attenuation ratio Φ can be expressed by $\Phi(f)$ = R_FFT(f) / IR_FFT(f).

[0046] When the frequency resolution of FFT is 0.1 Hz, $\Phi(f)$ is computed by separating the pulse wave into frequencies at intervals of 0.1 Hz.

Petitioner Ex-1004, 0704

BNSDOCID: <EP_____1757224A2_I_>

[0047] Figs. 2A to 2C illustrate a case where no noise are superimposed on the pulse wave. However, in the case of actually measured pulse wave, the attenuation ratio Φ includes Φs which corresponds to the attenuation changes in arterial blood, and Φn which corresponds to the attenuation changes of noise.

[0048] In a first embodiment of the invention, the attenuation ratios Φ are calculated for a plurality of frequencies, and the attenuation ratio Φ at a frequency fmax, at which the amplitude of each of the spectra becomes maximum, is set to be the attenuation ratio Φs of arterial blood.

[0049] Figs. 3A to 3C respectively correspond to Figs. 2A to 2C and are showing a case where noise is superimposed on the pulse wave signals.

[0050] In comparison with the waveforms shown in Fig. 2B, it is apparent that, in Fig. 3B, peaks due to the noise appear at frequencies other than the frequency of the pulse wave.

[0051] In a case where the amplitude due to the noise is relatively smaller than the amplitude of the pulse wave signal (e.g., in a case where the ratio of the amplitude due to the noise to the amplitude of the pulse wave signal is no greater than 0.7, preferably, no greater than 0.5), the attenuation ratio Φ at the frequency, at which each of the amplitude spectra shows a maximum value, is read and is determined to be the attenuation ratio Φs of arterial blood as shown in Fig. 3C. Thus, the attenuation ratio Φs of arterial blood can easily be obtained.

[0052] In a second embodiment of the invention, the attenuation ratios Φ are calculated for a plurality of frequencies, and a minimum value of the attenuation ratios Φ is set to be the attenuation ratio Φs of arterial blood.

[0053] Generally, the attenuation ratio Φn in the frequency, at which the amplitude due to noise appears, tends to be higher than the attenuation ratio Φs in the frequency at which the amplitude due to the pulse wave appears.

[0054] This is because of the fact that the change in the attenuation ratio, which is caused by the noise, results mainly from change in the thickness of venous blood. Because the oxygen saturation in venous blood is lower than that of arterial blood, the attenuation ratio Φn due to the change in thickness of venous blood is lower than the attenuation ratio Φs. Therefore, the minimum value of the attenuation ratios Φ can be read as the attenuation ratio Φs of arterial blood. Fig. 3D shows this processing.

[0055] It is apparent that the ratio Φs obtained by this processing is almost the same as that obtained by the processing illustrated in Fig. 3C. Here, the ratio Φs obtained by this processing may be taken into account of the judgment performed in the first embodiment.

[0056] In a case where the frequency, at which the amplitude peak due to the noise appears, overlaps with the frequency, at which the amplitude peak due to the pulse wave appears, the attenuation ratio Φ obtained at such a frequency becomes lower than the actual attenuation ratio Φs of arterial blood. Thus, the SpO_2 cannot correctly be measured when the attenuation ratio Φ obtained at the above frequency is employed. In such a case, a second-minimum attenuation ratio Φ obtained at a frequency other than the above frequency may be regarded as that Φs of arterial blood.

[0057] Next, grounds for the above determination will be described below by using a model in which arterial blood pulsates and increases in thickness when no body movement is present with reference to Fig. 7A, and in which the thickness of arterial blood and that of venous blood simultaneously change when a body movement is present with reference to Fig. 7B.

[0058] In the case illustrated in Fig. 7A, the attenuation change ΔA is measured according to Lambert-Beer's law as follows.

$$\Delta A = \Delta Aa = Ea \cdot Hb \cdot \Delta Da$$

where Aa designates an attenuation change caused by change in the thickness of arterial blood; Ea designates an absorption coefficient of arterial blood (dL/g/cm); Hb denotes a hemoglobin concentration (g/dL); and ΔDa designates change in the thickness of arterial blood (cm). The attenuation ratio Φ to be measured is given by the following equation.

$$\Phi = \Delta A_1/\Delta A_2 = (Ea_1 \cdot Hb \cdot \Delta Da) / (Ea_2 \cdot Hb \cdot \Delta Da) = Ea_1/Ea_2$$

where the suffixes designate wavelength numbers, and the suffix 1 corresponds to a wavelength of 660nm, and the suffix 2 corresponds to a wavelength of 940nm.

[0059] The attenuation ratio Φm to be measured in the case, in which no body movement is present, is given by the following equation.

Petitioner Ex-1004, 0705

BNSDOCID: <EP_____1757224A2_I_>

$$\Phi m = \Delta A_1 / \Delta A_2 = \Delta A_{a1} / \Delta A_{a2}$$

Thus, the measured Φm is the attenuation ratio Φa of arterial blood, that is, $\Phi a = \Delta A_{a1}/\Delta A_{a2}$.

[0060] On the other hand, in the case where a body movement is present, not only the thickness of arterial blood but the thickness of venous blood changes, as shown in Fig. 7B. The attenuation change ΔA caused in this case is a sum of the attenuation change ΔAa, which is caused by change in the thickness of arterial blood, and the attenuation change ΔAv, which is caused by change in the thickness of venous blood (i.e., ΔA = ΔAa + ΔAv). The attenuation ratio Φm to be measured in this case is given by the following equation.

$$\Phi m = \Delta A_1/\Delta A_2 = (\Delta A_{a1} + \Delta A_{v1}) / (\Delta A_{a2} + \Delta A_{v2})$$

[0061] The attenuation changes are given in the following equations expressed in vector notation below.

$$Aa = (\Delta A_{a2}, \Delta A_{a1})$$

$$Av = (\Delta A_{v2}, \Delta A_{v1})$$

$$Am = (\Delta A_{a2} + \Delta A_{v2}, \Delta A_{a1} + \Delta A_{v1})$$

The attenuation ratios Φ corresponding to the above attenuation changes are represented by the respective gradients of the vectors shown in Fig. 8.

[0062] Incidentally, oxygen contained in arterial blood is taken into the tissue. Thus, the oxygen saturation Sv in venous blood is lower than that Sa in arterial blood (Sa > Sv). However, because of the correlation between the attenuation ratio Φ and the oxygen saturation S of blood as shown in Fig. 9, the inequality Φa < Φv holds.

[0063] Therefore, as shown in Fig. 8, the measured attenuation ratio vector Am appears between the vector Aa, whose gradient is small, and the vector Av whose gradient is large. The gradient Φm of the measured signal Am is determined by the ratio in length between the vectors Aa and Av on condition that the values of the ratios Φa and Φv are constant.

[0064] In a case where a body movement is small and where the length of the vector Av is nearly equal to 0 ($|Av| \approx 0$), $\Phi m \approx \Phi a$. In a case where a body movement is large and where the length of the vector Av is much larger than that of the vector Aa ($|Av| \gg |Aa|$), $\Phi m \approx \Phi v$.

[0065] In a case where the attenuation change ratio Φm is observed by separating the pulse wave into a plurality of frequencies, the ratio Φ obtained at the frequency, at which the value of the ratio Φm is minimum, has a value closest to the attenuation ratio Φa of arterial blood.

[0066] The condition for minimizing the ratio Φm is that the ratio ($|Aa| / |Av|$) is maximum. However, the length |Aa| is maximum at the fundamental frequency of the pulse wave, among the plurality of frequencies. Thus, assuming that the noise is random like white noise, the ratio ($|Aa| / |Av|$) is maximum at the fundamental frequency of the pulse wave.

[0067] Consequently, on condition that the noise is random, the fundamental frequency of the pulse wave can be determined by searching for a frequency at which the ratio Φm is minimum.

[0068] Next, a third embodiment of the invention will be described. Figs. 10A and 10B respectively correspond to Figs. 3A and 3B. In this embodiment, an effective frequency band (e.g., from 0.5Hz to 5.0Hz) of each of the amplitude spectra is divided into a plurality of frequency bands (e.g., eight bands) each of which has a plurality of measurement points (e.g., four points) denoted by dashed lines in Fig. 10B.

[0069] In this embodiment, the divided frequency bands arranged such that parts of adjacent divided frequency bands are overlapped to each other. However, the adjacent divided frequency bands may not be overlapped to each other.

[0070] Next, as shown in Fig. 10C, an average value of the amplitudes at the plural measurement points is calculated for each of the divided frequency bands. The average value calculated for the spectrum corresponding to the red light

Petitioner Ex-1004, 0706

BNSDOCID: <EP_____1757224A2_I_>

R is denoted as R_FFT_ave. The average value calculated for the spectrum corresponding to the infrared light IR is denoted as IR_FFT_ave.

[0071] Further, as shown in Fig. 10D, a ratio between the thus calculated average values (R_FFT_ave /IR_FFT_ave) is calculated for each of the divided frequency bands.

[0072] Finally, the minimum value Rmin of the thus calculated ratios is regarded as an attenuation ratio in arterial blood, and the frequency associated with the minimum value is regarded as a fundamental frequency fp of the pulse wave.

[0073] In this embodiment, the average value of the amplitudes at the plural measurement points is first calculated for each of the divided frequency bands, and the ratio between the average values is then calculated as the attenuation ratio. However, a ratio between the amplitudes for each of the measurement points may be first calculated as an attenuation ratio, and an average value of the thus calculated ratios may be then calculated for each of the divided frequency bands.

[0074] In addition, the following processing may be adopted. It is determined whether a maximal point of the amplitude spectrum is included for each of the divided frequency shown in Fig. 10B. A divided frequency band which is judged as one including the maximal point becomes a candidate for a frequency band including an attenuation ratio in arterial blood. Among such candidates, one including the minimum value of the ratio between the average values (R_FFT_ave / IR_FFT_ave) is determined as the frequency band including an attenuation ratio in arterial blood.

[0075] The above judgment may be performed at least one of the amplitude spectrum corresponding to the red light R (R_FFT) and the amplitude spectrum corresponding to the infrared light IR (IR_FFT).

[0076] A divided frequency band which is judged as one not including the maximal point will not become the candidate even if the ratio of the average values (R_FFT_ave/ IR_FFT_ave) of the divided frequency band has a relatively small value.

[0077] Specifically, in order to judge whether one divided frequency band has a maximal point of the amplitude spectrum, it is judged an n-th measurement point in the divided frequency band denoted as FFT(n) is the maximal point when the FFT(n) satisfies both of the following inequalities: $FFT(n-1) < FFT(n)$ and $FFT(n) > FFT(n+1)$.

[0078] However, if the n-th measurement point judged as the maximal point is located at one of both ends of one of the divided frequency bands (2) through (7) shown in Fig. 10B, the frequency band including such an n-th measurement point will not be regarded as one including the maximal point. This is because both ends of one of these divided frequency bands is contained in an adjacent one of the divided frequency bands. In other words, since the measurement points corresponding to the minimum frequency in the divided frequency band (1) and the maximum frequency in the divided frequency band (8) are not contained in another divided frequency band, if these measurement points are judged as the maximal point, the judgment is made valid.

[0079] The above judgment in connection with the maximal point may be executed after the execution of the processings shown in Figs. 10A to 10D in order to enhance the accuracy of the determination of the attenuation ratio in arterial blood based on the minimum value Rmin.

[0080] In a case where the amplitude of the noise is relatively smaller than the amplitude of the pulse wave, the attenuation ratio Φ at the frequency, at which the amplitude spectrum shows a maximum value, can be read and is determined to be the attenuation ratio Φs of arterial blood. However, in a case where the amplitude of the noise is somewhat large, it is difficult to find out a peak corresponding to the pulse wave from the amplitude spectrum obtained by the FFT or the like.

[0081] Figs. 4A and 4B respectively correspond to Figs. 2A and 2B and are showing a case where large noise is superimposed on the pulse wave signals. The amplitude of the noise is almost the same as the amplitude of the pulse wave signal. Although the pulse wave can be still recognized in Fig. 4A, and the peak corresponding to the pulse wave can be recognized in Fig. 4B, in a case where a plurality of peaks having similar amplitudes, it is difficult to identify the peak corresponding to the pulse wave.

[0082] In such a case, a well-known signal separation method may be applied before the FFT processing is performed. As shown in Fig. 4C, the pulse wave signal and the noise can clearly be separated from each other. After the FFT processing is performed with respect to the thus separated signals, the frequency of the pulse wave can clearly be determined in the spectra as shown in Fig. 4D.

[0083] The attenuation ratio Φ of the arterial blood can be determined as well as the first or second embodiment as shown in Fig. 4E.

[0084] Figs. 5A to 5E respectively correspond to Figs. 4A to 4E and are showing a case where extreme large noise is superimposed on the pulse wave signals. The amplitude of the noise is about ten times the amplitude of the pulse wave signal. As shown in Figs. 5A and 5B, it is impossible to recognize pulse wave components from the measured waveforms and the amplitude spectra. During such a vigorous body movement, arterial blood is often moved due to the body movement. Thus, even if the signal separation method is applied, the obtained waveform of the signal shown in Fig. 5C entirely differs from the pulse wave.

[0085] Therefore, even when the movement of an arterial blood component corresponding to the signal can be separated from the movement of a venous blood component corresponding to the noise, the frequency of each of the pulse

Petitioner Ex-1004, 0707

BNSDOCID: <EP_____1757224A2_I_>

waves cannot be identified according to the waveforms shown in Fig. 5C and the those obtained after the FFT processing, which are shown in Fig. 5D.

[0086] In a case where the amplitude corresponding to the noise is larger than the amplitude of the pulse wave signal, it is difficult to calculate a pulse rate and an oxygen saturation by employing a frequency, at which the amplitude of the spectrum is maximum, as the fundamental frequency of the pulse wave. However, according to the method as explained in the second and third embodiments, the frequency of a pulse wave can be determined by searching a frequency, at which the attenuation ratio is minimum, as shown in Fig. 5E. The attenuation ratio at the determined frequency can be obtained as the oxygen saturation in arterial blood.

[0087] In a case where no noise is superimposed on the pulse wave, a maximum amplitude appears at the fundamental frequency of the pulse wave, and higher harmonic waves appear at frequencies which are twice and three times the fundamental frequency as shown in Fig. 2B. In a case where a large noise is superimposed on the pulse wave, frequencies, at each of which a peak amplitude is present, is not distributed in a narrow band, but is distributed in a wide band as shown in Fig. 5B. In a case where the amplitudes corresponding to noise are distributed in a narrow band, as shown in Fig. 3B, a peak appears at a frequency that differs from the fundamental frequency and from the frequencies of the higher harmonic waves.

[0088] In view of the above, the pulse oximeter may comprise a selector operable to select a frequency, at which the attenuation ratio is minimum, as a frequency representing an oxygen saturation in arterial blood, in a case where the frequency corresponding to the second-highest peak obtained by FFT is not twice the fundamental frequency that is the highest peak, or where the half-value width of the first peak obtained by FFT is neither equal to nor less than a prescribed value.

[0089] Fig. 6 shows an example in which a pulse wave, the SpO2 of which cannot be calculated by the conventional method because of the large noise, is divided into 8 frequency bands such that each of the bands has a band width of 1 Hz and center frequencies are ranged from 1.0Hz to 4.5Hz at a fixed interval of 0.5Hz, and SpO_2 is calculated for each of the divided bands. It is apparent that different values of SpO_2 corresponding to different attenuation ratios are obtained by the above measurement. Since arterial blood exhibits a higher oxygen saturation than venous blood, the SpO_2 of the band, which exhibits a highest value of the oxygen saturation, can be regarded as the oxygen saturation of arterial blood. Further, a representative frequency (e.g., a center frequency) of the frequency band including the highest value in the oxygen saturation can be regarded as the frequency of the pulse wave.

[0090] In the conventional method, the pulse wave signal and the noise are separated on the basis of the attenuation ratio. That is, in order to separate a pulse wave signal and noise at an analysis section of interest, it is necessary to input an attenuation ratio which is obtained in a previous section (i.e., data in the past is necessary). On the other hand, according to the method of the invention, since it is not necessary to refer data in the past, processing speed can be enhanced.

[0091] Although the present invention has been shown and described with reference to specific embodiments, various changes and modifications will be apparent to those skilled in the art from the teachings herein. Such changes and modifications as are obvious are deemed to come within the spirit, scope and contemplation of the invention as defined in the appended claims.

[0092] For example, in the above embodiments, the pulse wave is separated into a plurality of frequencies by the FFT. However, a plurality of bandpass filters, whose central frequencies differ from one another, may be used for separating the pulse wave into a plurality of frequencies.

[0093] The oxygen saturation measuring apparatus and method of the invention described in the appended claims 1 to 12 can realize a signal processing method enabled to alleviate a burden of calculation for extracting a common signal component by processing two signals of the same kind, which are substantially simultaneously extracted from a same medium. Also, the concentration of an object material can be measured with good accuracy by applying the signal processing method even when a noise due to the body movement of the medium is generated in a pulse wave signal. Also, even when a noise due to the body movement is generated in a pulse wave data signal, a pulse rate can be obtained with good precision by removing a noise from a pulse wave signal.

Claims

1. An apparatus for measuring an oxygen saturation in blood, comprising:

   a plurality of light emitters, adapted to irradiate a living tissue with a plurality of light beams having different wavelengths;
   a light receiver, adapted to receive the light beams reflected from or transmitted through the living tissue to generate pulse wave signals in accordance with pulsations of the blood in the living tissue;
   a separator, operable to separate each of the pulse wave signals into a plurality of amplitude signals each of

Petitioner Ex-1004, 0708

BNSDOCID: <EP_____1757224A2_I_>

which is associated with one frequency, thereby generating pairs of amplitude signals each of which is associated with one of a plurality of frequencies;
a first processor, operable to calculate a ratio between the amplitude signals in each of the pairs of the amplitude signals;
a selector, operable to select one of the pairs of the amplitude signals; and
a second processor, operable to calculate the oxygen saturation based on the ratio of the selected one of the pairs of the amplitude signals.

2. The apparatus as set forth in claim 1, wherein:

the separator comprises either an FFT processor or a digital filter.

3. The apparatus as set forth in claim 1, wherein:

the selector is operable to select such a pair of the amplitude signals that have maximum amplitude values.

4. The apparatus as set forth in claim 1, wherein:

the selector is operable to select such a pair of the amplitude signals that the ratio takes a minimum value.

5. The apparatus as set forth in claim 4, wherein:

the first processor comprises:

a first calculator, operable to define a plurality of frequency bands each of which includes a plurality of amplitude signals obtained from each of the pulse wave signals, and operable to calculate an average value of the amplitude signals in each of the frequency bands, thereby generating pairs of average values each of which is associated with one of the frequency bands; and
a second calculator, operable to calculate an average ratio between the average values in each of the pairs of the average values; and

the selector is operable to select such a frequency band that the average ratio takes a minimum value.

6. The apparatus as set forth in claim 4, wherein:

the first processor comprises:

a first calculator, operable to:

define a plurality of frequency bands each of which includes a plurality of amplitude signals obtained from each of the pulse wave signals;
judge whether there is a maximal point of the amplitude signals in each of the frequency bands; and
calculate an average value of the amplitude signals in at least one of the frequency bands which is judged as one including the maximal point, thereby at least one pair of average values each of which is associated with one of the frequency bands; and

a second calculator, operable to calculate an average ratio between the average values in each of the at least one pair of the average values; and

the selector is operable to select such a frequency band that the average ratio takes a minimum value.

7. The apparatus as set forth in claim 4, wherein:

the first processor comprises:

a first calculator, operable to calculate ratios each of which is a ratio between each of the pairs of the amplitude signals; and
a second calculator, operable to define a plurality of frequency bands each of which includes a plurality of

Petitioner Ex-1004, 0709

BNSDOCID: <EP_____1757224A2_I_>

amplitude signals obtained from each of the pulse wave signals, and operable to calculate an average value of the ratios in each of the frequency bands, thereby generating a plurality of average values; and

the selector is operable to select such a frequency band that the average value takes a minimum value.

8. The apparatus as set forth in claim 5, wherein:

a part of one of the frequency bands is overlapped with a part of another one of the frequency bands.

9. The apparatus as set forth in claim 6, wherein:

a part of one of the frequency bands is overlapped with a part of another one of the frequency bands.

10. The apparatus as set forth in claim 7, wherein:

a part of one of the frequency bands is overlapped with a part of another one of the frequency bands.

11. The apparatus as set forth in claim 1, wherein:

the selector is operable to select either such a pair of the amplitude signals that have maximum amplitude values or such a pair of the amplitude signals that the ratio takes a minimum value in accordance with a prescribed condition.

12. The apparatus as set forth in claim 11, wherein:

the prescribed condition includes a waveform of the amplitude signals.

13. The apparatus as set forth in claim 1, wherein the light beams include a red light beam and an infrared light beam.

14. A method for measuring an oxygen saturation in blood, comprising:

irradiating a living tissue with a plurality of light beams having different wavelengths;
receiving the light beams reflected from or transmitted through the living tissue to generate pulse wave signals in accordance with pulsations of the blood in the living tissue;
separating each of the pulse wave signals into a plurality of amplitude signals each of which is associated with one frequency, thereby generating pairs of amplitude signals each of which is associated with one of a plurality of frequencies;
calculating a ratio between the amplitude signals in each of the pairs of the amplitude signals;
selecting one of the pairs of the amplitude signals; and
calculating the oxygen saturation based on the ratio of the selected one of the pairs of the amplitude signals.

15. The method as set forth in claim 14, wherein:

the separating is performed with either an FFT processing or a digital filtering.

16. The method as set forth in claim 14, wherein:

such a pair of the amplitude signals that have maximum amplitude values is selected as the one of the pairs of the amplitude signals.

17. The method as set forth in claim 14, wherein:

such a pair of the amplitude signals that the ratio takes a minimum value is selected as the one of the pairs of the amplitude signals.

18. The method as set forth in claim 17, further comprising:

defining a plurality of frequency bands each of which includes a plurality of amplitude signals obtained from

Petitioner Ex-1004, 0710

BNSDOCID: <EP_____1757224A2_I_>

each of the pulse wave signals;
calculating an average value of the amplitude signals in each of the frequency bands, thereby generating pairs of average values each of which is associated with one of the frequency bands;
calculating an average ratio between the average values in each of the pairs of the average values; and
selecting such a frequency band that the average ratio takes a minimum value.

19. The method as set forth in claim 17, further comprising:

defining a plurality of frequency bands each of which includes a plurality of amplitude signals obtained from each of the pulse wave signals;
judging whether there is a maximal point of the amplitude signals in each of the frequency bands;
calculating an average value of the amplitude signals in at least one of the frequency bands which is judged as one including the maximal point, thereby at least one pair of average values each of which is associated with one of the frequency bands;
calculating an average ratio between the average values in each of the at least one pair of the average values; and
selecting such a frequency band that the average ratio takes a minimum value.

20. The method as set forth in claim 17, further comprising:

calculating ratios each of which is a ratio between each of the pairs of the amplitude signals;
defining a plurality of frequency bands each of which includes a plurality of amplitude signals obtained from each of the pulse wave signals;
calculating an average value of the ratios in each of the frequency bands, thereby generating a plurality of average values; and
selecting such a frequency band that the average value takes a minimum value.

21. The method as set forth in claim 18, wherein:

a part of one of the frequency bands is overlapped with a part of another one of the frequency bands.

22. The method as set forth in claim 19, wherein:

a part of one of the frequency bands is overlapped with a part of another one of the frequency bands.

23. The method as set forth in claim 20, wherein:

a part of one of the frequency bands is overlapped with a part of another one of the frequency bands.

24. The method as set forth in claim 14, wherein:

either such a pair of the amplitude signals that have maximum amplitude values or such a pair of the amplitude signals that the ratio takes a minimum value is selected as the one of the pairs of the amplitude signals in accordance with a prescribed condition.

25. The method as set forth in claim 24, wherein:

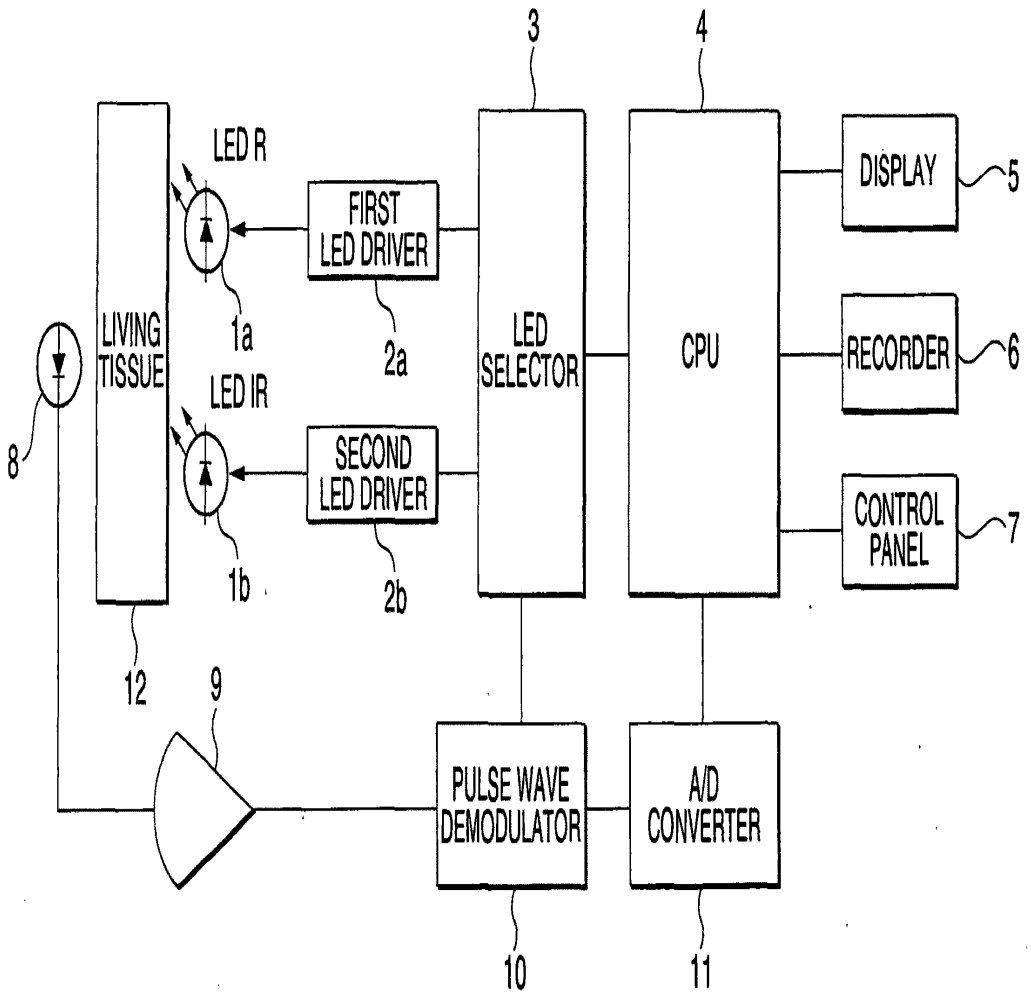
the prescribed condition includes a waveform of the amplitude signals.

Petitioner Ex-1004, 0711

BNSDOCID: <EP_____1757224A2_I_>

BNSDOCID: <EP 1757224A2_I_>

FIG. 1



Petitioner Ex-1004, 0712

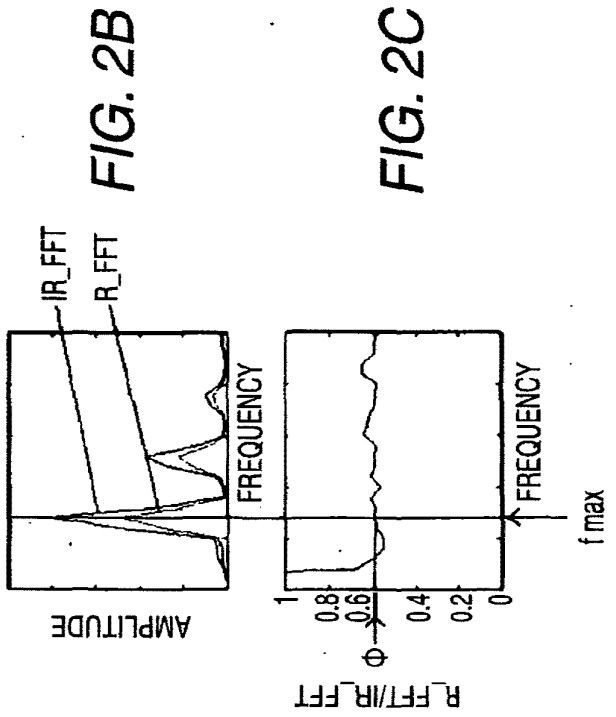


FIG. 2B

FIG. 2C

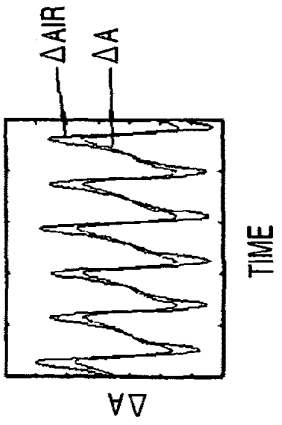


FIG. 2A

Petitioner Ex-1004, 0713

BNSDOCID: <EP_____1757224A2_1_>

BNSDOCID: <EP_____1757224A2_1_>

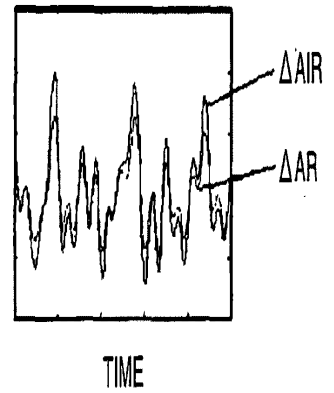


FIG. 3A

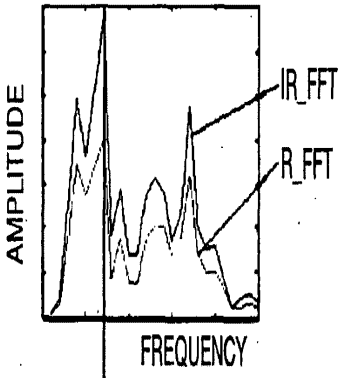


FIG. 3B

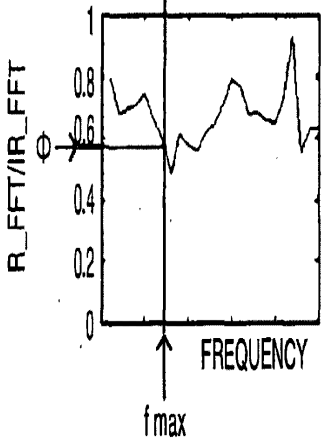


FIG. 3C

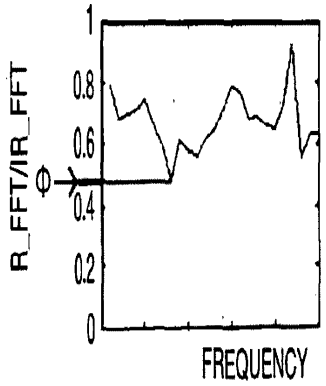


FIG. 3D

EP 1 757 224 A2

Petitioner Ex-1004, 0714

BNSDOCID: <EP_____1757224A2_I_>

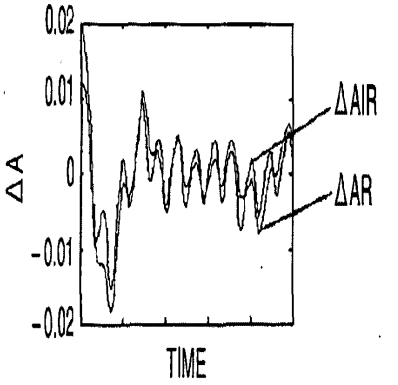


FIG. 4A

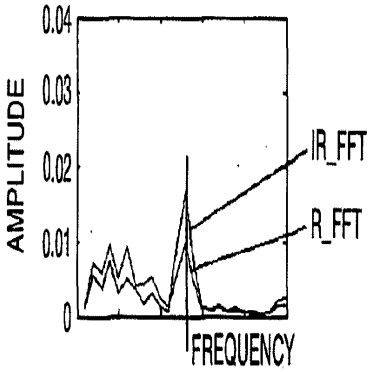


FIG. 4B

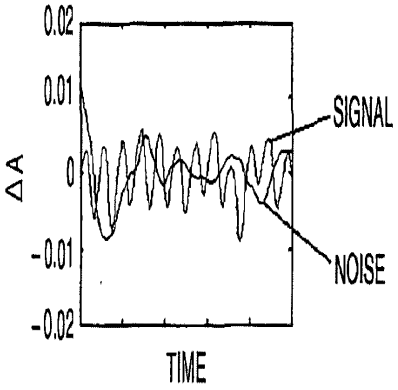


FIG. 4C

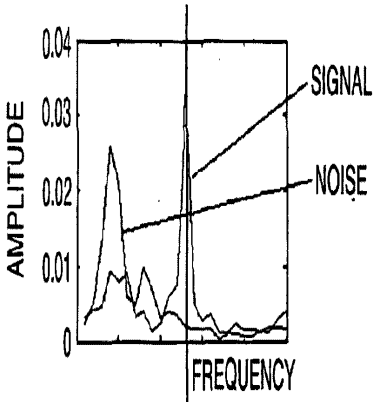


FIG. 4D

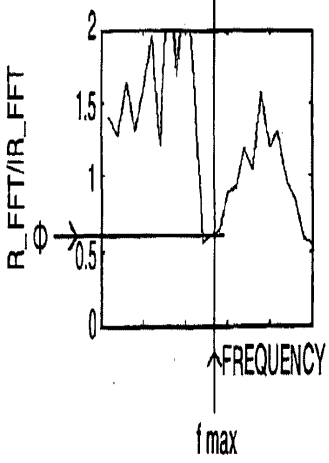


FIG. 4E

EP 1 757 224 A2

Petitioner Ex-1004, 0715

BNSDOCID: <EP 1757224A2_I>

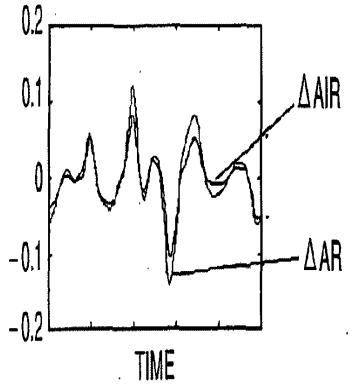


FIG. 5A

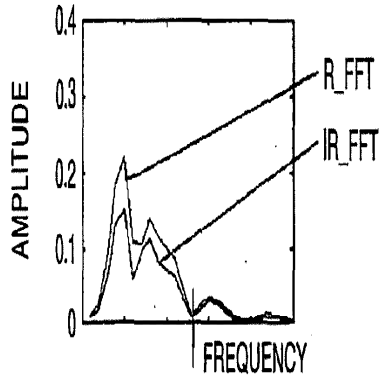


FIG. 5B

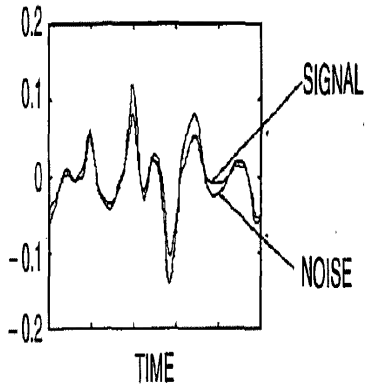


FIG. 5C

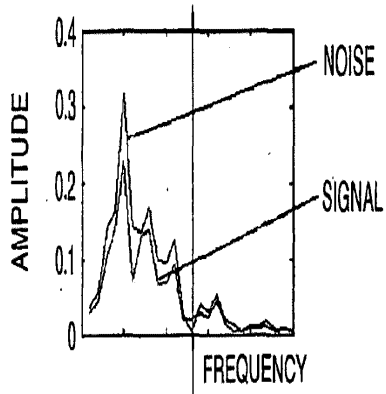


FIG. 5D

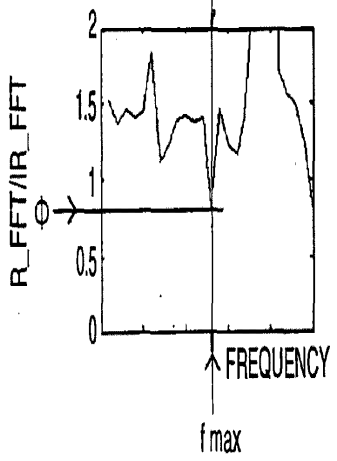


FIG. 5E

Petitioner Ex-1004, 0716

FIG. 6

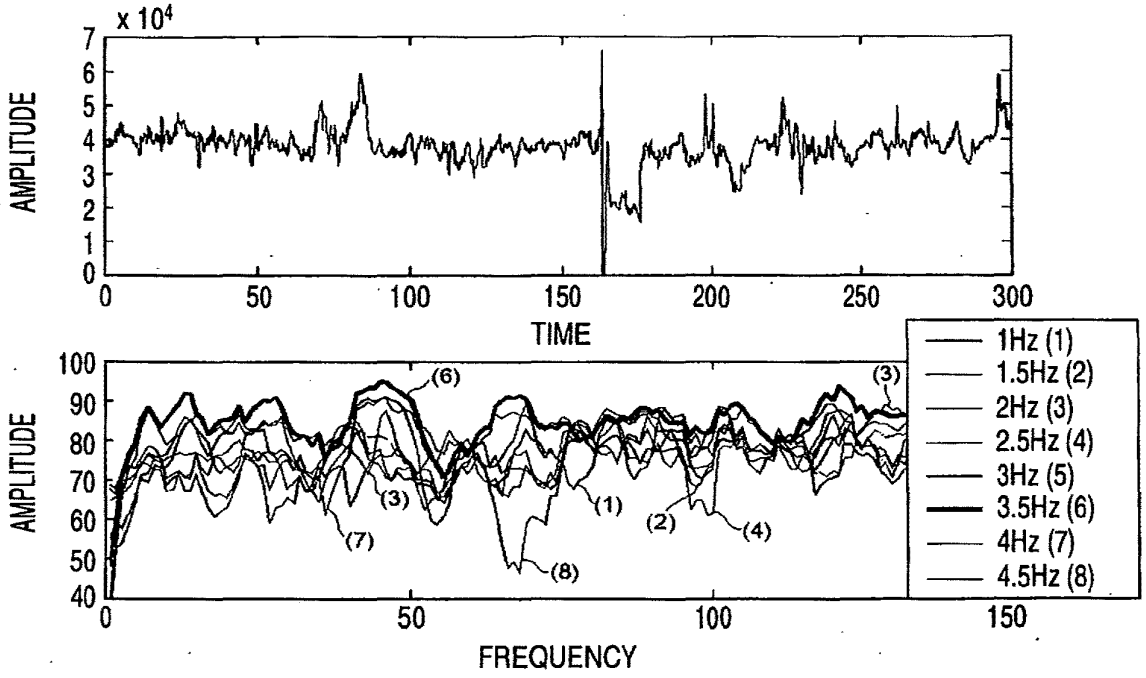


FIG. 7A

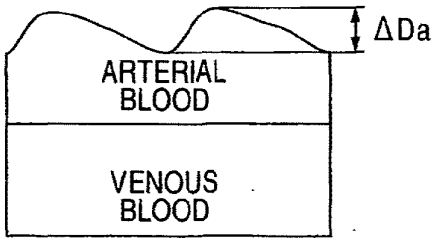
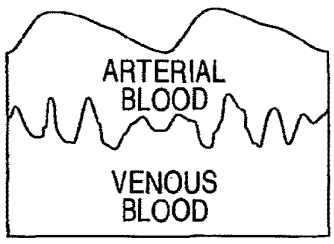


FIG. 7B



Petitioner Ex-1004, 0717

BNSDOCID: <EP_____1757224A2_I_>

FIG. 8

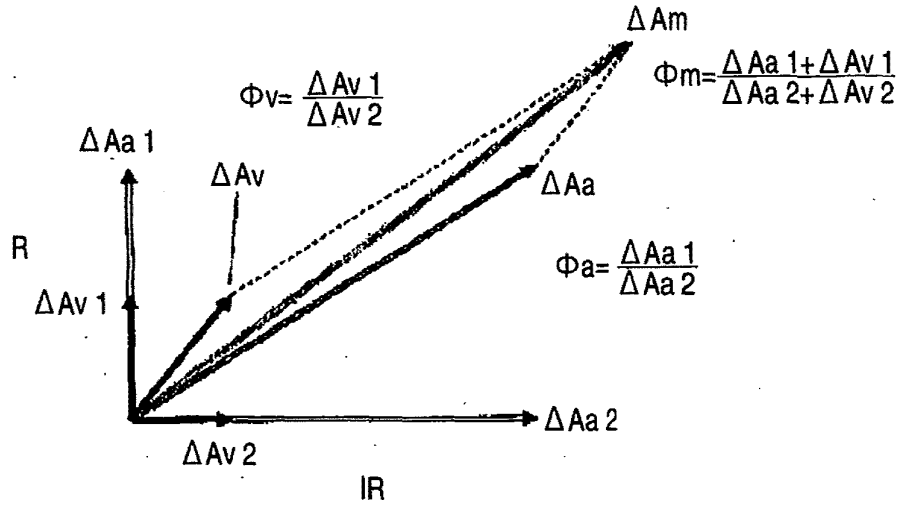
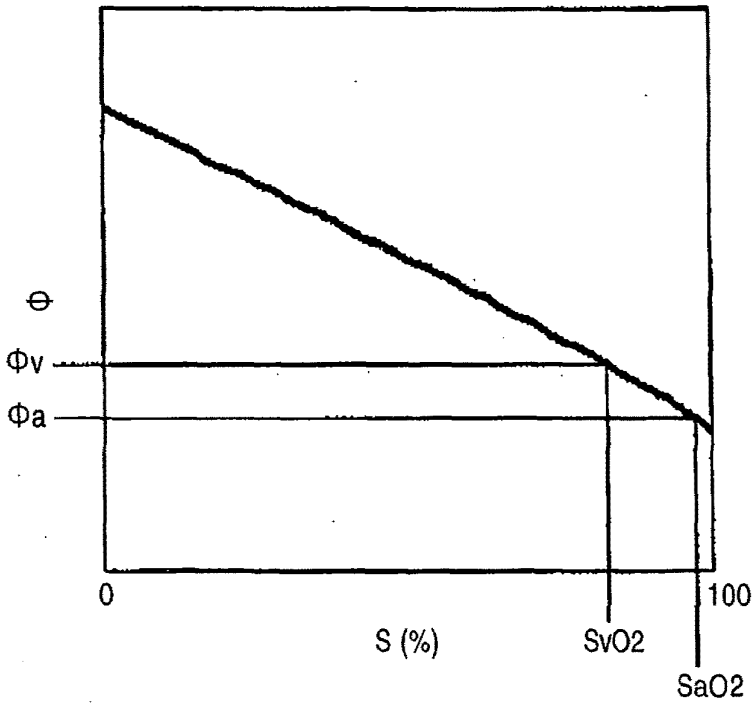


FIG. 9



Petitioner Ex-1004, 0718

BNSDOCID: <EP_____1757224A2_I_>

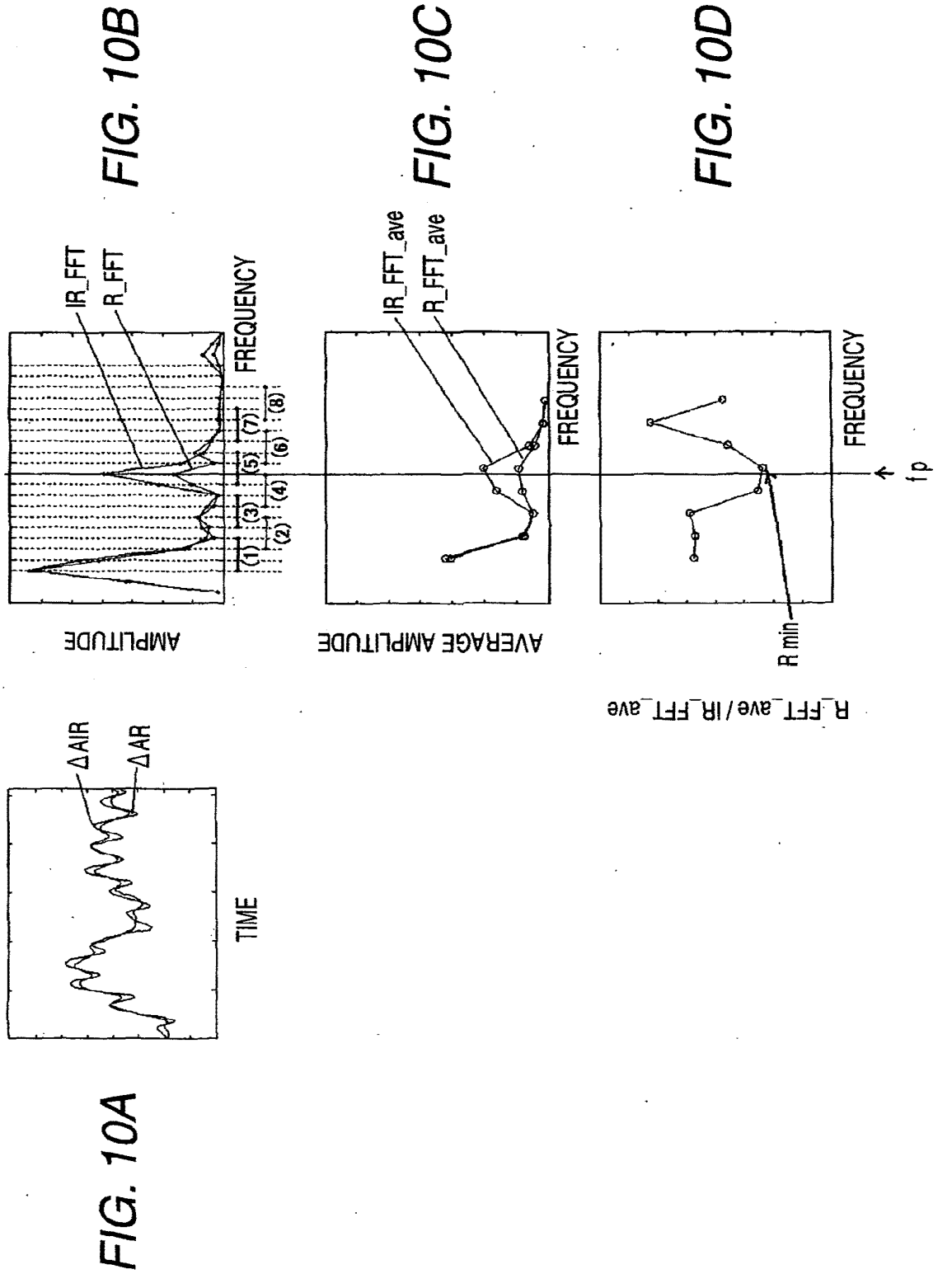


FIG. 10B

FIG. 10C

FIG. 10D

FIG. 10A

Petitioner Ex-1004, 0719

BNSDOCID: <EP_____1757224A2_I_>

REFERENCES CITED IN THE DESCRIPTION

This list of references cited by the applicant is for the reader's convenience only. It does not form part of the European patent document. Even though great care has been taken in compiling the references, errors or omissions cannot be excluded and the EPO disclaims all liability in this regard.

Patent documents cited in the description

- JP 3270917 B **[0006]**
- JP 2003135434 A **[0008]**
- JP 2005095581 A **[0008]**
- JP 2005245574 A **[0008]**

Petitioner Ex-1004, 0720

BNSDOCID: <EP_____1757224A2_I_>

(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 1 757 224 A3

(12) EUROPEAN PATENT APPLICATION

(88) Date of publication A3:
09.04.2008 Bulletin 2008/15

(43) Date of publication A2:
28.02.2007 Bulletin 2007/09

(21) Application number: **06017637.7**

(22) Date of filing: **24.08.2006**

(51) Int Cl.:
A61B 5/00 *(2006.01)*

(84) Designated Contracting States:
AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HU IE IS IT LI LT LU LV MC NL PL PT RO SE SI SK TR
Designated Extension States:
AL BA HR MK RS

(30) Priority: **24.08.2005 JP 2005242574**
28.07.2006 JP 2006205453

(71) Applicant: **Nihon Kohden Corporation**
Shinjuku-ku
Tokyo (JP)

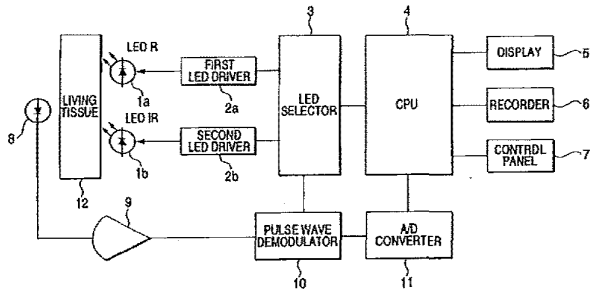
(72) Inventors:
- **Kobayashi, Naoki**
  Shinjuku-ku
  Tokyo (JP)
- **Miyata, Kenji**
  Shinjuku-ku
  Tokyo (JP)
- **Yarita, Masaru**
  Shinjuku-ku
  Tokyo (JP)
- **Ito, Kazumasa**
  Shinjuku-ku
  Tokyo (JP)

(74) Representative: **Grünecker, Kinkeldey,**
Stockmair & Schwanhäusser
Anwaltssozietät
Maximilianstrasse 58
80538 München (DE)

(54) Apparatus and method for measuring oxygen saturation in blood

(57) In an apparatus for measuring an oxygen saturation in blood, a plurality of light emitters are adapted to irradiate a living tissue with a plurality of light beams having different wavelengths. A light receiver is adapted to receive the light beams reflected from or transmitted through the living tissue to generate pulse wave signals in accordance with pulsations of the blood in the living tissue. A separator is operable to separate each of the pulse wave signals into a plurality of amplitude signals each of which is associated with one frequency, thereby generating pairs of amplitude signals each of which is associated with one of a plurality of frequencies. A first processor is operable to calculate a ratio between the amplitude signals in each of the pairs of the amplitude signals. A selector is operable to select one of the pairs of the amplitude signals. A second processor is operable to calculate the oxygen saturation based on the ratio of the selected one of the pairs of the amplitude signals.

FIG. 1



EP 1 757 224 A3

European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 06 01 7637

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	US 4 934 372 A (CORENMAN JAMES E [US] ET AL) 19 June 1990 (1990-06-19)	1-3, 11-16, 24,25	INV. A61B5/00
Y	* abstract * * column 4, line 18 - column 6, line 19 * * column 11, line 20 - column 13, line 22 *	4,17	
A	* column 15, line 18 - column 16, line 21 * * column 23, line 8 - column 24, line 45 * * figures 1a,10,10a-e * * claims 1-3,13-15,17,20-22,33-35,37 *	5-10, 18-23	
X	US 2004/059209 A1 (AL-ALI AMMAR [US] ET AL) 25 March 2004 (2004-03-25)	1-3, 11-16, 24,25	
Y	* abstract * * paragraph [0006] - paragraph [0087] *	4,17	
A	* figures 2-4,6-14 * * claims 1-11 *	5-10, 18-23	TECHNICAL FIELDS SEARCHED (IPC)
X	US 2005/033129 A1 (EDGAR REUBEN W [US] ET AL EDGAR JR REUBEN W [US] ET AL) 10 February 2005 (2005-02-10)	1-3, 11-16, 24,25	A61B
A	* abstract * * paragraph [0042] - paragraph [0095] * * figures 1-9 * * claims 1-6,18,19,25-28 *	4-10, 17-23	
X	US 2004/267140 A1 (ITO KAZUMASA [JP] ET AL) 30 December 2004 (2004-12-30) * abstract *	1,2, 13-15	
A	* paragraph [0043] - paragraph [0071] * * paragraph [0088] - paragraph [0147] * * figures 1-11 * * claims 1-14 *	4-10, 17-23	

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
Munich	25 February 2008	Doyle, Aidan

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document

EPO FORM 1503 03.82 (P04C01)

Petitioner Ex-1004, 0723

BNSDOCID: <EP_____1757224A3_I_>

ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 06 01 7637

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report. The members are as contained in the European Patent Office EDP file on
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

25-02-2008

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 4934372 A	19-06-1990	NONE	
US 2004059209 A1	25-03-2004	NONE	
US 2005033129 A1	10-02-2005	NONE	
US 2004267140 A1	30-12-2004	NONE	

EPO FORM P0459

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

Petitioner Ex-1004, 0724

BNSDOCID: <EP_____1757224A3_I_>

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
10 March 2011 (10.03.2011)

PCT

(10) International Publication Number
WO 2011/026669 A1

(51) International Patent Classification:
A61B 5/00 (2006.01)

(21) International Application Number:
PCT/EP2010/059616

(22) International Filing Date:
6 July 2010 (06.07.2010)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/272,238 3 September 2009 (03.09.2009) US

(71) Applicant *(for all designated States except US)*: **CSEM SA** [CH/CH]; Jaquet-Droz 1, CH-2002 Neuchâtel (CH).

(72) Inventors; and

(75) Inventors/Applicants *(for US only)*: **VETTER, Rolf** [CH/CH]; Chemin du Grand Pré 8, CH-1116 Cottens (CH). **CORREVON, Marc** [CH/CH]; Etroits 39, CH-2087 Cornaux (CH). **ROSSINI, Leopolodo** [CH/CH]; I Runch di Guèra 6, CH-6528 Camorino (CH). **RIDOLFI, Andrea** [IT/CH]; Kirchbergerstrasse 46, CH-3008 Bern (CH). **SOLA I CAROS, Josep** [ES/CH]; Cure 11A, CH-2035 Corcelles (CH).

(74) Agent: **P&TS**; Patents & Technology Surveys SA, Rue des Terreaux 7, PO Box 2848, CH-2001 Neuchâtel (CH).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

[Continued on next page]

(54) Title: MONITORING DEVICE AND METHOD FOR ESTIMATING BLOOD CONSTITUENT CONCENTRATION FOR TISSUES WITH LOW PERFUSION

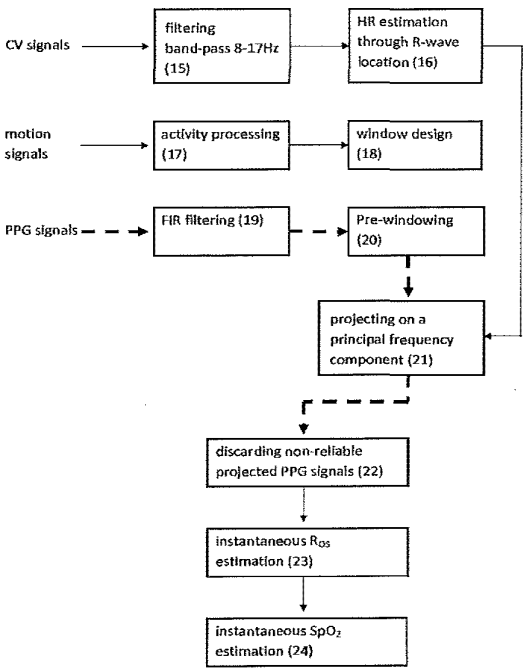


Fig. 3

(57) Abstract: The present disclosure concerns a method for estimating blood constituent concentration of a user under low perfusion conditions using a spectrophotometry-based monitoring device comprising a multi-channel sensor (1) formed from a plurality of channels (2, 5), and a cardiovascular sensor (7, 14); comprising: measuring a plurality of photoplethysmographic (PPG) signals, each PPG signal being measured by one of the channels (2, 5); measuring a cardio-synchronous (CV) signal by using the cardiovascular sensor (7, 14); detecting a instantaneous heart rate and determining a heart rate variability from the CV signal; for each detected heart rate, projecting the measured PPG signals multiplied by a window function on a principal frequency component, and selecting reliable projected PPG signals; and estimating a value of said blood constituent concentration from the magnitude of said reliable projected PPG signals selected over a predetermined time period; wherein said window function has a window length which is adjusted at each detected heart rate according to the determined heart rate variability; and wherein the frequency of said principal frequency component is estimated by averaging the heart rate over the window length.The disclosed method requires diminished computational load compared to conventional methods based on frequency domain approach as FFT or DCT,and provides better time and frequency resolution and thus optimal noise reduction and minimal signal distortion.

WO 2011/026669 A1

BNSDOCID: <WO_____2011026669A1_I_>

Published:

— *with international search report (Art. 21(3))*

BNSDOCID: <WO_____2011026669A1_I_>

Monitoring device and method for estimating blood constituent concentration for tissues with low perfusion

Reference data

This application claims priority to United States provisional patent application, Serial No. 61/272,238, filed on September 3, 2009. Priority to the provisional application is expressly claimed, and the disclosure of which is hereby incorporated herein by reference in its entirety and for all purposes.

Field of the invention

The present disclosure relates to a method for estimating blood constituent concentration of a user under low perfusion conditions using a spectrophotometry-based monitoring device.

Background

Pulse oximetry is a common, non-invasive method used in clinical environments to determine arterial oxygen (de-) saturation. Introduced in 1983 to permit accurate and fast assessment of oxygen delivery, it is recognized worldwide as the standard of care in anaesthesiology and is widely used in intensive care, operating rooms, emergency, patient transport, general wards, birth and delivery, neonatal care, sleep laboratories, home care, veterinary medicine and aerospace. Even more, pulse oximetry provides information not only for the blood oxygen saturation (SpO_2), but also for heart rate and local vascular irrigation. In commercial devices, either LEDs or LASERs generate the light to be injected into the skin. The backscattered light is then collected by a photodetector (e.g. .a photodiode). These two elements can be placed either side by side on the surface of the tissue, or on each sides of the tissue leading to two pulse oximetry techniques: reflectance and transmittance. Most SpO_2 sensors use the fingertip or more rarely, the toe, as the measurement site. The reason is that at these locations, the vascular bed is dense. Besides, the

BNSDOCID: <WO_____2011026669A1_I_>

body is not too thick at the finger or the toe; transmission photoplethysmography (PPG) is possible, which results in better accuracy than reflectance PPG. The earlobe is also sometimes used, although problems of perfusion variations have been reported. Finally, reflectance PPG is used mostly on the forehead, because of the reflectance of the skull and the relative stability with respect to motion artifacts. However, the pulsation signal is about ten times weaker. Besides, accuracy problems have been reported.

Commercially available SpO_2 sensors products are incompatible with comfortable and non obtrusive long-term monitoring because they are either inconvenient and cumbersome to wear while performing activities like running, cycling or other outdoor activities (for example at the fingertip) or their accuracy and reliability are limited (as for example for the earlobe and the forehead).

The information conveying part in pulse oximetry is the so called ratio of ratios (R_{OS}), which is the ratio of AC and DC components of a red signal divided by the ratio of AC and DC components of an infrared signal. From the signal processing point of view, the most crucial task leading to an accurate SpO_2 estimation is therefore the accurate assessment of AC and DC components of the photoplethysmographic signals. Conventionally, this is achieved either in the time domain by extrema location or template matching or in the frequency domain by extraction of the magnitude of specific spectral components [1]. Time domain methods, even in their most advanced implementation, currently based on weighted moving average technique, give a precision of no better than 2%. In contrast, frequency domain methods based on fast Fourier or cosine transform were identified as potentially superior, as described in reference 1: Webster J G, Design of Pulse Oximeters, Medical Science Series, IOP Publishing (1997). Moreover, in highly noisy environments it has been shown in numerous studies of applied signal processing that robust extraction of efficient and salient features of multidimensional times series is often related to an adequate attenuation of harmful noise contributions in a dual domain, such as, for example, the frequency domain or the domain spanned by the principal or

BNSDOCID: <WO_____2011026669A1_I_>

independent component of the observed signals (see reference 2: Virag N, Sutton R, Vetter R, Markowitz T, Erickson M (2007), Prediction of vasovagal syncope from heart rate and blood pressure trend and variability: Experience in 1,155 patients. Heart Rhythm, vol. 4, No. 11, pp. 1377-1382).

The use of ECG signal, or more generally the heart beat information, brings along another advantage in processing noisy PPG signal due to low perfusion. Indeed, in order to improve the noise robustness of pulse oximetry under low perfusion, methods have been proposed which process PPG signals in the time domain in synchronization with ECG (see reference 1).

Known methods for monitoring SpO_2 based on frequency domain, such as FFT or DCT, typically require a high computational load. Moreover, the signal is analyzed over a window that is constant such that the analyzed signal can be more or less reliable depending on the possible artifacts and the intrinsic heart rate variability, resulting in a less reliable SpO_2 estimated value.

Summary

The present application discloses a spectrophotometry-based monitoring method which overcomes at least some limitations of the prior art.

According to the embodiments, a method for estimating blood constituent concentration of a user under low perfusion conditions using a spectrophotometry-based monitoring device comprising a multichannel sensor formed of a plurality of channels, and a cardiovascular sensor; can comprise: measuring a plurality of photoplethysmographic (PPG) signals, each PPG signal being measured by one of a plurality of channels; measuring a cardio-synchronous (CV) signal by using the cardiovascular sensor; detecting a instantaneous heart rate and determining a heart rate variability from the CV signal; for each detected heart rate, projecting the measured PPG signals multiplied by a window function on a principal

BNSDOCID: <WO_____2011026669A1_I_>

frequency component, and selecting reliable projected PPG signals; and estimating a value of said blood constituent concentration from the magnitude of said reliable projected PPG signals selected over a predetermined time period; characterized in that said window function has a window length which is adjusted at each detected heart rate according to the determined heart rate variability; and in that the frequency of said principal frequency component is estimated by averaging the heart rate over the window length.

In an embodiment, said blood constituent concentration can comprise oxyhemoglobin, reduced-hemoglobin, carboxyhemoglobin, methemoglobin, or a combination of any of them.

In another embodiment, the principal frequency component can be a harmonic component with its phase being determined by the time instant of the instantaneous heart rate and with its frequency being determined by the averaged heart rate.

In yet another embodiment, the principal frequency component can be a wavetable oscillator with its phase being determined by the instantaneous heart rate and with its frequency being determined by the averaged heart rate.

In yet another embodiment, said averaging the heart rate can comprise determining the mean heart rate value of heart rate detected prior to the instantaneous heart rate, over the whole window length.

In yet another embodiment, said selecting reliable projected PPG signals can comprise selecting projected PPG signals having a predetermined magnitude and a predetermined phase and/or coherence between the PPG signals and the principal frequency component.

In yet another embodiment, said predetermined coherence can be equal or above 0.7.

BNSDOCID: <WO_____2011026669A1_I_>

In yet another embodiment, the monitoring device can further comprise a motion sensor for measuring a motion signal, and the method can further comprise extracting a motion frequency from the motion signal.

In yet another embodiment, the window function can be designed according to the extracted motion frequency.

In yet another embodiment, for the motion artifacts being smaller than large-band background noise, the window function can have maximal attenuation of lateral lobes, and the window function can be a Hanning window or a Kaiser window.

In yet another embodiment, for the motion artifacts being larger than large-band background noise, the window function yields an equivalent frequency response having zeros at the motion frequency and its harmonics, and the window function is a rectangular window.

The disclosure also pertains to a monitoring device for estimating blood constituent concentration in tissue under low perfusion of a user using the method disclosed herein and comprising the disclosed multichannel sensor, and a cardiovascular sensor for delivering a cardio-synchronous (CV) signal.

In an embodiment, the monitoring device can further comprise a motion sensor for measuring a motion signal.

In another embodiment, each of said plurality of channels can comprise an emitter containing a first and second radiation source emitting at the red and infrared wavelengths, respectively, and a receiver for receiving optical radiation emitted by the emitter.

In yet another embodiment, said cardiovascular sensor can be an ECG sensor and the CV signal is a surface ECG signal, or an ECG sensor and the CV signal is a PPG signal.

BNSDOCID: <WO_____2011026669A1_I_>

The method disclosed herein provides reliable estimation of the blood constituent concentration even for tissues under very poor perfusion. This is mainly due to fact that detection of the time instant of heart beat and estimation of the instantaneous heart rate may be performed with high reliability and accuracy on ECG and projection on according principal frequency component provides highest noise reduction if the projection length is chosen optimally with respect to heart rate variability and noise in PPG signals. The disclosed method requires computational load that is highly diminished compared to conventional methods based on frequency domain approach as FFT or DCT.

Brief Description of the Drawings

The preferred embodiments will be better understood with the aid of the description of an embodiment given by way of example and illustrated by the figures, in which:

Fig. 1 represents schematically a multichannel sensor according to an embodiment;

Fig. 2 illustrates schematically a monitoring device comprising the multichannel sensor, according to an embodiment;

Fig. 3 is a flow chart illustrating a method for estimating a value of gas concentration in blood under low perfusion conditions using the monitoring device; and

Figs. 4 and 5 show a plot of SpO_2 estimation (upper graph) and relative error (lower graph) for different measurement examples.

Detailed Description of the preferred embodiments

Fig. 2 illustrates schematically a spectrophotometry-based monitoring device according to an embodiment. The monitoring device comprises a multichannel sensor 1, containing a plurality of

BNSDOCID: <WO_____2011026669A1_I_>

photoplethysmographic (PPG) sensor channels, and fitted in a strap band 10 such as to be located in contact with the user's skin, in the sternum area. Such placement is comfortable and non obtrusive for long-term monitoring while performing activities like running, cycling or other outdoor activities. Other placements of the multichannel sensor 1 are however possible, for example, on a wrist strap, on a forehead-band, or on any suitable location within the scope of the embodiments. An advantage of the disclosed monitoring device setup and measurement method is that the multichannel sensor 1 can be located in an area having low perfusion while providing reliable estimation of constituents in blood such as blood oxygen saturation (SpO_2) as will be described below.

The multichannel sensor 1 is represented schematically Fig. 1, according to an embodiment. The multichannel sensor 1 comprises eight equally radially disposed individual PPG sensor channels. The multichannel sensor 1 can measure a plurality of PPG signals, each PPG signal being measured by one of the channels 2, 5. Each PPG sensor channel is formed from an emitter 2 comprising a first radiation source 3 emitting at the red wavelengths and a second radiation source 4 emitting at the infrared wavelengths. The first and second light sources 3, 4 can be LEDs, preferably emitting at 660 nm and 940 nm, respectively. Each PPG sensor channel also comprises a receiver 5, such as a photodetector, for receiving the optical radiation emitted by the emitter 2 and transmitted through the skin tissue. The receiver 5 is connected to an analog-to-digital converter (ADC) module (not represented) delivering corresponding measured PPG signals. In the example of Fig. 1, the multichannel sensor 1 contains four equally radially spaced receivers 5, each receiver 5 being used to receive the PPG signals transmitted from two adjacent emitters 2. Other numbers and arrangements of the emitters 2 and receivers 5 are also possible as long as it provides sufficient spatial diversity in order to remove artifacts due to tissue inhomogeneities. Spatial diversity allows one to overcome poor PPG signal quality related to inhomogeneous and poor subcutaneous blood flow, to attenuate non-correlated measurement noise in the different channel, as well as reduce artifacts related to movements which may not be

BNSDOCID: <WO_____2011026669A1_I_>

recorded by an accelerometer. However, this requires a more sophisticated signal processing.

In an embodiment, the multichannel sensor 1 further comprises a motion sensor 6 for measuring a motion signal representative of the user's movements. As schematically shown in Fig. 1, the motion sensor 6 is placed within the multichannel sensor 1, possibly forming an integrated sensor comprising the multichannel sensor 1 and the motion sensor 6. In this configuration, the motion signal is better correlated with the measured multichannel sensor 1 signal than if the motion sensor 6 is placed further from the multichannel sensor 1. Moreover, the placement of the multichannel sensor 1 on the sternum is advantageous since it approximates essentially gravity center based accelerometer measurement on the user. The motion sensor 6 can comprise an ADC module (not shown) outputting acquired motion signals.

The motion sensor 6 is preferably a MEMS-based three dimensional accelerometer adapted to deliver an acceleration signal along three axes, as described in U.S. patent serial number 7,018,338 by the present applicant. It will however be appreciated that other types of accelerometers or motion detecting devices can be used provided they deliver a reliable measure of motion. For example, the motion sensor 6 could be a gyro-sensor of any suitable technology incorporating a one or multi-dimensional accelerometer, or a rotating or vibrating element.

In the example of Fig. 2, the monitoring device further comprises a cardiovascular sensor for measuring a cardio-synchronous (CV) signal. The cardiovascular sensor is an ECG sensor and contains two signal ECG electrodes 7 being fixed on a chest band 13, connected to the strap band 10, such as to be in contact with the user's skin. The ECG sensor also comprises an ECG ground electrode shown by the numeral 14 in Fig. 1. ECG electrodes 7, 14 are preferably widely spaced across the patient's body. Other arrangements of the ECG electrodes are also possible. Flexible ECG electrodes, for example such as described in U.S. patent application serial No. 2006/0142654, can be integrated into the chest band and/or the strap

BNSDOCID: <WO_____2011026669A1_I_>

tissue or into a garment fabric. The ECG electrodes can be connected to a comparator (not shown) for determining a difference value between the measured electric potentials at the different ECG electrode locations. The ECG sensor can comprise more than two signal ECG electrodes 7. Moreover, the ECG sensor can comprise an ADC module (also not shown) outputting the acquired measured CV signal.

In another embodiment, the cardiovascular sensor is a PPG-based CV sensor and the CV signal is a PPG-based CV sensor signal. Here, the multichannel sensor 1 can be utilized for measuring the PPG-based CV sensor signal, or the PPG-based CV sensor can be an additional PPG-based sensor (not shown). Alternatively, the cardiovascular sensor can be based on impedance cardiography, ultrasound, or any other measurement device adapted to provide a reliable CV signal from the user.

The measuring the CV signal and the plurality of PPG signals can comprise acquiring the CV and PPG signal with a predetermined sampling rate. The sampling rate is typically comprised between 20 and 30 Hz. In the following text, the expressions "measured CV signal" or "measured PPG signal" and "CV sample" or PPG sample" will be used indifferently.

In an embodiment, the respective ADC modules of the PPG sensor channels 2, 5, motion sensor 6, and ECG sensor 7, 14 further comprise a signal filtering and shaping device (not shown). The respective ADC modules can be formed from a single ADC module placed in the strap band 10 or chest band 13. Filtering of the measured analog PPG, motion, and CV signals can be performed by means of an analog low-pass filter whose band is of 10 Hz for the PPG signals and 50 Hz for the ECG and motion signals, for example. The measured signals are then transferred to a signal processing module (not shown). Eliminating artifacts due to movements of the user in the PPG and CV signals can be performed in the signal processing module by using the motion signal delivered by the motion sensor 6. Such processing is described in more details in the European patent application No. 1297784 and U.S. patent 7,175,601, both by the present applicant. A battery (also not shown) can also be placed in one of the bands 10, 13 to power the multichannel sensor 1 and ECG sensor 7, 14.

BNSDOCID: <WO_____2011026669A1_I_>

The processing module can be an adequately programmed digital signal processor or DSP or a general purpose microcontroller (not represented). The measured PPG, motion, and CV signals can be transferred to the signal processing module through a cable (not shown) or wirelessly.

In yet another embodiment not represented, the multichannel sensor 1 and/or ECG sensor 7, 14 can include an embedded signal processor or other type of dedicated processors for performing any desired processing of the measured PPG, CV or motion signals, prior to outputting signals to the signal processing module.

A method for estimating a value of gas concentration in blood under low perfusion conditions using the monitoring device disclosed herein is diagrammatically shown in Fig. 3 according to an embodiment. The method comprises the steps of:

measuring the CV signal by using the ECG sensor 7, 14;

measuring the plurality of PPG signals, each PPG signal being measured by one of the channels 2, 5;

detecting heart beats, or an instantaneous heart rate, and determining a heart rate variability from the measured CV signal (numeral 16 in Fig. 3);

for each detected heart rate, projecting the measured PPG signals multiplied by a window function on a principal frequency component (numeral 21 in Fig. 3), and selecting reliable projected PPG signals (numeral 22 in Fig. 3); and

estimating a SpO_2 value from the magnitude of said reliable projected PPG signals selected over a predetermined measurement time period (numeral 24 in Fig. 3).

The method can further comprise a step of filtering the measured PPG and CV signals. This step is shown respectively by numerals 15 and 19 in Fig. 3. Filtering of the measured CV signals can be performed by using a numerical finite length band-pass filter, preferably using a band-pass in the frequency range comprised between 15 and 30 Hz. Filtering the measured

BNSDOCID: <WO_____2011026669A1_I_>

PPG signals can be performed by using a numerical band-pass filter, such as a finite impulse response (FIR) filter.

Heart beats can be detected from the CV signals using the maximum of the R-Wave. The instantaneous heart rate can then be determined from the time difference between the R-R intervals, between the two adjacent R-Wave maxima. The instantaneous heart rate variability, then, corresponds to the maximal variation of the R-R intervals over the analysis window length defined below.

In an embodiment, the projecting of the PPG samples, or the instantaneous projecting of the PPG samples, for each detected heart rate is obtained by using Equation 1:

$$PPG_{proj}(n) = \sum_{l=-w_{len/2}}^{w_{len/2}} w(l)\, PPG\left(k_{HR(n)} - w_{len/2} - l\right) PC(l)$$

(Equation 1),

where $PPG_{proj(n)}$ corresponds to the projected PPG sample for the nth heart rate detected in the CV signal at a time instant $t_{R(n)}$ of the maximum of the associated R-wave and which corresponds to a sample $k_{HR(n)}$ in the PPG signal, w(l) is the window function, and w_{len} a window length of the projection. The principal frequency component PC(*l*) phase adjusted to the nth heart beat $n_{HR(k)}$ is defined by Equation 2:

$$PC(l) = e^{j2\pi f_c(k_{HR(k)} - w_{len/2} - l)} \quad with \quad -w_{len/2} < l < w_{len/2}$$

(Equation 2),

where f_c is the mean heart rate over the window length w_{len} as defined in the procedure below, normalized with respect to the sampling frequency of the PPG signals.

The window function can be designed, for example, from a rectangular, Hanning, Hamming, or Blackman window function. The step of designing the window function is represented by the numeral 20 in Fig. 3 and is described in more details below.

BNSDOCID: <WO_____2011026669A1_I_>

The window length w_{len} can be optimally adjusted at each heart rate by a procedure taking into account the maximal heart rate variability over the window length comprising the steps of:

1. starting at instantaneous heart rate (detected from the R-Wave) and evaluating an associated RR interval using Equation 3:

$RR(n) = t_{R(n)} - t_{R(n-1)}$ (Equation 3),

where $t_{R(n)} - t_{R(n-1)}$ corresponds to the difference of time instant of the nth and $(n-1)^{th}$ heart rates;

2. setting iteration index i = 1.

3. evaluating an equivalent bandwidth $B_{eq}(i)$ as in Equation 4:

$$Beq(i) = f(\frac{1}{RR(n)})$$ (Equation 4),

where f is a function depending on a given window;

4. evaluating the RR interval with:

$RR_{(n-i)} = t_{R(n-i)} - t_{R(n-i-1)}$ (Equation 5);

5. evaluating the equivalent bandwidth as:

$$Beq(i+1) = f(1/\sum_{q=0}^{i} RR(n-q))$$ (Equation 6);

6. and while:

$\max([1/RR_{(n-i)}, \ldots, 1/RR_{(n)}]) -$

$\min([1/RR_{(n-i)}, \ldots, 1/RR_{(n)}]) < B_{eq}(i+1)$ (Equation 7),

increment i and go to step 4.

At the end of this procedure the optimal window length t_{win} can be determined by Equation 8:

$$t_{win} = \sum_{q=0}^{i-1} RR(n-q)$$ (Equation 8),

which yields in samples:

$$w_{len} = t_{win} * (PPG\ sampling\ frequency)$$ (Equation 9),

BNSDOCID: <WO_____2011026669A1_I_>

and the mean heart rate f_c is determined by:

$$f_c = \text{mean}([1/RR_{(n-i+1)}, \ldots, 1/RR_{(n)}]) \quad \text{(Equation 10).}$$

Moreover, the time instant of the last $t_{R(n)}$ provides the trigger for the generation of the principal frequency component. In Fig. 3, bold dashed lines indicate the PPG signals measured from the multichannel sensor 1 with their associated information, such as coherence, phase, and magnitude of the principal frequency component projection.

In an embodiment corresponding to a simplest case, the principal frequency component is a harmonic component with its phase being determined by the R-wave location, or instantaneous heart rate, on the corresponding CV signal delivered by the ECG-based sensor 7, 14, and with its frequency being determined by the mean heart rate value. Here, the mean heart rate value can be determined from the heart rates detected over the whole window length w_{len} (past heart rates), prior to the instantaneous heart rate.

In another embodiment, the principal frequency component is a wavetable oscillator with its phase being determined by the instantaneous heart beat, or R-wave location, on the corresponding CV signal delivered by the ECG-based sensor 7, 14, and with its frequency being determined from the instantaneous heart rate and the heart rates detected over the whole window length w_{len} (past heart rates). The fundamental wavelet of the wavetable oscillator can be updated as a function of the reliable projected PPG signals. This technique can yield a more robust projection of the PPG signals.

In an embodiment, reliability of the PPG signals is determined from the magnitude of the projected PPG signals and the phase, and/or coherence between the PPG signals and the principal frequency component. More particularly, the maximum attenuation of the PPG signals by the tissue occurs during the cardiac systole phase of the cardiac cycle, starting substantially at the R-wave. Therefore, the phase between the R-

BNSDOCID: <WO_____2011026669A1_I_>

wave triggered principal frequency component and the PPG signal should vary within given bounds which can be fixed for a given channel location.

Reliable projected PPG samples can then be selected from the instantaneous projected PPG signals having a predetermined magnitude and for a predetermined phase, and/or coherence between the PPG signals and the principal frequency component. Reliable projected PPG signals can be selected for projected PPG signals obtained during a measurement period extending over several heart beats on the past, based on the magnitude, phase and coherence values estimated for each of the projected PPG signals.

In an embodiment, the reliable projected PPG signals are selected based on the coherence between the PPG signals and the principal frequency component having a value equal or above 0.7. The magnitude of the projected PPG signal depends on the electronics used but should be above background noise, or noise floor, for example at least twice the noise floor, but not too large where it would correspond to movement artifacts. Moreover, the phase should be comprised between a value above zero and less than a maximal angle ϕ which depends mainly on the sensor location and the heart rate, resulting in a linear phase relationship determined by:

$$\phi = 2\pi f_c \delta t \qquad \text{(Equation 11)}$$

where δt is the maximally elapsed time between the occurrence of the heart beat and PPG pulse wave at the sensor location, typically δt may be in the range of 5 to 30 ms).

In an embodiment, the method further comprises a step of extracting a motion frequency of the motion artifacts of the user (shown by numeral 17 in Fig. 3), and determining an activity of the user, by using motion signals measured by the motion sensor 6. Motion artifacts of the user can comprise regular periodical movement artifact related to activities like, for example, running, cycling, walking, etc., or voluntary and

BNSDOCID: <WO_____2011026669A1_I_>

involuntary (respiration) subject movements. A fundamental, or central, motion frequency can be extracted from the motion signals through one of the following technique comprising zero-crossing, parametric or non-parametric spectral estimation, autocorrelation, recurrence plots. Such central motion frequency is typically representative of to the most harmful regular noise contributions from motion artifacts.

The window function can then be optimally designed according to the estimated motion frequency, or relative importance of the level of large-band background noise and movement artifacts, and possibly along with the determined heart rate, and a maximal heart rate variability. This step is represented by numeral 18 in Fig. 3. The maximal heart rate variability can be determined as the maximal heart rate variation over the window length as processed in step 6 of the above procedure.

For example, in the absence of regular movement artifacts or in the case the movement artifacts are smaller than large-band background noise, the design criterion of the window function is the maximization of the signal-to-noise ratio (SNR) of the PPG signals with respect to large-band background noise. In these conditions, the window function should preferably have maximal attenuation of lateral lobes, and the window function can be, for example, a Hanning or Kaiser window. The equivalent projection bandwidth should be minimal but even though retain the main signal characteristics. In these conditions, the projection, or window length w_{len}, can be determined by a frequency response of the window function having a bandwidth corresponding to the maximal heart rate variability, determined over the same window length w_{len}.

In the case where movement artifacts are larger than large-band background noise, the window function is such as to yield an equivalent frequency response having its zeros at the frequency of harmful regular noise contributions due to regular movement artifacts, or central motion frequency. For example, a rectangular window can be chosen in the case harmonic movement artifacts are predominant and the difference between heart rate and motion frequency is very small.

BNSDOCID: <WO_____2011026669A1_I_>

Values of ratio of ratios (R_{OS}) are obtained from the principal frequency component of the reliable projected PPG signals at each heart beat (detected from R-wave) and for each channel of the multichannel sensor 1. Here R_{OS} stands for the ratio of the magnitudes of projections of harmonic components at heart rate and 0 Hz of the PPG signals in the red wavelengths, divided by the ratio of magnitude of projections of harmonic components at heart rate and 0 Hz of the PPG signals in the infrared wavelengths. The R_{OS} is evaluated from the magnitude of the projections of all channels. An instantaneous R_{OS} estimation can then be determined by applying a statistical technique (for example mean, median, maximum likelihood) to a matrix comprising the R_{OS} values obtained from the reliable projected PPG signals at each heart beat and for each channel, during the measurement time period extending over several heart beats on the past (numeral 23 in Fig. 3).

In a last step shown by numeral 24 in Fig. 3, an instantaneous SpO_2 estimation is obtained as in conventional pulse oximetry by Equation 12:

$$SpO_2(t) = a - b\ ROS(t) \qquad \text{(Equation 12).}$$

This simple linear projection may be refined as a more complex functional approximation. However, this would require a large clinical study which was out of the scope of actual study.

The measurement time period used for estimating the instantaneous R_{OS} is typically chosen with respect to a given application. For example, in the case highly accurate instantaneous SpO_2 estimations are required and a slow dynamic response is tolerated, the statistical operation may be performed during the measurement time period corresponding to up to 120 heart beats or even more. In contrast, in the case a faster and less accurate instantaneous SpO_2 estimation the statistical operation can be performed during the measurement time period corresponding to up 60 heart beats or even less.

BNSDOCID: <WO_____2011026669A1_I_>

A further improvement may be achieved by replacing the statistical operator by spatiotemporal principal component analysis. Indeed, it has been shown that for PPG signals with high intrinsic time and spatial correlations, spatiotemporal principal component analysis yields improved performance in adverse highly noisy environment. Indeed, on the one hand, the multichannel sensor 1 provides R_{OS} estimates from different channel locations which should be highly correlated. On the other hand, the physiological basis for pulse oximetry ensures that SpO_2 values from one heart beat to the next have high intrinsic correlations. Spatiotemporal principal component analysis (PCA) allows estimating a reliable evolution of the R_{OS} values over a short time window of typically 20 to 120 sec. Finally, subsequent short term evolution profiles of the R_{OS} can be combined in a windowing averaging technique as it is often achieved in speech processing (see reference 3: Deller J R, Hansen J H, Proakis J G (1999) Discrete-time processing of speech signals. Wiley-IEEE Press).

While the invention may be susceptible to various modifications and alternative forms, specific embodiments have been shown by way of example in the drawings and have been described in detail herein. However, it should be understood that the invention is not intended to be limited to the particular forms disclosed. Indeed, the monitoring device and the method disclosed herein may not only be applied to measurements and estimation of SpO_2, but may also be utilized for the measurement and/or analysis of other blood constituents in blood. For example, using the same, different, or additional wavelengths, the present monitoring device and the method can be utilized in conjunction with the measurement and/or analysis of blood constituent concentration comprising oxyhemoglobin, reduced-hemoglobin, carboxyhemoglobin (SpCO), methemoglobin (SpMet), or a combination of any of them. An example of combination of blood constituent concentrations is SpO2, defined as the ratio of oxyhemoglobin concentration over total hemoglobin concentration.

An ambulatory validation according to a first example was conducted using the monitoring device of Fig. 2. The first conventional finger clip sensor 8 was a NELLCOR N-595 combined with OxiMax finger-

BNSDOCID: <WO_____2011026669A1_I_>

clip. The second conventional finger clip sensor 9 was a BIOPAC finger-clip transducer TSD123 AC connected to BIOPAC MP150 acquisition platform. The SpO_2 estimations obtained with the multichannel sensor 1 were compared to the ones obtained with the two finger-clip sensors. The two finger-clip sensors 8, 9 used here were chosen for the cross-validation procedure because of their reliability and the ease to ensure no motion at this sensor location. The validation follows the procedure for non-invasive laboratory testing on healthy volunteers of the ISO9919 international standard for Medical electrical equipment and particular requirements for the basic safety and essential performance of pulse oximeter equipment for medical use. Also visible in Fig. 2 is the ECG sensor 5 (BIOPAC).

Ten male volunteers, non-smokers, 25-54 years old, took part in this validation. Informed consent to induced hypoxia was obtained from each patient in resting supine position with a gradual breathe down protocol for SpO_2 values ranging from 100 to 70%. A non re-breathing system 11 attached to an oxygen (O_2) / Nitrogen (N_2) / Air gas delivery apparatus (AltiTrainer, SMTEC SA) provided the hypoxic gas mixture to the volunteer, via a facemask held in place by a fabric elastic head cradle.

SpO_2 estimation provided by the method disclosed above has been compared to the SpO_2 values of the reference devices, and the performances evaluated on the basis of the average means square error (AMSE), the bias, and the percentage of time the absolute relative error was <0.3%. Table 1 below summarizes the performance evaluation.

Similar performances have been observed in nine out of the ten tested subjects. Fig. 4 reports the results for one of the subjects (subject 5) where the method showed similar performances. Fig. 5 reports the results of another subject (subject 10), where the method provided poor SpO_2 estimation. More particularly, the upper graphs of Figs. 4 and 5 plot the SpO_2 estimation obtained with the multichannel sensor 1 (thick line, noted as "$@ST_{CSEM}$" in the legend). Confidence intervals determined by the measurements with the conventional finger-clip sensors 8, 9 are shown by the dotted lines (denoted "$@FC_{ref,\pm 3\%}$" in the legend). The relative error

BNSDOCID: <WO_____2011026669A1_I_>

(Error in %) with confidence intervals for the SpO_2 estimation obtained with the multichannel sensor 1, first and second conventional finger-clip sensors 8, 9 are shown in the bottom graphs of Figs. 4 and 5 by the circles. In the bottom graphs of Figs. 4 and 5, the lines represent the different confidence intervals as described in the corresponding legends. It can be noticed that when the algorithm poorly estimates the SpO_2 (subject 10) it also indicates the low reliability of the estimation (see Fig. 5).

Subject	AMSE	bias	% abs err < 3%
1	1.3555	0.1137	95.4395
2	1.9861	-0.2712	88.9400
3	1.0477	0.1905	99.1556
4	2.0555	1.5006	85.4915
5	1.2782	0.0516	97.5844
6	1.5020	0.8062	98.4399
7	1.9408	-1.3643	87.2347
8	2.0642	-0.0779	85.9316
9	1.8069	-1.5085	95.0396
10	2.7272	1.6410	69.4551

Table 1 Evaluation results of our algorithm

In contrast to classical frequency based pulse oximetry algorithms using FFT or DCT, the disclosed method requires computational load that is highly diminished since only one component is used while frequency resolution and associated projection bandwidth is even improved. Indeed, whereas in FFT or DCT frequency resolution is determined by the order of the applied transform, the method disclosed herein provides the exact location of the principal frequency component as the short-term mean of the instantaneous heart rate. Moreover, the projection bandwidth which is determined by the type and length of the pre-window can be adjusted depending on the relative levels of movement artifacts and large-band background noise, and/or the level of accuracy required in SpO_2 estimation.

BNSDOCID: <WO_____2011026669A1_I_>

Reference numbers

1	multichannel sensor
2	emitter
3	first radiation source
4	second radiation source
5	receiver
6	motion sensor
7	ECG electrodes
8	first conventional finger clip sensor
9	second conventional finger clip sensor
10	strap band
11	non re-breathing system
13	chest band
14	ECG ground electrode
15	filtering, band-pass 8 to 17 Hz
16	HR estimation through R-wave location
17	activity processing
18	window design
19	FIR filtering
20	pre-windowing
21	projecting on a principal frequency component
22	discarding non-reliability projected PPG signals
23	instantaneous R_{OS} estimation
24	instantaneous SpO_2 estimation

ADC	analog-to-digital converter
CV	cardio-synchronous
FIR	finite impulse response
PC	principal frequency component
PPG	photoplethysmographic
W_{len}	window length

BNSDOCID: <WO_____2011026669A1_I_>

Claims

1. Method for estimating blood constituent concentration of a user under low perfusion conditions using a spectrophotometry-based monitoring device comprising a multichannel sensor (1) formed from a plurality of channels (2, 5), and a cardiovascular sensor (7, 14); comprising:

measuring a plurality of photoplethysmographic (PPG) signals, each PPG signal being measured by one of the channels (2, 5);

measuring a cardio-synchronous (CV) signal by using the cardiovascular sensor (7, 14);

detecting an instantaneous heart rate and determining a heart rate variability from the CV signal;

for each detected heart rate, projecting the measured PPG signals multiplied by a window function on a principal frequency component, and selecting reliable projected PPG signals; and

estimating a value of said blood constituent concentration from the magnitude of said reliable projected PPG signals selected over a predetermined time period;

characterized in that

said window function has a window length (w_{len}) which is adjusted at each detected heart rate according to the determined heart rate variability; and in that;

the frequency of said principal frequency component is estimated by averaging the heart rate over the window length (w_{len}).

2. The method according to claim 1, wherein said blood constituent concentration comprises blood oxygen saturation, carboxyhemoglobin, met-hemoglobin, or a combination of any of them.

3. The method according to the claims 1 or 2, wherein the principal frequency component is a harmonic component with its phase

BNSDOCID: <WO_____2011026669A1_I_>

being determined by the instantaneous heart rate and with its frequency being determined by the averaged heart rate.

4. The method according to the claims 1 or 2, wherein the principal frequency component is a wavetable oscillator with its phase being determined by the instantaneous heart rate and with its frequency being determined by the averaged heart rate.

5. The method according to any of the claims from 1 to 4, wherein said averaging the heart rate comprises determining the mean heart rate value of heart rate detected prior to the instantaneous heart rate, over the whole window length (w_{len}).

6. The method according to any of the claims from 1 to 5, wherein said selecting reliable projected PPG signals comprises selecting projected PPG signals having a predetermined magnitude and a predetermined phase and/or coherence between the PPG signals and the principal frequency component.

7. The method according to claim 6, wherein said predetermined coherence is equal or above 0.7.

8. The method according to any one of claims 1 to 7, wherein the monitoring device further comprises a motion sensor (6) for measuring a motion signal, and wherein the method further comprises extracting a motion frequency from the motion signal.

9. The method according to claim 8, wherein the window function is designed according to the extracted motion frequency.

BNSDOCID: <WO_____2011026669A1_I_>

10. The method according to claim 9, wherein for the motion artifacts being smaller than large-band background noise, the window function has maximal attenuation of lateral lobes.

11. The method according to claim 10, wherein the window function is a Hanning window or a Kaiser window.

12. The method according to claim 11, wherein for the motion artifacts being larger than large-band background noise, the window function yields an equivalent frequency response having zeros at the motion frequency and its harmonics.

13. The method according to claim 12, wherein the window function is a rectangular window.

14. Monitoring device for estimating blood constituent concentration in tissue under low perfusion of a user using the method characterized by any of the claims from 1 to 13, and comprising a multichannel sensor (1) formed from a plurality of channels (2, 5), for delivering photoplethysmographic (PPG) signals; and a cardiovascular sensor (7, 14), for delivering a cardio-synchronous (CV) signal.

15. The monitoring device according to claim 14, further comprising a motion sensor (6) for measuring a motion signal.

16. The monitoring device according to the claims 14 or 15, wherein each of said plurality of channels comprises an emitter (2) containing a first and second radiation source (3, 4) emitting at the red and infrared wavelengths, respectively, and a receiver (5) for receiving optical radiation emitted by the emitter (2).

17. The monitoring device according to any of claims from 14 to 16, wherein

BNSDOCID: <WO_____2011026669A1_I_>

said cardiovascular sensor is an ECG sensor (7, 14) and the CV signal is a surface ECG signal.

18. The monitoring device according to any of claims from 14 to 16, wherein

said cardiovascular sensor is an ECG sensor and the CV signal is a PPG signal.

BNSDOCID: <WO_____2011026669A1_I_>

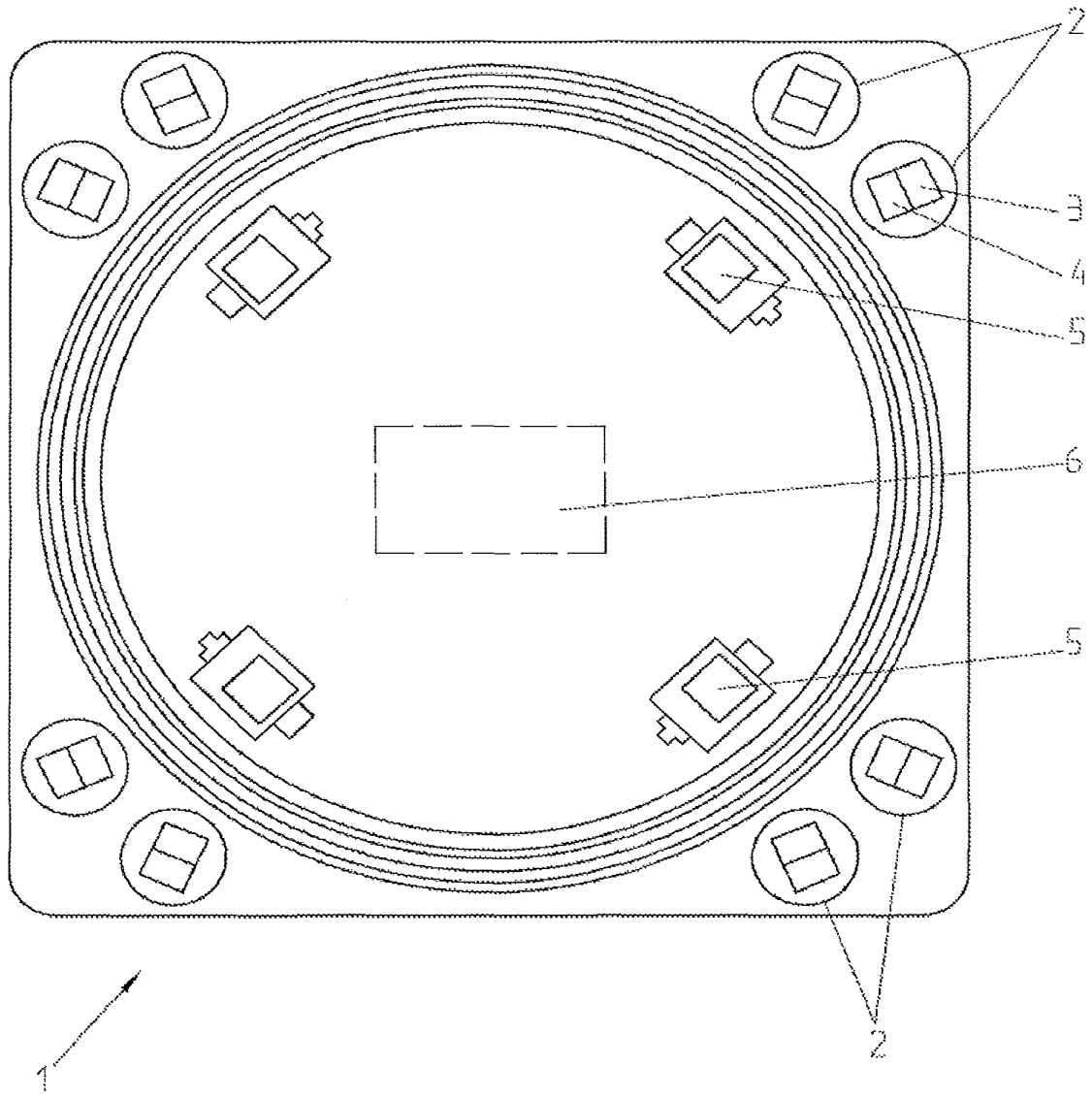


Fig. 1 (Prior art)

BNSDOCID: <WO_____2011026669A1_I_>

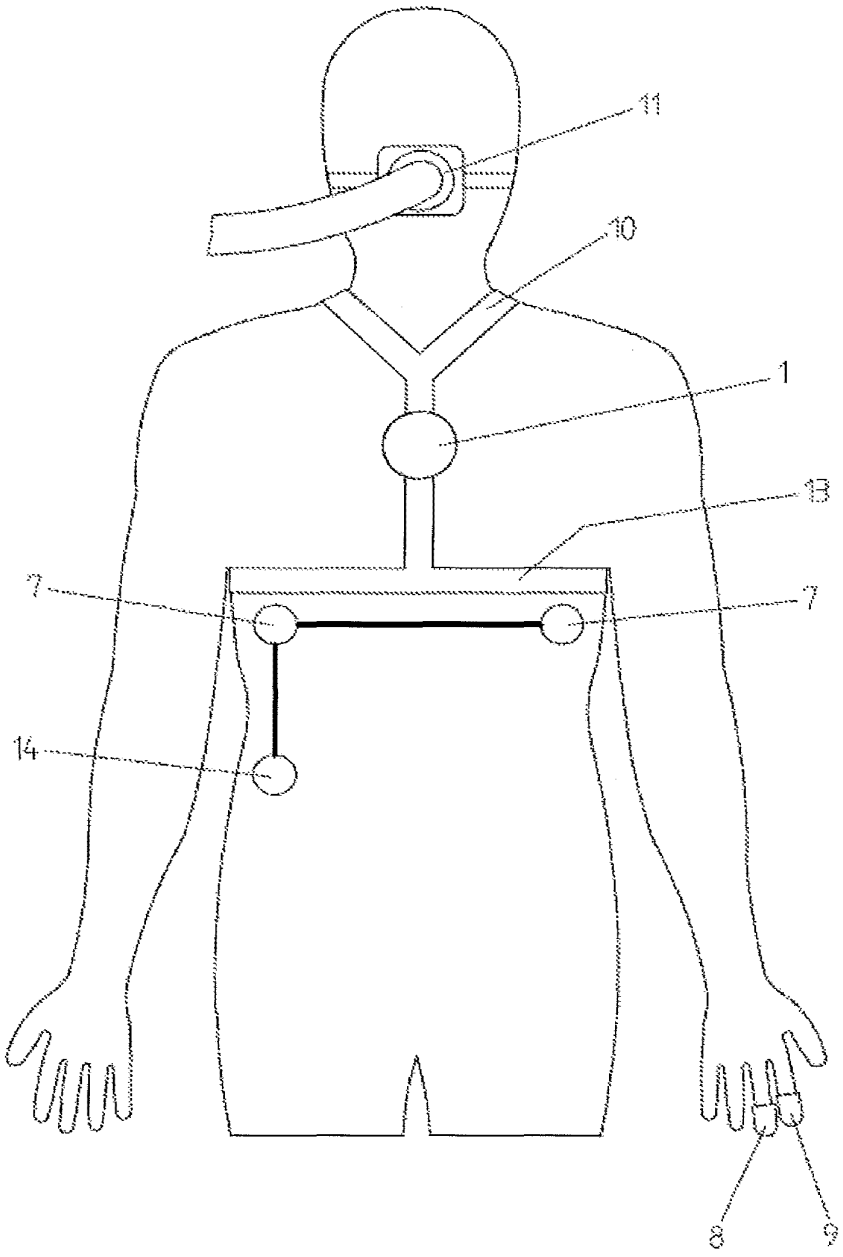


Fig. 2

BNSDOCID: <WO_____2011026669A1_I_>

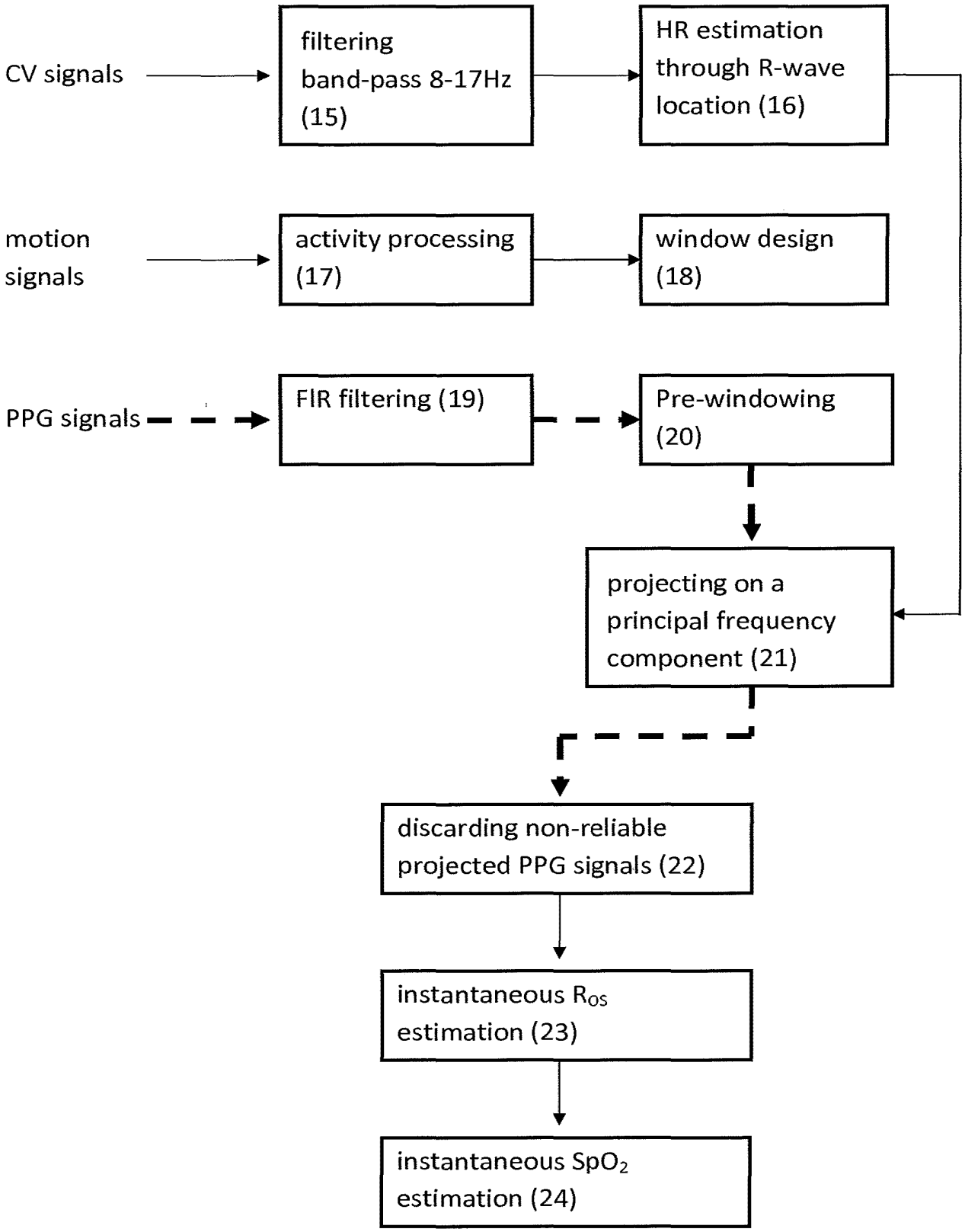
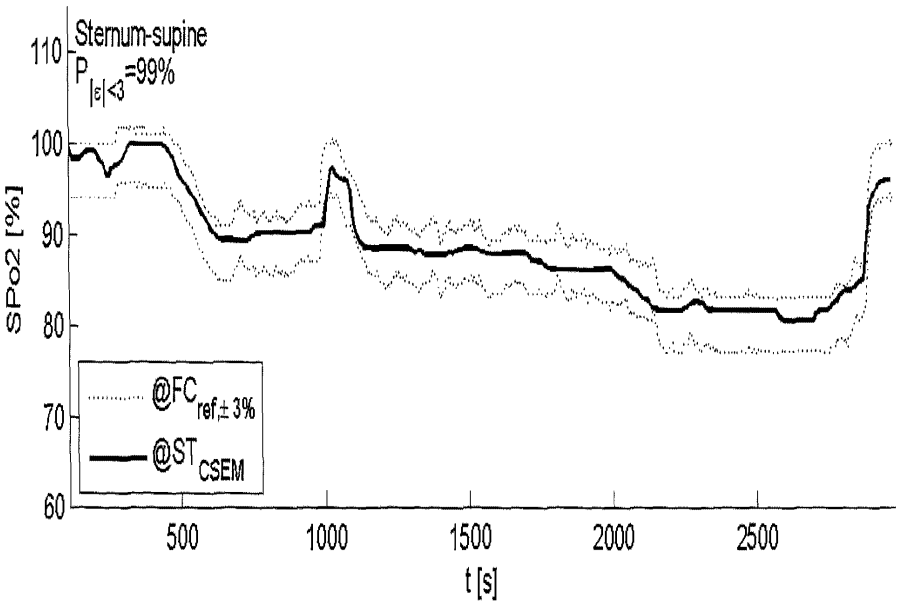


Fig. 3

BNSDOCID: <WO_____2011026669A1_I_>

BNSDOCID: <WO_____2011026669A1_I_>



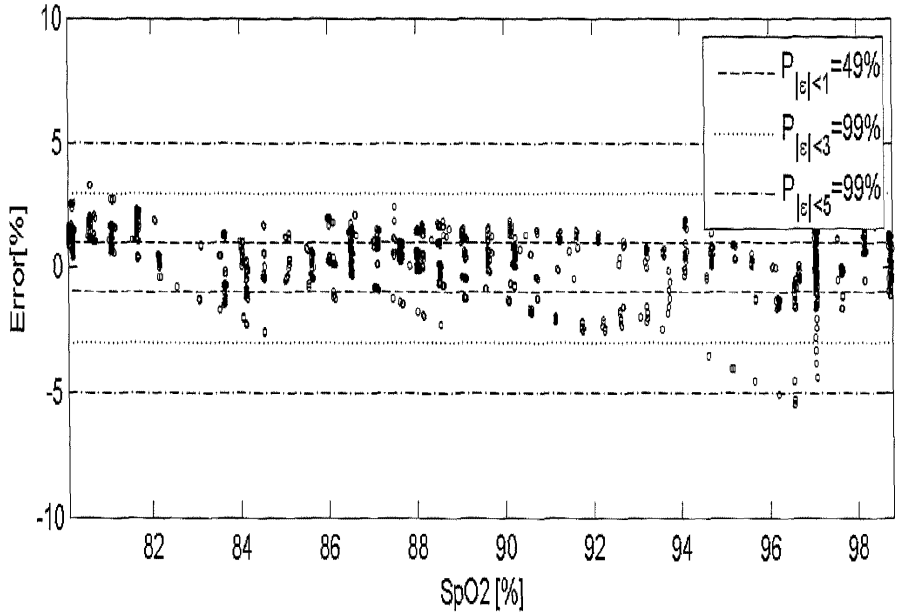
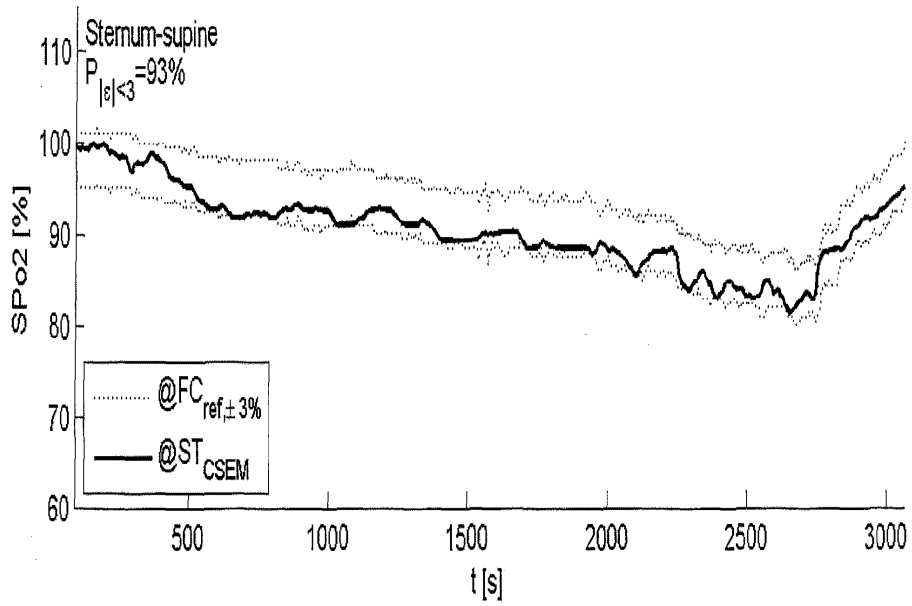


Fig. 4

BNSDOCID: <WO_____2011026669A1_I_>



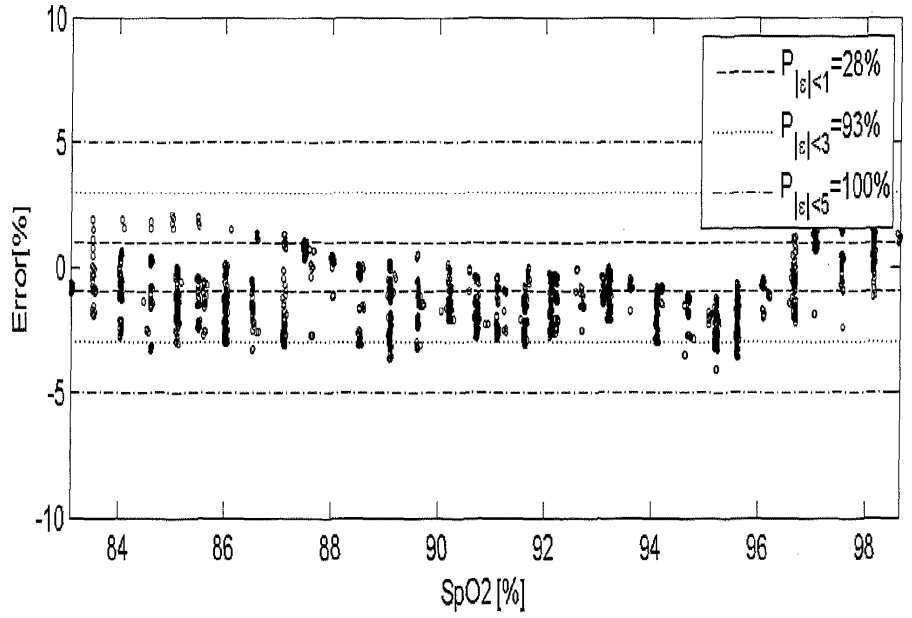


Fig. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2010/059616

A. CLASSIFICATION OF SUBJECT MATTER
INV. A61B5/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
A61B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X,P	VETTER R ET AL: "Frequency domain SpO2 estimation based on multichannel photoplethysmographic measurements at the sternum" IFMBE PROCEEDINGS (INTERNATIONAL FEDERATION FOR MEDICAL AND BIOLOGICAL ENGINEERING), vol. 25, no. 4, 7 September 2009 (2009-09-07), - 12 September 2009 (2009-09-12) pages 326-329, XP008127734 SPRINGER, DE ISSN: 1680-0737 the whole document ----- -/--	1-18

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
15 October 2010	19/11/2010

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Fax: (+31–70) 340–3016	Trachterna, Morten

Form PCT/ISA/210 (second sheet) (April 2005)

BNSDOCID: <WO_____2011026669A1_I_>

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2010/059616

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	A. RIDOLFI: "Biomedical Signal Processing and Portable Physiological Monitoring Devices"[Online] 13 June 2009 (2009-06-13), pages FRP-41, XP002605193 Retrieved from the Internet: URL:http://www.dcc.fc.up.pt/{mcoimbra/lectures/PSI_0809/PSI_2009_ARidolfi.pdf> [retrieved on 2010-10-07] pages 12-20,31	14-18
L	Miguel Tavares Coimbra: "Processamento de Sinal e Imagem (Mest. Inf. Médica) 2008/09"[Online] pages 1-2, XP002605174 Retrieved from the Internet: URL:http://www.dcc.fc.up.pt/{mcoimbra/lectures/psi_0809.html> [retrieved on 2010-10-07] * the document validates the publication date of: A. RIDOLFI: Biomedical Signal Processing and Portable Physiological Monitoring Devices *	
A	FRANS M COETZEE* ET AL: "Noise-Resistant Pulse Oximetry Using a Synthetic Reference Signal" IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING, vol. 47, no. 8, 1 August 2000 (2000-08-01), XP011006931 IEEE SERVICE CENTER, PISCATAWAY, NJ, US ISSN: 0018-9294 * III Noise and saturation ratio calculation P. 1019-1020 * * VI Noide removal by subspace projection p. 1020- 1023 *	1,14
A	US 2003/065269 A1 (VETTER ROLF [CH] ET AL) 3 April 2003 (2003-04-03) paragraphs [0033] - [0054]	1,14

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2010/059616

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2003065269 A1	03-04-2003	AT 481922 T	15-10-2010
		EP 1297784 A1	02-04-2003

Petitioner Ex-1004, 0758

BNSDOCID: <WO_____2011026669A1_I_>

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
20 September 2012 (20.09.2012)

WIPO | PCT

(10) International Publication Number
WO 2012/123828 A1

(51) International Patent Classification:
A61B 5/113 (2006.01)

(21) International Application Number:
PCT/IB2012/050561

(22) International Filing Date:
8 February 2012 (08.02.2012)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
11157945.4 11 March 2011 (11.03.2011) EP

(71) Applicant *(for all designated States except US)*: **KONINKLIJKE PHILIPS ELECTRONICS N.V.** [NL/NL]; Groenewoudseweg 1, NL-5621 BA Eindhoven (NL).

(72) Inventors; and

(75) Inventors/Applicants *(for US only)*: **GOPAL SAMY, Mathan Kumar** [IN/DE]; c/o PHILIPS IP&S - NL, High Tech Campus 44, NL-5656 AE Eindhoven (NL). **YIN, Bin** [CN/CN]; c/o PHILIPS IP&S - NL, High Tech Campus 44, NL-5656AE Eindhoven (NL).

(74) Agents: **Van VELZEN, Maaike** et al.; Philips Ip&s - Nl, High Tech Campus 44, NL-5656 AE Eindhoven (NL).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE,

[Continued on next page]

(54) Title: MONITORING APPARATUS FOR MONITORING A PHYSIOLOGICAL SIGNAL.

(57) Abstract: The invention relates to a monitoring apparatus for monitoring a physiological signal. A segmentation unit (4) determines signal segments from a physiological signal, which correspond to periods of the physiological signal, a classification unit (5) classifies the signal segments into a valid class and a non-valid class based on characteristics related to the signal segments, and a physiological information determination unit (7) determines physiological information from at least one of i)signal segments classified into the valid class and ii) signal segments classified into the non-valid class. The physiological information can therefore be determined based on the knowledge whether the respective signal segment is valid or not. For example, a physiological parameter like a breathing rate can be determined depending on valid adapted segments of the physiological signal, which are adapted to periods of the physiological signal. This improves the quality of determining physiological information from a physiological signal.

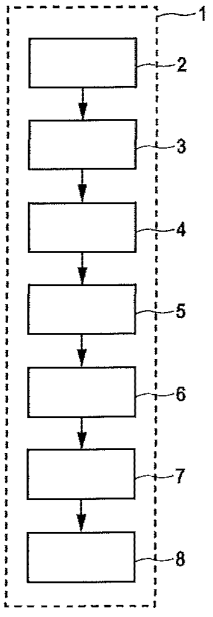


FIG. 1

WO 2012/123828 A1

BNSDOCID: <WO_____2012123828A1_I_>

DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

Published:

— *with international search report (Art. 21(3))*

BNSDOCID: <WO_____2012123828A1_I_>

Monitoring apparatus for monitoring a physiological signal

FIELD OF THE INVENTION

The invention relates to a monitoring apparatus, a monitoring method and a monitoring computer program for monitoring a physiological signal.

BACKGROUND OF THE INVENTION

US 6,997,882 B1 discloses a method for monitoring respiratory functions of a subject. Acceleration signals are acquired from at least one accelerometer module attached to the subject. The acceleration signals are processed to obtain anterior-posterior acceleration signals representing anterior-posterior acceleration vectors largely free of medio-lateral acceleration vectors. An acceleration component that is due to breathing is extracted from the anterior-posterior acceleration signals, wherein the extraction comprises the application of a least means square adaptive noise-cancellation technique. The extracted acceleration component is likely to be adversely affected by non-breathing motion. The quality of the extracted acceleration component is therefore reduced.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a monitoring apparatus, a monitoring method and a monitoring computer program for monitoring a physiological signal, wherein the quality of determining physiological information can be improved.

In a first aspect of the present invention a monitoring apparatus for monitoring a physiological signal is presented, wherein the monitoring apparatus comprises:

- a physiological signal providing unit for providing a periodic physiological signal,
- a segmentation unit for determining signal segments from the physiological signal, which correspond to periods of the physiological signal,
- a classification unit for classifying the signal segments into a valid class and a non-valid class based on characteristics related to the signal segments,

BNSDOCID: <WO_____2012123828A1_I_>

a physiological information determination unit for determining physiological information from at least one of i) signal segments classified into the valid class and ii) signal segments classified into the non-valid class.

Since the segmentation unit determines signal segments from the physiological signal, which correspond to periods of the physiological signal, wherein then the classification unit classifies the signal segments into a valid class and a non-valid class based on characteristics related to the signal segments, and the physiological information determination unit determines physiological information from at least one of i) signal segments classified into the valid class and ii) signal segments classified into the non-valid class, the physiological information can be determined based on the knowledge whether the respective signal segment is valid or not. For example, the physiological information determination unit can be adapted to determine a physiological parameter like a breathing rate depending on valid adapted segments of the physiological signal, which are adapted to periods of the physiological signal, for example, which are adapted to single breaths of a breathing signal. This allows improving the quality of determining physiological information from a periodic physiological signal.

The physiological signal providing unit can be a storing unit, in which the periodic physiological signal is stored already and from which the physiological signal can be retrieved for providing the same. The physiological signal providing unit can also be a receiving unit for receiving the periodic physiological signal via a wireless or wired data connection, wherein the physiological signal providing unit provides the received periodic physiological signal. The physiological signal providing unit can also be a measurement unit for measuring the periodic physiological signal. For example, the physiological signal providing unit can be an accelerometer for measuring an accelerometer breathing signal. The period of the physiological signal corresponds preferentially to single breath.

It is preferred that the segmentation unit is adapted to find valleys in the physiological signal and to determine a signal segment as a segment of the physiological signal between two neighbored valleys. The valleys can indicate a start and an end of a period of the physiological signal. Thus, by defining a signal segment by two neighbored valleys the signal segment can represent a period of the physiological signal.

It is further preferred that the segmentation unit is adapted to i) find valleys in the physiological signal, ii) apply a set of predefined rules to characteristics of the physiological signal around the found valleys, wherein the set of rules defines whether a found valley is a start or an end of a period of the physiological signal based on the

BNSDOCID: <WO_____2012123828A1_I_>

characteristics of the physiological signal around the found valleys, iii) discard the found valleys which do not define a start or an end of a period, iv) determine a signal segment as a segment of the physiological signal between two neighbored non-discarded valleys. In a preferred embodiment, the segmentation unit is adapted to apply a set of rules according to which at least one of the amplitude, skewness and slope of the physiological signal before the respective found valley is compared with that of the respective physiological signal after the respective found valley, and to determine whether the respective found valley is caused by a beginning or an end of a period of the physiological signal depending on the comparison. The physiological signal can be corrupted by, for example, artifacts, noise and other imperfections, or may deviate from a sinusoidal waveform due to the nature of the respective measurement principle used for measuring the physiological signal, which may result in valleys which are not caused by a beginning or an end of a period of the physiological signal. Thus, by applying the set of rules and by discarding the found valleys which, according to the set of rules, do not define a start or an end of a period of the physiological signal, the quality of determining the signal segments can be improved.

The classification unit is adapted to classify the signal segments into a valid class and a non-valid class based on characteristics related to the signal segments. Characteristics related to the signal segments are, for example, temporal, spectral and spatial characteristics. They can be characteristics of the respective signal segment itself. Characteristics related to the signal segments can also be characteristics which correspond to properties of a measuring unit used for measuring the physiological signal, the condition of the person or animal, et cetera, while the respective signal segment has been measured. For instance, the physiological signal can be an accelerometer signal, wherein the classification unit can be adapted to classify the signal segments based on a rotation angle defining the rotation of the accelerometer while the respective signal segment has been measured. The rotation angle is preferentially defined as the angle to which an accelerometer is rotated in space during a single period, i.e. the rotation angle can be defined as the difference between the orientation of the accelerometer at the start of the respective signal segment and the orientation at the end of the respective signal segment. For signal segments from motion artifacts the rotation angles are usually larger when compared to signal segments from physiological signals. In particular, breathing signals, which do not comprise motion artifacts, can in principle yield a zero net rotation angle during a single breathing period, i.e. the accelerometer returns substantially to its initial orientation at the end of one breath. The classification unit can also be adapted to classify the signal segments based on other

BNSDOCID: <WO_____2012123828A1_I_>

characteristics related to the signal segments like the spectral entropy of the respective signal segment, the number of valleys within the respective signal segment and/or the shape of valleys within the respective signal segment.

Preferentially, the classification unit is adapted to use a decision tree classifier for classifying the signal segments into a valid class and a non-valid class. This allows classifying the signal segments in a simple way and in realtime.

It is also preferred that the classification unit is adapted to determine an accuracy value being indicative of the accuracy of classifying a signal segment into the valid class or the non-valid class depending on the respective signal segment. For example, if the classification unit is adapted to use a decision tree classifier for classifying the signal segments into a valid class and a non-valid class, a cross-validation of the decision tree classifier with ground truth can be performed, wherein an accuracy value can be determined for a certain leaf node, to which a valid label or a non-valid label has been assigned, by determining the ratio of correct decisions made at the leaf node to that of all decisions at the leaf node. The accuracy value can be used as an indication for the quality of the classification, which can be shown to a user and/or used in further processings.

In a preferred embodiment, the monitoring apparatus further comprises a classification correction unit for correcting the classification of the signal segments into the valid class and the non-valid class. In particular, the classification correction unit can be adapted to correct a classification of a certain signal segment, if the accuracy value of the certain signal segment is below a predefined accuracy threshold. For example, depending on the criticality of the physiological parameters and the application scenario, an appropriate value for the accuracy threshold can be set. In an embodiment, the classification correction unit can comprise assignments between a) physiological parameters and/or applications and b) accuracy thresholds, wherein the classification correction unit can use an accuracy threshold based on the assignments and the currently monitored physiological parameter and/or the current application. The classification correction unit can comprise a set of correction rules, which define, whether and how a classification of a segment has to be corrected based on at least one of correction features like the accuracy value, characteristics of the respective segment, characteristics of neighboring segments, user characteristics like a user activity level, environmental characteristics like the environmental temperature, the time of day, et cetera. For example, the set of rules can define that, if a segment is labeled as being valid and has an accuracy value being smaller than the accuracy threshold, which may be 60%, and if the temporarily neighboring segments are non-valid segments, the classification

BNSDOCID: <WO_____2012123828A1_I_>

correction unit corrects the particular segment's label as non-valid. This allows improving the quality of the classification of the segments into valid and non-valid segments, thereby further improving the quality of the determination of the physiological parameter.

The physiological information determination unit can be adapted to determine a physiological parameter as the physiological information from the signal segments classified into the valid class. For example, a breathing rate or a heart rate can be determined as the physiological parameter. In particular, the physiological signal providing unit can be adapted to provide a breathing signal as the physiological signal, wherein the physiological information determination unit can be adapted to determine the respiration rate as the physiological parameter from the signal segments classified into the valid class by, for example, inverting the duration of a signal segment classified into the valid class. The physiological information determination unit can further be adapted to determine a physiological pattern as the physiological information from the signal segments classified into the valid class and from the signal segments classified into the non-valid class. The physiological pattern is, for example, a breathing pattern or a heart beat pattern, i.e. a cardiac pattern. In particular, the physiological information determination unit can be adapted to determine breathing patterns such as Cheyne-stokes respiration, periodic breathing, Apnea et cetera. For determining a breathing pattern, the physiological information determination unit is preferentially adapted to not only use valid segments, but also non-valid segments. In particular, the physiological information determination unit can be adapted to determine a breathing pattern based on valid and non-valid segments, which cover a duration of, for example, two minutes, and characteristics of these valid and non-valid segments. The physiological information determination unit can comprise a set of rules, which determine a breathing pattern based on these valid and non-valid segments and their characteristics. For example, the set of rules can define that, if a part of the physiological signal with contiguous non-valid segments with a variance being lower than a predefined variance threshold is followed by a part of the physiological signal with contiguous valid segments of modulated amplitudes, a Cheyne-stokes respiration pattern is present. The part of the physiological signal with contiguous non-valid segments with the low variance can represent apnea and the part of the physiological signal with contiguous valid segments of modulated amplitudes can represent hyperpnea.

It is preferred that the monitoring apparatus further comprises a pre-processing unit for pre-processing the physiological signal by performing at least one of the following: filtering, normalization, offset removing, down-sampling. The pre-processing can improve

BNSDOCID: <WO_____2012123828A1_I_>

the quality of the physiological signal and/or reduce the computational load for further processing of the respiratory signal. For example, by down-sampling of the physiological signal, the computation time and load for further processing can be reduced. In an embodiment, the physiological signal is a respiratory signal and the respiratory signal is down-sampled to less than 20 Hz, preferentially to about 16 Hz.

In an embodiment, the physiological signal providing unit is adapted to provide several periodic physiological signals like a respiratory signal and a pulse signal. The segmentation unit can then be adapted to determine signal segments for the different physiological signals, the classification unit can be adapted to classify the signal segments of the different physiological signals, and the physiological information determination unit can be adapted to determine physiological parameters for the different physiological signals. For example, a respiration rate and a pulse rate can be determined. In order to use the physiological parameters determined for the different physiological signals for an evaluation of the condition of the monitored object, in particular, the condition of a human being or an animal, the pre-processing unit can be adapted to apply a phase correction to the different physiological signals such that they are in phase.

In an embodiment, the physiological signal is a breathing signal and the pre-processing unit is adapted to apply a band-pass filter of 0.1 to 2 Hz to the breathing signal. Thus, only frequencies pass the pre-processing unit, which may be correlated to the breathing, thereby improving the quality of the breathing signal.

In a further embodiment, the physiological signal providing unit is adapted to provide three physiological signals, which correspond to three axes of a tri-axial accelerometer, wherein the pre-processing unit is adapted to fuse the three physiological signals to a single physiological signal. For example, the pre-processing unit can apply a principle component analysis (PCA) to the physiological signal. The PCA transforms a data set of three correlated signals, which preferentially correspond to three different axes of an accelerometer, into a data set of three orthogonal signals, where the first principle component carries maximum variance. The pre-processing unit can be adapted to determine the first principle component of the PCA as the fused single physiological signal, thereby reducing three-dimensional data to one-dimensional data. This can lower the computational time and load for further processing.

Preferentially, the monitoring apparatus further comprises a display for displaying the determined physiological parameter.

BNSDOCID: <WO_____2012123828A1_I_>

In a further aspect of the present invention a monitoring method for monitoring a physiological signal is presented, wherein the monitoring method comprises:

- providing a periodic physiological signal by a physiological signal providing unit,
- determining signal segments from the physiological signal, which correspond to periods of the physiological signal, by a segmentation unit,
- classifying the signal segments into a valid class and a non-valid class based on characteristics related to the signal segments by a classification unit,
- determining physiological information from at least one of i) signal segments classified into the valid class and ii) signal segments classified into the non-valid class by a physiological information determination unit.

In a further aspect of the present invention a monitoring computer program for monitoring a physiological signal is presented, wherein the monitoring computer program comprises program code means for causing a monitoring apparatus as defined in claim 1 to carry out the steps of the monitoring method as defined in claim 14, when the computer program is run on a computer controlling the monitoring apparatus.

It shall be understood that the monitoring apparatus of claim 1, the monitoring method of claim 14 and the monitoring computer program of claim 15 have similar and/or identical preferred embodiments, in particular, as defined in the dependent claims.

It shall be understood that a preferred embodiment of the invention can also be any combination of the dependent claims with the respective independent claim.

These and other aspects of the invention will be apparent from and elucidated with reference to the embodiments described hereinafter.

BRIEF DESCRIPTION OF THE DRAWINGS

In the following drawings:

Fig. 1 shows schematically and exemplarily an embodiment of a monitoring apparatus for monitoring a physiological signal,

Figs. 2 and 3 show exemplarily a part of a breathing signal with valleys and peaks,

Fig. 4 shows exemplarily a breathing signal with valid signal segments and non-valid signal segments, and

Fig. 5 shows a flowchart exemplarily illustrating an embodiment of a monitoring method for monitoring a physiological signal.

BNSDOCID: <WO____2012123828A1_I_>

DETAILED DESCRIPTION OF EMBODIMENTS

Fig. 1 shows schematically and exemplarily an embodiment of a monitoring apparatus for monitoring a physiological signal. The monitoring apparatus 1 comprises a physiological signal providing unit 2 for providing a periodic physiological signal. In this embodiment, the physiological signal providing unit 2 is a storing unit, in which the periodic physiological signal is stored already. The physiological signal is preferentially an accelerometer breathing signal, which has been measured by using an accelerometer. The accelerometer is an electromechanical sensor that measures both, gravitational, induced by the earth gravity ($g = 9.8\ \mathrm{ms}^2$), and inertia accelerations induced by movements. In particular, the accelerometer is a three-axial accelerometer, which is attached to a thorax, preferably on the left rib cage, of a human being, in order to measure projections of the gravity vector onto its sensing axes. During breathing, the movement of the rib cage rotates the sensor in an earth reference system, thus causing a change of the projections of the gravity vector on the three axes, which is reflected on the sensor axes signals. Thus, the accelerometer is preferentially used as an inclinometer, in order to measure accelerometer breathing signals. By using the accelerometer, a cable-less, unobtrusive, low-cost and continuous respiration monitoring can be provided. Instead of or in addition to attaching the accelerometer to the thorax, the accelerometer can also be attached to another part of a human being, which moves with breathing, like the abdomen.

In another embodiment, the physiological signal providing unit is adapted to measure the periodic physiological signal. In particular, the physiological signal providing unit can comprise an accelerometer for measuring an accelerometer breathing signal, an analogue-to-digital converter for converting the measured analogue accelerometer breathing signal to a digital accelerometer breathing signal and a buffer for storing the digital accelerometer breathing signal before providing it to a pre-processing unit 3.

The pre-processing unit 3 is adapted to pre-process the provided physiological signal by performing at least one of the following: filtering, normalization, offset-removing and down-sampling. This pre-processing is preferentially performed such that the following signal processing is simplified, without losing relevant information. For example, the pre-processing unit 3 can be adapted to apply a band-pass filter of 0.1-1 Hz or 0.1-2 Hz to the breathing signal. Thus, the filtering can be performed such that only frequencies pass the pre-processing unit 3, which may be correlated to the breathing, thereby improving the quality of the breathing signal. The band-pass filter of 0.1-1 Hz corresponds to the normal breathing

BNSDOCID: <WO_____2012123828A1_I_>

rate of 6-60 breaths per minute. The band-pass filter of 0.1-2 Hz also considers neonatal breathing.

In this embodiment, the physiological signal providing unit 2 is adapted to provide three accelerometer signals of a tri-axial accelerometer as breathing signals. The three accelerometer signals, which correspond to the three axes of the accelerometer, are preferentially fused into one breathing signal by using PCA by the pre-processing unit 3. The first principle component of the PCA is preferentially the single breathing signal, which is used for further processing.

The monitoring apparatus 1 further comprises a segmentation unit 4 for determining signal segments from the physiological signal, i.e., in this embodiment, the breathing signal, which correspond to periods of the physiological signal. The segments can be regarded as breath candidates, wherein the segmentation unit 4 prepares the breathing signal for breath detection by generating the breath candidates, which are basic units of a classification, which will be described further below. A typical breathing cycle resembles a sinusoidal-shaped breathing signal with a peak separating inspiration and expiration, while the start of inspiration and the end of expiration are marked by local minima in the breathing signal.

The segmentation unit 4 can be adapted to find valleys in the physiological signal and to determine a signal segment as a segment of the physiological signal between two neighbored valleys. Thus, the segmentation unit 4 can be adapted to find valleys in the breathing signal, which may be defined as local minima below the mean of the breathing signal, to identify start and end of a breath candidate. Since not all of the valleys may be a true beginning/or end of a breath due to, for example, the nature of the measurement principle used for measuring the physiological signal, small artifacts, noise and other imperfections, invalid valleys may be present, which may lead to false candidates. The segmentation unit 4 can therefore be adapted to apply a set of predefined rules to characteristics of the breathing signal around the found valleys, wherein the set of rules defines, whether a found valley is a start of an end of a period of the breathing signal, based on the characteristics of the breathing signal around the found valleys. In particular, the segmentation unit 4 can be adapted to apply a set of rules according to which at least one of the amplitude, the skewness and slope of the breathing signal before the respective found valley is compared with that of the respective breathing signal after the respective found valley, wherein it is determined that the respective found valley is caused by a beginning or an end of a period of the breathing signal depending on the comparison. The set of rules can

BNSDOCID: <WO_____2012123828A1_I_>

be determined by calibration or training, wherein the set of rules is defined such that for the calibration or training breathing signals the accuracy of determining, whether the respective found valley is caused by a beginning or an end of a period of the breathing signal or not, is optimized. Thus, a set of rules can be defined by learning from occurrences of, for example, false candidates, wherein the set of rules are defined such that the occurences of false candidates are minimized.

The segmentation unit 4 can be further adapted to discard the found valleys, which do not define a start or an end of a period of the breathing signal and to determine a signal segment as a segment of the breathing signal between two neighboring non-discarded valleys.

Figs. 2 and 3 show schematically and exemplarily a part of a fused accelerometer breathing signal, in particular, the amplitude A of the signal in arbitrary units depending on the time t in arbitrary units. In these figures, the crosses indicate valleys, the vertical lines indicate peaks and the ellipses indicate valleys to be removed. The segmentation unit 4 can be adapted to find the valleys, which are denoted in Figs. 2 and 3 by ellipses, in order to identify these valleys as valleys, which do not define a start or an end of a breathing period.

The monitoring apparatus further comprises a classification unit 5 for classifying the signal segments into a valid class and a non-valid class based on characteristics related to the signal segments. Thus, the classification unit 5 is preferentially adapted to calculate characteristics, which can also be regarded as a feature, related to the respective signal element, i.e. to the respective breath candidate, and to classify the respective signal segment depending on the calculated characteristics. The characteristics can be, for example, at least one of temporal, spectral and spatial characteristics related to the respective signal element. For example, a rotation angle defining the rotation of the accelerometer while the respective signal segment has been measured can be calculated as a spatial characteristic, the spectral entropy of the respective signal segment can be determined as a spectral characteristic, and the number of valleys of the respective signal segment and the shape of valleys of the respective signal segment can be calculated as temporal characteristics. The rotation angle is preferentially defined as the angle to which an accelerometer is rotated in space during a single period, i.e. the rotation angle can be defined as the difference between the orientation of the accelerometer at the start of the respective signal segment and the orientation at the end of the respective signal segment. The classification unit 5 can, for example, be adapted to classify a respective signal segment as valid, if the rotation angle is

BNSDOCID: <WO_____2012123828A1_I_>

smaller than a predefined rotation angle threshold, and to classify the respective signal segment as non-valid, if the rotation angle is larger than the predefined rotation angle threshold. The rotation angle threshold can be predefined by calibration or training with signal segments, which are unknown to be valid or non-valid.

The classification unit 5 is preferentially adapted to determine a feature vector, which represents the characteristics related to the respective signal element, for the signal segments, i.e. for the breath candidates. The classification unit then preferentially uses the feature vector to categorize a particular breath candidate as either valid or non-valid, i.e. as a breath segment or a non-breath segment. The classification unit 5 can use various types of classifiers that may fulfill the task. Preferentially, the classification unit 5 uses a decision tree classifier, which allows to classify the signal segments in a simple way and in realtime.

The decision tree classifier is also preferentially trained or calibrated by using signal segments, of which it is known, whether they are valid or non-valid. For example, the decision tree classifier can be trained from manually annotated breathing data, wherein it is annotated whether the respective signal segment is valid or non-valid. The breathing data can be breathing data of several persons located in one or several hospitals.

In an embodiment, the feature vector comprises several features, spanning across in time, frequency and/or spatial domains. For example, the feature vector can comprise at least one of the following features: width, mean, median, amplitude variance, peak amplitude, amplitude at signal element start, amplitude at signal element end, relative location of peak within the respective signal element, positive width, number of valleys inside signal segment but above mean, slope of line passing through signal segment start and end amplitudes, area under the signal segment curve, dominant frequency, magnitude at dominant frequency, spectral entropy, spectral centroid, magnitude in several, in particular, four, different predefined frequency bands, rotation angle et cetera. The several frequency bands can be predefined by using training data sets comprising signal segments of which the correct assignment to the valid class or the non-valid class is known, wherein the frequency bands are chosen such that the number of incorrectly classified signal segments of the training data set is minimized.

The classification unit 5 can be adapted to pre-classify the signal segments before performing the above described classification. Preferentially, the pre-classification is performed by using a decision tree pre-classifier, which is smaller than the decision tree classifier described above. In particular, less features are determined for a signal segment and the pre-classification is performed based on these few features. For example, the features

BNSDOCID: <WO_____2012123828A1_I_>

used for the pre-classification can be easy-to-compute features like the width or amplitude variance of the respective signal segment.

The pre-classification is preferentially used to identify obvious non-valid signal segments and can be trained be using a training data set. The decision tree pre-classifier can, for example, be adapted such that a signal segment having an amplitude variance smaller than an apnea threshold is regarded as being an obvious non-valid segment, because it is assumed that such a signal segment is inside apnea. Moreover, the pre-classification can be performed such that a signal segment having an amplitude variance above a motion threshold is identified as a non-valid signal segment, because it is assumed that the relatively high variance of the amplitude is caused by a motion artifact. The main classification is then performed on the signal segments, which have not been identified as being obvious non-valid signal segments by the pre-classification. The main classification is therefore performed on less signal segments, thereby reducing the computational load of performing the main classification.

The decision tree classifier performing the main classification and the optional decision tree pre-classifier performing the pre-classification can be, for example, a standard C 4.5 decision tree classifier or a classification and regression tree (CART).

The classification unit 5 is preferentially further adapted to determine an accuracy value being indicative of the accuracy of classifying a signal segment into the valid class or the non-valid class depending on the respective signal segment. This accuracy value, which is indicative of the accuracy of classifying the respective signal segment, i.e., which is indicative of the label decision, is directly correlated to the quality of the corresponding breath. The classification unit 5 can be adapted to cross-validate the decision tree classifier with ground truth and to determine the accuracy value as a ratio of correct decisions made at the leaf, which assigns a valid or non-valid label to the respective signal segment, to that of all decisions at the leaf. In an embodiment, a training data set comprising signal segments, of which is it known whether they are valid or non-valid signal segments, is classified by the decision tree classifier. Since the correct classification of the respective signal segment is known, the classification resulting by using the decision tree classifier can be compared with the correct classification, in order to determine for each leaf of the decision tree classifier an accuracy value. For example, the accuracy value can be defined as the number of correct decisions made at a respective leaf divided by the overall number of decisions made at the respective leaf. After for each leaf an accuracy value has been determined, the decision tree classifier can be applied to an actual signal segment, of which the correct classification is not

BNSDOCID: <WO_____2012123828A1_I_>

known, wherein, after the classification has been performed, the respective actual signal segment is assigned to a certain leaf of the decision tree classifier, thereby defining the class of the respective actual signal segment and the corresponding accuracy value.

Fig. 4 shows schematically and exemplarily the amplitude A of a breathing signal depending on the time t. The different signal segments are defined by the valleys, which are indicated by crosses. The valid signal segments are denoted by a solid line and the non-valid signal segments are denoted by a dashed line. The numbers shown in Fig. 4 above the respective signal segment indicate the respective accuracy value.

As can be seen in Fig. 4, the signal segments 9 deviate from a sinusoidal shape and have a lower accuracy value. This deviation and the small accuracy values may be caused by an influence of the accelerometer signal by non-breathing motion.

The monitoring apparatus 1 preferentially further comprises a classification correction unit 6 for correcting the classification of the signal segments into the valid class and the non-valid class. In particular, depending on the accuracy in labeling and the knowledge of surrounding labels, a classifier decision can be revoked to improve reliability.

The classification correction unit 6 can be adapted to correct a classification of a certain signal segment, if the accuracy value of the certain signal segment is below a predefined accuracy threshold. For example, depending on the criticallity of the physiological parameters and the application scenario, an appropriate value for the accuracy threshold can be set. In an embodiment, the classification correction unit 6 can comprise assignments between a) physiological parameters and/or applications and b) accuracy thresholds, wherein the classification correction unit 6 can use an accuracy threshold based on the assignments and the currently monitored physiological parameter and/or the current application. For instance, the accuracy thresholds can be predefined such that the classification of the signal segments 9 shown in Fig. 4 and having an accuracy value smaller than 0.8 is corrected from the valid class to the non-valid class.

The classification correction unit 6 can comprise a set of correction rules, which define, whether and how a classification of a segment has to be corrected based on the accuracy threshold, characteristics of the respective segment, characteristics of neighboring segments, user characteristics like a user activity level, environmental characteristics like the environmental temperature, the time of day, et cetera. For example, the set of rules can define that, if a segment is labeled as being valid and has an accuracy value being smaller than the accuracy threshold, which may be 60%, and if the temporarily neighboring segments are non-valid segments, the classification correction unit 6 corrects the particular segment's label as

BNSDOCID: <WO_____2012123828A1_I_>

non-valid. This allows improving the quality of the classification of the segments into valid and non-valid segments, thereby further improving the quality of the determination of the physiological parameter.

The monitoring apparatus 1 further comprises a physiological information determination unit 7 for determining physiological information from at least one of i) signal segments classified into the valid class and ii) signal segments classified into the non-valid class. In particular, the physiological information determination unit 7 is adapted to determine a physiological parameter from the signal segments classified into the valid class. In this embodiment, the physiological information determination unit 7 is adapted to determine the respiration rate as the physiological parameter from the signal segments classified into the valid class. For example, the physiological information determination unit 7 can be adapted to determine the respiration rate by inverting the duration of a signal segment classified into the valid class. The physiological information determination unit 7 can further be adapted to determine breathing patterns such as Cheyne-stokes respiration, periodic breathing, apnea, et cetera. For determining a breathing pattern, the physiological information determination unit 7 is preferentially adapted to not only use valid segments, but also non-valid segments. In particular, the physiological information determination unit 7 can be adapted to determine a breathing pattern based on the valid and non-valid labels of signal segments, which cover a duration of, for example, two minutes, and characteristics of these valid and non-valid segments. The physiological information determination unit 7 can comprise a set of rules, which determine a breathing pattern based on the valid and non-valid labels of the signal segments and the characteristics of the signal segments. For example, the set of rules can define that, if a part of the physiological signal with contiguous non-valid segments, which have preferentially a duration of at least 10 seconds, with a variance being lower than a predefined variance threshold is followed by a part of the physiological signal with contiguous valid segments of modulated amplitudes, a Cheyne-stokes respiration pattern is present. The part of the physiological signal with contiguous non-valid segments with the low variance can represent apnea and the part of the physiological signal with contiguous valid segments of modulated amplitudes can represent hyperpnea. Also the set of rules used by the physiological information determination unit 7 can be defined by calibration or training, wherein signal segments representing a known physiological parameter and/or a known physiological pattern are used.

The monitoring apparatus 1 further comprises a display 8 for displaying, for example, the physiological parameter like the breathing rate, the physiological pattern like

BNSDOCID: <WO_____2012123828A1_I_>

the breathing pattern, the valid signals and/or the non-valid signals. In particular, the display can be adapted to show the valid and non-valid signal segments as exemplarily shown in Fig. 4.

In the following an embodiment of a monitoring method for monitoring a physiological signal will exemplarily be described with reference to a flowchart shown in Fig. 5.

In step 101, the physiological signal providing unit 2 provides periodic physiological signals, which are, in this embodiment, accelerometer breathing signals. In step 102, the physiological signals are pre-processed by the pre-processing unit 3. In particular, the physiological signals are filtered by using a band-pass filter of 0.1-2 Hz. Moreover, the pre-processing unit 3 fuses the accelerometer breathing signals, which are preferentially three accelerometer breathing signals of a three-axial accelerometer, to a single breathing signal by PCA. In step 103, the segmentation unit 4 determines signal segments from the pre-processed physiological signal, which correspond to periods of the physiological signal, and, in step 104, the classification unit 5 classifies the signal segments into a valid class and a non-valid class based on characteristics related to the signal segments. In step 105, the classification correction unit 6 corrects the classification of the signal segments into the valid class and the non-valid class, if required, and, in step 106, the physiological information determination unit 7 determines physiological information, for example, a physiological parameter like the breathing rate from the signal segments classified into the valid class or a physiological pattern like the breathing pattern from the signal segments classified into the valid class and the signal segments classified into the non-valid class. In step 107, at least the determined physiological parameter and/or the physiological pattern is shown on the display 8.

Although in the above described embodiments, the physiological signal is an accelerometer breathing signal, the monitoring apparatus and the monitoring method can also be adapted to monitor a breathing signal, which is measured by another device like a respiratory belt. The monitoring apparatus and the monitoring method can also be adapted to monitor another physiological signal like a cardiac signal, in particular, like an electro-cardiography signal.

The monitoring apparatus and the monitoring method can be adapted to monitor one or several physiological signals. For example, one or several accelerometers can be used for monitoring one or several breathing signals. Moreover, the monitoring apparatus and the monitoring method can be adapted to monitor different physiological signals like a breathing signal and a cardiac signal, simultaneously.

BNSDOCID: <WO_____2012123828A1_I_>

Physiological parameters like breathing and heart rates can have a high clinical value as an early indicator of patient's health deterioration. Traditionally, patients in the intensive and medium care units are well-monitored, while those in medical and post-surgical care units are not. Generally, a continuous monitoring of patient's physiological parameters over a long time period is an arduous task due to the shortage of nursing personnel, lack of supervision and unavailability of a suitable monitoring system, which may lead to a sub-optimal care. The above described monitoring apparatus can be a reliable, automatic and easy-to-use device to measure physiological parameters for the general ward patients.

The acceleration sensor is preferentially attached to the patient's thorax or abdomen and can be used to detect breathing effort along with information such as heart-beating, body-posture and activity level of the patient. The acceleration sensor can be attached to patients, who are physically more active than traditionally monitored patients of an intensive care unit (ICU), wherein the sensor signals can be mixed-up with accelerations due to patient's body movements. The monitoring apparatus and the monitoring method can be adapted to ensure a reliable interpretation of the measured data by deriving the physiological parameters from clinical relevant signals rather than motion-contaminated signals. By doing so, false alarms are limited and the patient's status can be properly supervised. In particular, the monitoring apparatus and the monitoring method are preferentially adapted to discard motion-contaminated signals, i.e. motion-contaminated signal segments, which are classified as non-valid, and reliably extract respiration/pulse rates and trends from the rest of the signal. Thus, an automatic algorithm can be provided, which intelligently identifies and removes motion-contaminated measurements to make a continuous monitoring of vital body signs in general ward patients meaningful.

The monitoring apparatus and monitoring method are preferentially adapted to accurately detect every single breath in a breathing signal. Thus, in contrast to a fixed time frame analysis, in which a breathing signal is segmented and processed in fixed-sized frames of, for example, 25 s, the monitoring apparatus and monitoring method can be adapted to operate at the finest resolution and thus captures every single breath that is valid, thereby increasing the availability of breathing information. The output such as the respiration rate (RR), the accuracy value, which can also be regarded as a confidence index (CI), the breathing pattern, et cetera, are preferentially sent to the display to notify an observer. The monitoring apparatus and monitoring method detect preferentially every single breath after an adaptive segmentation of the breathing signal. A sequence of operations is performed on the breathing signal to calculate, for example, RR and a corresponding CI. The CI quantifies

BNSDOCID: <WO_____2012123828A1_I_>

preferentially the confidence in evaluation of the respiratory rate from a single breath. It reflects the accuracy in the breath detection and the quality of the breath.

The breathing signal is preferentially a digitized signal of an accelerometer and is preferentially buffered up to one cycle of respiration, for example, for 10 seconds, before being pre-processed by the pre-processing unit which preferentially carries out operations such as filtering, DC-removal, normalization, et cetera on the digitized and buffered raw sensor signals. The segmentation unit then preferentially demarcates the signal to generate breath candidates based on pre-defined rules. In comparison to a fixed-frame classification, the breath candidates, i.e. the signal segments, can be seen as the high-resolution frames with time-varying lengths, which are the basic units, on which the classification unit operates. The classification unit calculates preferentially a set of breath-specific features for each breath-candidate, which are then classified into "breathing", i.e. into valid, and "non-breathing", i.e. non-valid, categories using a classification algorithm such as a decision tree. The physiological information determination unit then preferentially calculates the respiratory rate along with the corresponding index of confidence from the breath candidates that were classified as "breathing".

The monitoring apparatus and the monitoring method can be adapted to be applied in a setting, where vital body signs such as respiration are monitored by using one or more sensors, in particular, one or more accelerometers. The monitoring apparatus and the monitoring method can be adapted to monitor respiration in general wards at the hospital. But, the monitoring apparatus and the monitoring method can also be adapted for ICU monitoring and home healthcare.

Although in above described embodiments PCA is used as a technique for fusing physiological signals, also other fusion techniques can be used like weighted sum beamforming (WSB), geometrical coordinates rotation and other heuristic fusion methods.

Other variations to the disclosed embodiments can be understood and effected by those skilled in the art in practicing the claimed invention, from a study of the drawings, the disclosure, and the appended claims.

In the claims, the word "comprising" does not exclude other elements or steps, and the indefinite article "a" or "an" does not exclude a plurality.

A single unit or device may fulfill the functions of several items recited in the claims. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measures cannot be used to advantage.

BNSDOCID: <WO_____2012123828A1_I_>

Calculations like the determination of signal segments, the classification of the signal segments or the determination of physiological information, performed by one or several units or devices, can be performed by any other number of units or devices. For example, steps 102 to 106 can be performed by a single unit or by any other number of different units. The calculations and/or the control of the monitoring apparatus in accordance with the monitoring method can be implemented as program code means of a computer program and/or as dedicated hardware.

A computer program may be stored/distributed on a suitable medium, such as an optical storage medium or a solid-state medium, supplied together with or as part of other hardware, but may also be distributed in other forms, such as via the Internet or other wired or wireless telecommunication systems.

Any reference signs in the claims should not be construed as limiting the scope.

The invention relates to a monitoring apparatus for monitoring a physiological signal. A segmentation unit determines signal segments from a physiological signal, which correspond to periods of the physiological signal, a classification unit classifies the signal segments into a valid class and a non-valid class based on characteristics related to the signal segments, and a physiological information determination unit determines physiological information from at least one of i) signal segments classified into the valid class and ii) signal segments classified into the non-valid class. The physiological information can therefore be determined based on the knowledge whether the respective signal segment is valid or not. For example, a physiological parameter like a breathing rate can be determined depending on valid adapted segments of the physiological signal, which are adapted to periods of the physiological signal. This improves the quality of determining physiological information from a physiological signal.

BNSDOCID: <WO_____2012123828A1_I_>

CLAIMS:

1. A monitoring apparatus for monitoring a physiological signal, the monitoring apparatus (1) comprising:

- a physiological signal providing unit (2) for providing a periodic physiological signal,
- a segmentation unit (4) for determining signal segments from the physiological signal, which correspond to periods of the physiological signal,
- a classification unit (5) for classifying the signal segments into a valid class and a non-valid class based on characteristics related to the signal segments,
- a physiological information determination unit (7) for determining physiological information from at least one of i) signal segments classified into the valid class and ii) signal segments classified into the non-valid class.

2. The monitoring apparatus as defined in claim 1, wherein the segmentation unit (4) is adapted to:

- find valleys in the physiological signal,
- determine a signal segment as a segment of the physiological signal between two neighbored valleys.

3. The monitoring apparatus as defined in claim 1, wherein the segmentation unit (4) is adapted to:

- find valleys in the physiological signal,
- apply a set of predefined rules to characteristics of the physiological signal around the found valleys, wherein the set of rules defines whether a found valley is a start or an end of a period of the physiological signal based on the characteristics of the physiological signal around the found valleys,
- discard the found valleys which do not define a start or an end of a period,
- determine a signal segment as a segment of the physiological signal between two neighbored non-discarded valleys.

BNSDOCID: <WO_____2012123828A1_I_>

4. The monitoring apparatus as defined in claim 3, wherein the segmentation unit (4) is adapted to:

- apply a set of rules according to which at least one of the amplitude, skewness and slope of the physiological signal before the respective found valley is compared with that of the respective physiological signal after the respective found valley,
- determine whether the respective found valley is caused by a beginning or an end of a period of the physiological signal depending on the comparison.

5. The monitoring apparatus as defined in claim 1, wherein the classification unit (5) is adapted to classify the signal segments based on at least one of the temporal, the spectral and the spatial characteristics of the respective signal segment.

6. The monitoring apparatus as defined in claim 1, wherein the physiological signal is an accelerometer signal measured by an accelerometer and wherein the classification unit (5) is adapted to classify the signal segments based on a rotation angle defining a rotation of the accelerometer while the respective signal segment has been measured.

7. The monitoring apparatus as defined in claim 1, wherein the classification unit (5) is adapted to use a decision tree classifier for classifying the signal segments into a valid class and a non-valid class.

8. The monitoring apparatus as defined in claim 1, wherein the classification unit (5) is further adapted to determine an accuracy value being indicative of the accuracy of classifying a signal segment into the valid class or the non-valid class depending on the respective signal segment.

9. The monitoring apparatus as defined in claim 1, wherein the monitoring apparatus (1) further comprises a classification correction unit (6) for correcting the classification of the signal segments into the valid class and the non-valid class.

10. The monitoring apparatus as defined in claim 1, wherein the physiological information determination unit (7) is adapted to determine at least one of i) a physiological parameter as the physiological information from the signal segments classified into the valid class and ii) a physiological pattern as the physiological information from the signal

BNSDOCID: <WO_____2012123828A1_I_>

segments classified into the valid class and from the signal segments classified into the non-valid class.

11. The monitoring apparatus as defined in claim 10, wherein the physiological signal providing unit (2) is adapted to provide a breathing signal as the physiological signal and wherein the physiological information determination unit (7) is adapted to determine the respiration rate as the physiological parameter from the signal segments classified into the valid class.

12. The monitoring apparatus as defined in claim 1, wherein the monitoring apparatus further comprises a pre-processing unit (3) for pre-processing the physiological signal by performing at least one of the following: filtering, normalization, offset removing, down-sampling.

13. The monitoring apparatus as defined in claim 12, wherein the physiological signal providing unit (2) is adapted to provide three physiological signals, which correspond to three axes of a tri-axial accelerometer, wherein the pre-processing unit (3) is adapted to fuse the three physiological signals to a single physiological signal.

14. A monitoring method for monitoring a physiological signal, the monitoring method comprising:

- providing a periodic physiological signal by a physiological signal providing unit,
- determining signal segments from the physiological signal, which correspond to periods of the physiological signal, by a segmentation unit,
- classifying the signal segments into a valid class and a non-valid class based on characteristics related to the signal segments by a classification unit,
- determining physiological information from at least one of i) signal segments classified into the valid class and ii) signal segments classified into the non-valid class by a physiological information determination unit.

15. A monitoring computer program for monitoring a physiological signal, the monitoring computer program comprising program code means for causing a monitoring apparatus as defined in claim 1 to carry out the steps of the monitoring method as defined in

BNSDOCID: <WO_____2012123828A1_I_>

claim 14, when the computer program is run on a computer controlling the monitoring apparatus.

BNSDOCID: <WO_____2012123828A1_I_>

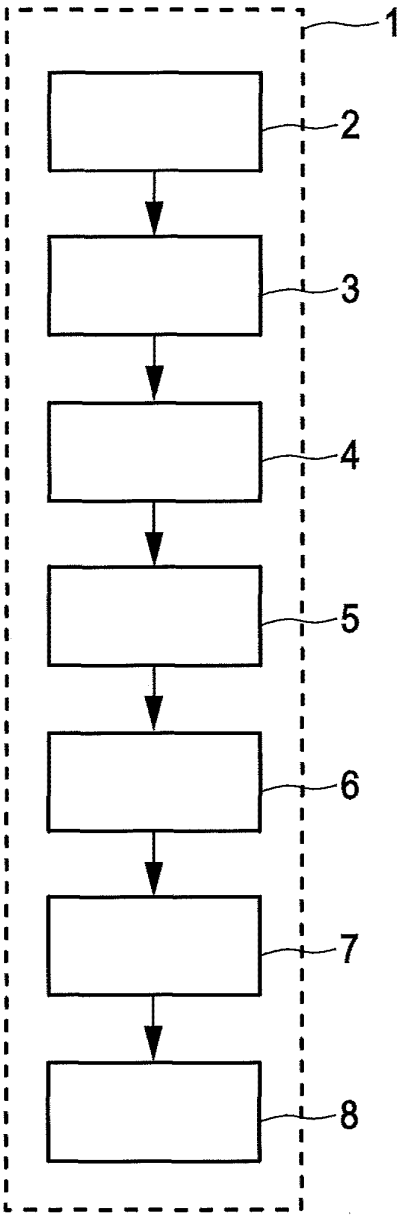


FIG. 1

BNSDOCID: <WO_____2012123828A1_I_>

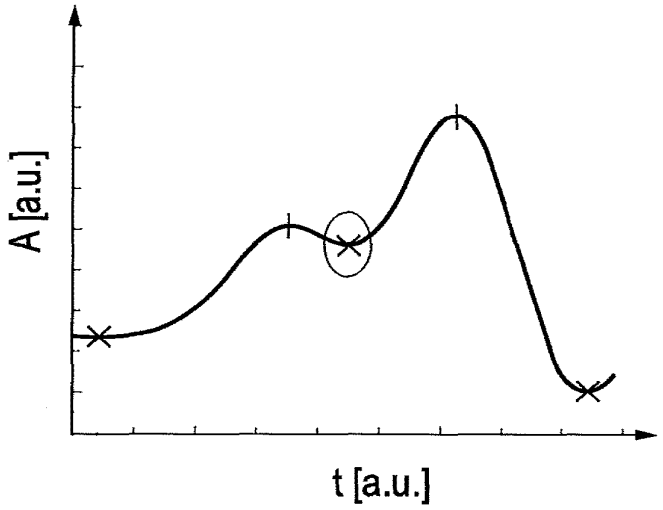


FIG. 2

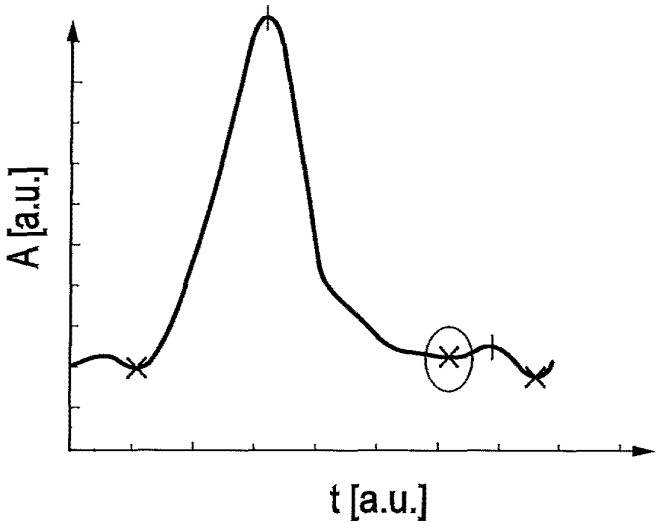


FIG. 3

BNSDOCID: <WO_____2012123828A1_I_>

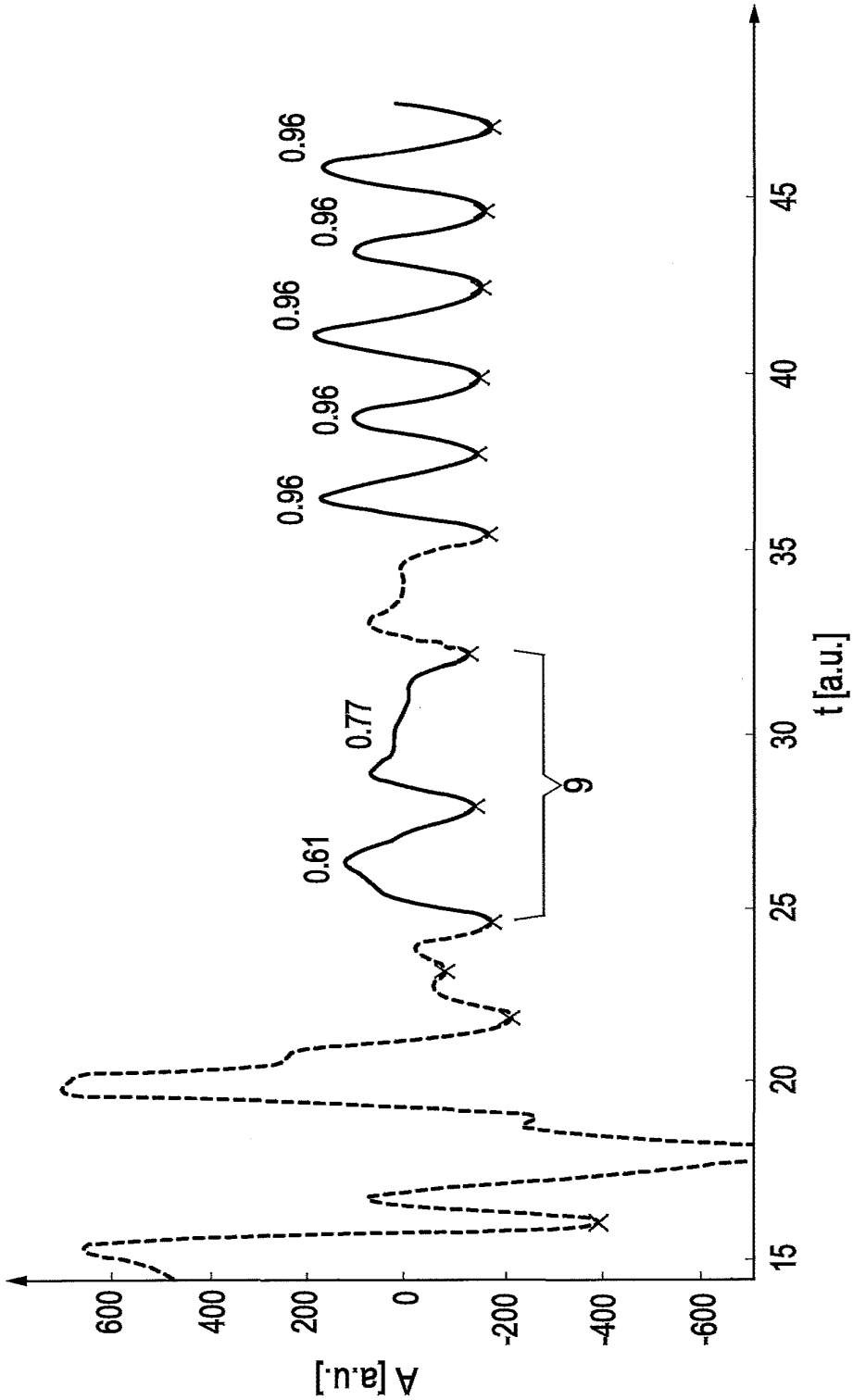


FIG. 4

BNSDOCID: <WO_____2012123828A1_I_>

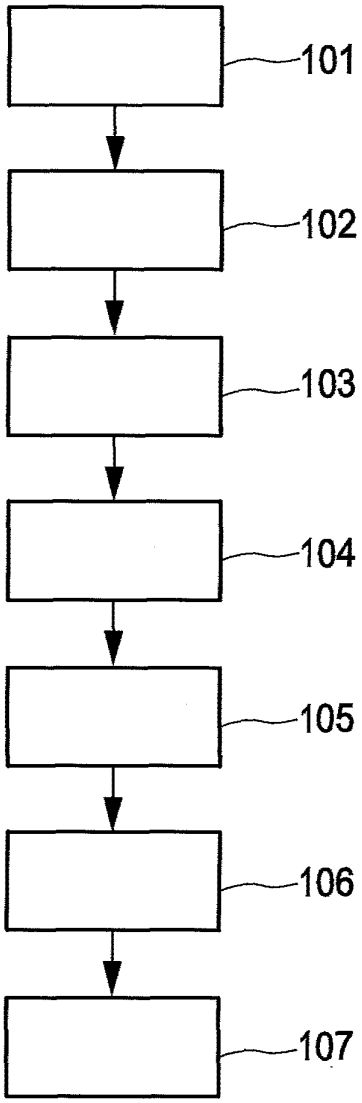


FIG. 5

BNSDOCID: <WO_____2012123828A1_I_>

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2012/050561

A. CLASSIFICATION OF SUBJECT MATTER
INV. A61B5/113
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
A61B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2010/191076 A1 (LEWICKE AARON [US] ET AL) 29 July 2010 (2010-07-29) abstract; figure 8 paragraphs [0005], [0016], [0019], [0022], [0035], [0056] ----- -/--	1,5-15

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
2 May 2012	09/05/2012

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Jonsson, P.O.

Form PCT/ISA/210 (second sheet) (April 2005)

BNSDOCID: <WO_____2012123828A1_I_>

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2012/050561

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	ANMIN JIN ET AL: "Performance evaluation of a tri-axial accelerometry-based respiration monitoring for ambient assisted living", 2009 ANNUAL INTERNATIONAL CONFERENCE OF THE IEEE ENGINEERING IN MEDICINE AND BIOLOGY SOCIETY : EMBC 2009 ; MINNEAPOLIS, MINNESOTA, USA, 3 - 6 SEPTEMBER 2009, IEEE, PISCATAWAY, NJ, USA, 3 September 2009 (2009-09-03), pages 5677-5680, XP031638390, ISBN: 978-1-4244-3296-7 abstract; figure 1 paragraphs [00II], [0III]	1,5,6, 10-15
X	US 2010/130873 A1 (YUEN ANDREA [US] ET AL) 27 May 2010 (2010-05-27) paragraphs [0006], [0029], [0030], [0118], [0181]	1-5, 10-12, 14,15
X,P	WO 2011/098942 A1 (KONINKL PHILIPS ELECTRONICS NV [NL]; PHILIPS INTELLECTUAL PROPERTY [DE) 18 August 2011 (2011-08-18) abstract; figure 1 page 9, line 1 - page 10, line 28 page 13, line 1	1-15

BNSDOCID: <WO_____2012123828A1_I_>

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/IB2012/050561

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2010191076 A1	29-07-2010	NONE	
US 2010130873 A1	27-05-2010	AU 2009231586 A1	08-10-2009
		CA 2720871 A1	08-10-2009
		EP 2265169 A1	29-12-2010
		JP 2011519288 A	07-07-2011
		KR 20110008080 A	25-01-2011
		US 2010130873 A1	27-05-2010
		WO 2009124297 A1	08-10-2009
WO 2011098942 A1	18-08-2011	NONE	

BNSDOCID: <WO_____2012123828A1_I_>

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
2 February 2017 (02.02.2017)

WIPO | PCT

(10) International Publication Number
WO 2017/019184 A2

(51) International Patent Classification: Not classified

(21) International Application Number:
PCT/US2016/036734

(22) International Filing Date:
9 June 2016 (09.06.2016)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/172,862 9 June 2015 (09.06.2015) US
62/299,944 25 February 2016 (25.02.2016) US

(71) Applicant: **UNIVERSITY OF CONNECTICUT** [US/US]; 400 Farmington Avenue, MC 6400, Farmington, CT 06032 (US).

(72) Inventors: **SALEHIZADEH, Seyed, M., A.**; 74 Hickory Drive, Coventry, CT 06238 (US). **CHON, Ki, H.**; 30 Liberty Drive, Mansfield Center, CT 06250 (US). **NOH, Yeonsik**; 380 Daleville Road, Apt. 98, Willington, CT 06279 (US).

(74) Agents: **SOLOMON, Mark, B.** et al.; Hamilton, Brook, Smith & Reynolds, P.C., 530 Virginia Rd., P.O. Box 9133, Concord, MA 01742-9133 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *of inventorship (Rule 4.17(iv))*

Published:

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

(54) Title: METHOD AND APPARATUS FOR REMOVING MOTION ARTIFACTS FROM BIOMEDICAL SIGNALS

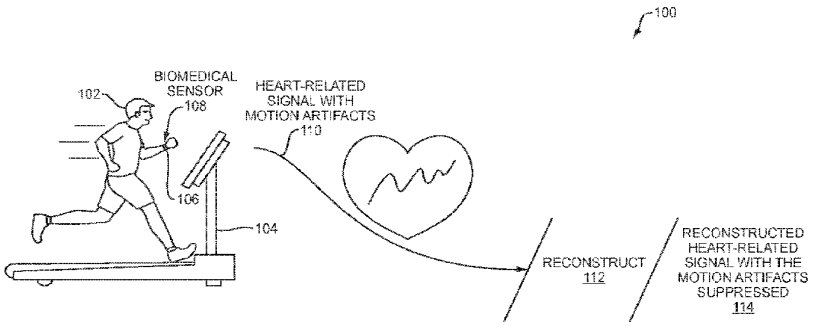


FIG. 1

(57) Abstract: A method and corresponding apparatus employ a time-varying spectral analysis approach for reconstructing a heart-related signal that includes motion artifacts. The motion artifacts are produced by motion of a biomedical sensor relative to a sensing location. By comparing time-varying spectra of the heart-related signal and a motion signal, those frequency peaks resulting from the motion artifacts may be suppressed in a time-varying spectrum of the heart-related signal. The time-varying spectral analysis based approach enables the heart-related signal to be reconstructed with accuracy by suppressing the motion artifacts. Example applications for the method and corresponding apparatus include training aids (e.g., runners' heart-rate monitors) and hospital patient heart-rate monitors.

WO 2017/019184 A2

METHOD AND APPARATUS FOR REMOVING MOTION ARTIFACTS FROM BIOMEDICAL SIGNALS

RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 62/172,862 filed June 9, 2015 and U.S. Provisional Application No. 62/299,944 filed February 25, 2016.

The entire teachings of the above applications are incorporated herein by reference.

GOVERNMENT SUPPORT

[0002] This invention was made with government support under Grant No. W81XWH-12-1-0541 from the US Army Medical Research and Material Command (USAMRMC). The government has certain rights in the invention.

BACKGROUND

[0003] Heart rate monitors have become widely-used training aids for a variety of sports. Some heart rate monitors use sensors based on photoplethysmography (PPG) technology. The PPG sensors include infrared light-emitting diodes (LEDs) and photodetectors, and offer a simple, reliable, low-cost means of monitoring pulse rate noninvasively, both at rest and during exercise.

SUMMARY

[0004] During exercise and other activities, PPG and other sensors may experience movement, such as shifting position or rotating, relative to a sensing location (*e.g.*, wrist or finger). The movement typically results in an introduction of a motion artifact in an electrical signal produced by the sensor. The motion artifact may be interpreted by a processor as a heart-related signal if not addressed in advance of or as part of the processing in the processor. By properly addressing the motion artifact, an embodiment disclosed herein has improved accuracy in reconstructing the heart-related signal, thereby enabling processes that use the heart-related signal to have better performance.

[0005] Accordingly, a method for reconstructing a heart-related signal output by a biomedical sensor may comprise reconstructing a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal. The reconstructing may be based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and the classification of the movement may be based on (ii) a classification of the movement. The method may further comprise outputting the reconstructed representation of the heart-related signal.

[0006] The motion artifacts may be suppressed in the reconstructed representation of the heart-related signal.

[0007] The time-varying spectral analysis may include pre-processing the heart-related signal to produce a pre-processed heart-related signal. In an event the classification indicates that the movement does not rise to a level causing the motion artifacts, the reconstructed representation may be based on an average value of peak-to-peak intervals in the pre-processed heart-related signal.

[0008] The pre-processing may include filtering the heart-related signal to produce a filtered heart-related signal.

[0009] The pre-processing may further include down-sampling the filtered heart-related signal, the down-sampling being at a sampling rate less than an original sampling rate.

[0010] The time-varying spectral analysis may include computing a first time-frequency spectrum (TFS) of the heart-related signal and computing a second TFS of the motion signal.

[0011] The first TFS computed and the second TFS computed may be 3-dimensional spectra, the first TFS computed and the second TFS computed each including a respective time-varying amplitude or power distribution with respect to time and frequency.

[0012] The first TFS computed may be a first time-varying power spectral density (PSD) and the second TFS computed may be a second time-varying PSD.

[0013] The reconstructed representation may be a current reconstructed representation. Based on the classification indicating that the movement does rise to a level causing the motion artifacts and is a pseudo-periodic movement or a periodic movement, the reconstructing may include determining whether at least one spectral peak is present having a corresponding frequency within a given frequency range at a point in time in the first TFS

computed, the current reconstructed representation being reconstructed for the point in time. Based on a determination that the at least one spectral peak is not present, the current reconstructed representation may be based on a prior reconstructed representation, the prior reconstructed representation associated with a previous point in time in the first TFS computed. The given frequency range may be 0.5 Hz to 3 Hz.

[0014] The reconstructing may include retaining up to a pre-determined number of candidate spectral peaks located at a first point in time in the first TFS computed. The candidate spectral peaks retained may be based on having corresponding frequencies within a given frequency range and highest amplitude or power values relative to other spectral peaks located at the first point in time, the other spectral peaks having respective frequencies within the given frequency range. The reconstructing may further include discarding each of the candidate spectral peaks retained that is associated with a same frequency as a dominant spectral peak located at a second point in time in the second TFS computed. The first point in time and the second point time may have same time values. The given frequency range may be 0.5 Hz to 3 Hz.

[0015] The representation may be a current representation and the reconstructed representation may be a current reconstructed representation. In an event the discarding discards each of the candidate spectral peaks retained, reconstructing the current representation may be based on a prior reconstructed representation, the prior reconstructed representation associated with a previous point in time in the first TFS computed, the previous point in time being an earlier point in time with respect to the first point in time.

[0016] The discarding may be a first discarding, the representation may be a current representation and, in an event the first discarding results in at least one remaining candidate spectral peak retained, reconstructing the current representation may further include second discarding. The second discarding may discard remaining candidate spectral peaks, of the at least one remaining candidate spectral peak retained, based on whether a corresponding frequency of the at least one remaining candidate spectral peak retained is distanced by at least a frequency difference threshold from a prior reconstructed representation's frequency. The prior reconstructed representation associated with a previous point in time in the first TFS computed. The previous point in time may be an earlier point in time with respect to the first point in time.

[0017] Based on each of the at least one remaining candidate spectral peak retained having been discarded by the second discarding, reconstructing the current representation may be based on the prior reconstructed representation. Based on at least one last candidate spectral peak remaining, the at least one last candidate spectral peak remaining not discarded by the second discarding, reconstructing the current representation may be based on a selected candidate spectral peak. The selected candidate spectral peak may be selected from amongst the at least one last candidate spectral peak remaining having a closest corresponding frequency to the prior reconstructed representation's frequency relative to respective frequencies of each of the at least one last candidate spectral peak remaining.

[0018] The dominant spectral peak may have a largest power or amplitude value relative to other peaks located at the second point in time in the second TFS.

[0019] The retaining and the discarding may be based on the classification indicating that the movement is a pseudo-periodic movement or a periodic movement, and determining that at least one spectral peak with a corresponding frequency in the given frequency range is present at the first point in time.

[0020] The time-varying spectral analysis may further include pre-processing the heart-related signal and the motion signal for the computing of the first TFS and the second TFS.

[0021] The pre-processing may include filtering the heart-related signal and the motion signal to produce a filtered heart-related signal and a filtered motion signal, respectively. The pre-processing may further include down-sampling both the filtered heart-related signal and the filtered motion signal, the down-sampling being at a sampling rate less than an original sampling rate.

[0022] The method may further include classifying the classification of the movement by comparing an amount of amplitude modulation in the second TFS computed to an amplitude modulation threshold. The amplitude modulation threshold may be dependent on a type of the motion detector sensor. The classification may indicate whether the movement rises to a level causing the motion artifacts based on a result of the comparing. In an event the result indicates that the movement does rise to the level causing the motion artifacts, classifying the classification of the movement may further include determining whether the movement is either a pseudo-periodic movement or a periodic movement, versus a random movement.

[0023] In determining whether the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement, the method may further include

identifying a first, second, and third frequency associated, respectively, with a first, second, and third spectral peak in the second TFS at a point in time in the second TFS. The first, second, and third peaks may have largest power or amplitude values relative to other peaks in the second TFS at the point in time. The first spectral peak may be a largest spectral peak amongst the first, second, and third spectral peaks.

[0024] In determining whether the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement, the method may further include computing a first ratio of the second frequency identified to the first frequency identified. The method may determine a first comparison result by comparing the first ratio computed to a first ratio value. The method may compute a second ratio of the third frequency identified to the first frequency identified. The method may determine a second comparison result by comparing the second ratio computed to a second ratio value. The classification may further indicate the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement, based on the first comparison result and the second comparison result. The first ratio value may be 2 and the second ratio value may be 3.

[0025] The time-varying signal analysis may include pre-processing the heart-related signal to produce a pre-processed heart-related signal and, in an event the classification of the movement indicates the random movement, the reconstructing may include computing an average value of a number of prior reconstructed representations outputted prior to the reconstructing. The number may be based on a duration of consecutive motion artifacts, detected prior to the reconstructing. The time-varying signal analysis may further include computing a bandpass filter cutoff frequency based on the average value computed, and filtering the pre-processed heart-rate signal by applying the band pass filter computed to produce a filtered, pre-processed heart-related signal. The reconstructed representation may be based on an average peak-to-peak interval value of the filtered, pre-processed heart-rate signal.

[0026] The heart-related signal and the motion signal may be produced, concurrently.

[0027] The method may comprise segmenting the heart-related signal into a plurality of windowed heart-related signal data segments and segmenting the motion signal into a corresponding plurality of windowed motion signal data segments. The method may comprise repeating the reconstructing and the outputting for each windowed heart-related

signal data segment and each corresponding motion signal data segment. The time window may be a value in a range from 2 to 32 seconds.

[0028] The biomedical sensor may be at least one of: a photoplethysmogram (PPG) sensor, piezoelectric sensor, Light Emitting Diode (LED) based sensor, camera sensor, and pulse oximeter sensor, and the motion sensor may be an accelerometer.

[0029] The biomedical sensor and the motion sensor may be co-located.

[0030] The method may further comprise employing the reconstructed representation to determine a heart rate estimate.

[0031] The method may further comprise employing the reconstructed representation to determine an arterial oxygen saturation (SpO2) estimate.

[0032] The method may further comprise employing the reconstructed representation to detect or predict a heart-related ailment. The heart-related ailment may include at least one of a heart rate variability (HRV) condition, atrial fibrillation condition, congestive heart failure condition, and tachycardia condition.

[0033] The reconstructing and the outputting may be performed in real-time with respect to production of the heart-related signal and the motion signal.

[0034] The reconstructing and the outputting may be performed in non-real-time with respect to production of the heart-related signal and the motion signal.

[0035] According to another embodiment, an apparatus for reconstructing a heart-related signal output by a biomedical sensor may comprise a reconstruction unit. The reconstruction unit may be configured to reconstruct a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal, the reconstructing based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of the movement. The apparatus may further comprise an output unit configured to output the reconstructed representation of the heart-related signal.

[0036] Yet another example embodiment may include a non-transitory computer-readable medium having stored thereon a sequence of instructions which, when loaded and executed by a processor, causes the processor to complete methods disclosed herein.

[0037] It should be understood that embodiments disclosed herein can be implemented in the form of a method, apparatus, system, or computer readable medium with program codes embodied thereon.

BRIEF DESCRIPTION OF THE DRAWINGS

[0038] The patent or application file contains at least one drawing executed in color. Copies of this patent or patent application publication with color drawing(s) will be provided by the Office upon request and payment of the necessary fee.

[0039] The foregoing will be apparent from the following more particular description of example embodiments of the invention, as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating embodiments of the present invention.

[0040] FIG. 1 is a block diagram of an example application for which embodiments disclosed herein may be applied.

[0041] FIG. 2 is a flow diagram of an example embodiment of a method for reconstructing a heart-related signal output by a biomedical sensor.

[0042] FIGS. 3A-C are flow diagrams of example embodiments of a method for reconstructing a heart-related signal output by a biomedical sensor.

[0043] FIG. 4 is a block diagram of an example embodiment of a system.

[0044] FIG. 5 is a block diagram of an example embodiment of an apparatus for reconstructing a heart-related signal output by a biomedical sensor.

[0045] FIGS. 6A-6C show Time-Frequency spectra of a recording from a dataset.

[0046] FIG. 7 is a filtered time-frequency spectral plot of a photoplethysmogram (PPG) signal.

[0047] FIGS. 8A-8B show motion artifact detection in a PPG spectrum according to embodiments disclosed herein.

[0048] FIG. 9 shows a comparison of reconstructed heart rate (HR) obtained, according to embodiments disclosed herein, to reference HR obtained from simultaneous electrocardiogram (ECG) recordings.

[0049] FIG. 10A is an example embodiment of PPG signal reconstruction according to embodiments disclosed herein.

[0050] FIG. 10B is a zoomed-in version of FIG. 10A.

[0051] FIGS. 11A-B show comparisons of heart rate variability (HRV) spectra between a reference and a reconstructed HRV time series (*e.g.*, as shown in FIGS. 10A-B) from a motion artifact-contaminated PPG signal for a given dataset.

[0052] FIGS. 12A, 12B, 13A, 13B, 14A, and 14B show the reconstructed HR and corresponding power spectral density (PSD) of a sample-sample windowed HR, according to embodiments disclosed herein, in comparison to a reference HR from an ECG.

[0053] FIGS. 15A-B show an example resultant variable frequency complex demodulation (VFCDM) time-frequency spectrum of recordings from a given subject.

[0054] FIG. 16 shows twelve components corresponding to the Infrared (IR) and Red signal for the given subject.

[0055] FIGS. 17A-C are example spectra plots corresponding to three scenarios.

[0056] FIG. 18A shows a representative filtered time-frequency spectral plot of PPG recording from subject #5.

[0057] FIG. 18B shows tracking of HR based on embodiments disclosed herein.

[0058] FIGS. 19A-B represent comparisons of an estimated 8 second moving average HR from a spectral approach for filtering motion artifacts for oxygen saturation estimation (OxiMA) method to a reference HR, and an HR calculated from a motion-corrupted PPG signal compared to a reference HR from an ECG, respectively.

[0059] FIGS. 20A-C are example plots of data showing less motion-corrupted data that can be used for oxygen saturation estimation.

[0060] FIGS. 21A-C and FIGS. 22A-B show reconstructed arterial oxygen saturation (SpO2) and HR in comparison to the reference HR from ECG recordings for the given subject.

[0061] FIG. 23 is a block diagram of an example internal structure of a computer optionally within an embodiment disclosed herein.

DETAILED DESCRIPTION

[0062] A description of example embodiments of the invention follows.

[0063] Accurate estimation of a heart rate (HR) and changing arterial oxygen saturation (SpO2) from a heart-related signal, such as a photoplethysmogram (PPG) signal, during intense physical activity is a very challenging problem. This is because strenuous and high

intensity exercise can result in severe motion artifacts (MAs) in the heart-related signal, making accurate HR and SpO2 estimation difficult.

[0064] HR monitoring using PPG signals has many advantages compared to using traditional ECG sensors, such as simpler hardware implementation, lower cost, and no need for daily application of electrodes (Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263). Fluctuations of the PPG signal are caused by changes in arterial blood volume associated with each heartbeat, where the magnitude of the fluctuations depends on the amount of blood rushing into the peripheral vascular bed, the optical absorption of the blood, skin, and tissue, and the wavelength used to illuminate the blood. The pulse oximeter signal contains not only the blood oxygen saturation and heart rate (HR) data, but also other vital physiological information (Chon, K.H., S. Dash, and J. Kihwan, Estimation of Respiratory Rate From Photoplethysmogram Data Using Time–Frequency Spectral Estimation. Biomedical Engineering, IEEE Transactions on, 2009. 56(8): p. 2054-2063; Lee, J. and K.H. Chon, Respiratory Rate Extraction Via an Autoregressive Model Using the Optimal Parameter Search Criterion. Annals of Biomedical Engineering, 2010. 38(10): p. 3218-3225; Dash, S., et al., Estimation of Respiratory Rate From ECG, Photoplethysmogram, and Piezoelectric Pulse Transducer Signals: A Comparative Study of Time–Frequency Methods. Biomedical Engineering, IEEE Transactions on, 2010. 57(5): p. 1099-1107; Jinseok, L. and K.H. Chon, Time-Varying Autoregressive Model-Based Multiple Modes Particle Filtering Algorithm for Respiratory Rate Extraction From Pulse Oximeter. Biomedical Engineering, IEEE Transactions on, 2011. 58(3): p. 790-794. The fluctuations of PPG signals contain the influences of arterial, venous, autonomic and respiratory systems on the peripheral circulation. Utilizing a pulse oximeter as a multi-purpose vital sign monitor has clinical appeal, since it is familiar to the clinician and comfortable for the patient (Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263). Even simple knowledge of HR patterns would provide more useful clinical information than just HR and blood oxygenation, especially in situations in which a pulse oximeter is the sole monitor available. One major example of such benefits can be seen in a study by Chong et al. which shows that

accurate detection of atrial fibrillation can be obtained from PPG data (Jo Woon, C., et al., Arrhythmia Discrimination Using a Smart Phone. Biomedical and Health Informatics, IEEE Journal of, 2015. 19(3): p. 815-824). In addition to the acquisition of HR in response to exercise, research has recently focused on obtaining HRV information from wearable sensors including devices that use PPGs (Achten, J. and A.E. Jeukendrup, Heart rate monitoring: applications and limitations. Sports medicine (Auckland, N.Z.), 2003. 33(7): p. 517-538). Increased HRV has been associated with lower mortality rates and is affected by both age and sex (Achten, J. and A.E. Jeukendrup, Heart rate monitoring: applications and limitations. Sports medicine (Auckland, N.Z.), 2003. 33(7): p. 517-538). During graded exercise, the majority of studies show that HRV decreases progressively up to moderate intensities, after which it stabilizes (Laughlin, M.H., Cardiovascular response to exercise. Am J Physiol, 1999. 277(6 Pt 2): p. S244-59). Although there are many promising and attractive features of using pulse oximeters for vital sign monitoring, currently they are mainly used on stationary patients. This is because motion artifacts (MAs) result in unreliable HR and SpO_2 estimation (Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263). Clinicians have cited motion artifacts in pulse oximetry as the most common cause of false alarms, loss of signal, and inaccurate readings (Jubran, A., Pulse oximetry. Crit Care, 1999. 3(2): p. R11-r17). During physical activities, MA contamination in PPG signals seriously interferes with HR estimation. The MAs are mainly caused by ambient light leaking into the gap between the PPG sensor surface and skin surface. Besides, the change in blood flow due to movements is another MA source (Maeda, Y., M. Sekine, and T. Tamura, Relationship between measurement site and motion artifacts in wearable reflected photoplethysmography. J Med Syst, 2011. 35(5): p. 969-76). In practice, MAs are difficult to remove because they do not have a predefined narrow frequency band and their spectrum often overlaps that of the desired signal (Thakor, N.V. and Y.S. Zhu, Applications of adaptive filtering to ECG analysis: noise cancellation and arrhythmia detection. IEEE Trans Biomed Eng, 1991. 38(8): p. 785-94). Consequently, development of methods capable of reconstructing the corrupted signal and removing artifacts is challenging. There are a number of general techniques used for artifact detection and removal. One of the methods used to remove motion artifacts is adaptive filtering (Diniz, P., Adaptive filtering: algorithms and practical implementation.

2008: . Springer Science, Business Media L.L.C., Kalman, R.E., A New Approach to Linear Filtering and Prediction Problems Transactions of the ASME – Journal of Basic Engineering, 1960. Series D(82); Morbidi, F., et al., Application of Kalman Filter to Remove TMS-Induced Artifacts from EEG Recordings. Control Systems Technology, IEEE Transactions on, 2008. 16(6): p. 1360-1366; Seyedtabaii, S.S.a.L., Kalman filter based adaptive reduction of motion artifact from photoplethysmographic signal. World Academy of Science, Engineering and Technology, 2008. 37). An adaptive filter is easy to implement and it also can be used in real-time applications, though the requirement of additional sensors to provide reference inputs is the major drawback of such methods. There are many motion and noise artifact reduction techniques based on the concept of blind source separation (BSS). The aim of BSS is to estimate a set of uncorrupted signals from a set of mixed signals which is assumed to contain both the clean and noisy sources (Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263). Some of the popular BSS techniques are independent component analysis (ICA) (Comon, P., Independent component analysis, A new concept? Signal Processing, 1994. 36(3): p. 287-314), canonical correlation analysis (CCA) (Thompson, B., Canonical Correlation Analysis: Uses and Interpretation. 1984: SAGE Publications), principle component analysis (PCA) (Jolliffe, I.T., Principal Component Analysis. 2 ed. Springer Series in Statistics. 2002: Springer-Verlag New York. 488), and singular spectrum analysis (SSA) (Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263; Elsner, J.B. and A.A. Tsonis, Singular Spectrum Analysis: A New Tool in Time Series Analysis. 1996: Springer). Kim and Yoo (Kim, B.S. and S.K. Yoo, Motion artifact reduction in photoplethysmography using independent component analysis. IEEE Trans Biomed Eng, 2006. 53(3): p. 566-8) suggested using a basic ICA method and block interleaving to remove MA. Krishnan et al. (Krishnan, R., B. Natarajan, and S. Warren, Two-Stage Approach for Detection and Reduction of Motion Artifacts in Photoplethysmographic Data. Biomedical Engineering, IEEE Transactions on, 2010. 57(8): p. 1867-1876) later proposed using frequency-domain-based ICA. However, the key assumption in ICA, namely statistical independence or uncorrelation, does not hold in PPG

signals contaminated by MA (Yao, J. and S. Warren, A short study to assess the potential of independent component analysis for motion artifact separation in wearable pulse oximeter signals. Conf Proc IEEE Eng Med Biol Soc, 2005. 4: p. 3585-8). Salehizadeh et al. (Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263) proposed a motion artifact removal method using SSA. In Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263, SSA is used to decompose the corrupted segment adjacent to the clean segment and the SSA components are chosen in the corrupted segment that have a similar frequency range to that of the adjunct clean components. Although Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263 reports good performance, the method cannot be applied in scenarios where the HR and SpO_2 are varying rapidly due to corruption and movement. Acceleration data are also shown to be helpful to remove MA. For example, Fukushima et al. (Fukushima, H., et al., Estimating heart rate using wrist-type Photoplethysmography and acceleration sensor while running. Conf Proc IEEE Eng Med Biol Soc, 2012. 2012: p. 2901-4) suggested a spectral subtraction technique to remove the spectrum of acceleration data from that of a PPG signal. Acceleration data can be also used to reconstruct the observation model for Kalman filtering (Boreom Lee, J.H., Hyun Jae Baek, Jae Hyuk Shin, Kwang Suk Park and Won Jin Yi, Improved elimination of motion artifacts from a photoplethysmographic signal using a Kalman smoother with simultaneous accelerometry. Physiological Measurement, 2010. 31(12): p. 1585) to remove MA.

[0065] Two noteworthy methods are TROIKA and JOSS (Zhilin, Z., P. Zhouyue, and L. Benyuan, TROIKA: A General Framework for Heart Rate Monitoring Using Wrist-Type Photoplethysmographic Signals During Intensive Physical Exercise. Biomedical Engineering, IEEE Transactions on, 2015. 62(2): p. 522-531; Zhang, Z., Photoplethysmography-Based Heart Rate Monitoring in Physical Activities via Joint Sparse Spectrum Reconstruction. Biomedical Engineering, IEEE Transactions on, 2015. PP(99): p. 1-1) in which sparsity-based spectrum estimation and spectral peak tracking with verification, are used to estimate

and monitor heart rate during intensive physical activity, respectively. Both approaches make use of PPG and accelerometer information to obtain an accurate estimation of heart rate while running on a treadmill. TROIKA has two extra stages of signal decomposition and reconstruction using singular spectrum analysis (SSA) and then applies temporal difference operations on the SSA-reconstructed PPG. SSA components are compared to the accelerometer signals and those components with close frequencies to the accelerometer signals are discarded and the rest are used to reconstruct the signal. In JOSS and TROIKA, spectral peak tracking with verification aims to select the spectral peaks corresponding to HR. JOSS, which has been shown to estimate HR more accurately than TROIKA, is based on the idea that the spectra of PPG signals and simultaneous acceleration signals have some common spectrum structures, and, thus, formulates the spectrum estimation of these signals into a joint sparse signal recovery model using the multiple measurement vector (MMV) model. MMV is used for joint spectrum estimation based on PPG and accelerometer data, which is in contrast to the single measurement vector (SMV) model that was used in TROIKA and was based on only a single PPG signal. Although JOSS has been shown to be much more accurate than previous methods for reconstruction of heart rate from MA-contaminated PPG signals, the main disadvantage of the method is it can merely provide smoothed HR reconstruction estimations. Neither time-domain PPG signal reconstruction nor heart rate variability analysis can be done using JOSS or TROIKA. Temko proposed an approach to HR estimation based on Wiener Filtering and the Phase Vocoder (WFPV) (Temko, A. Estimation of Heart Rate from Photoplethysmography during Physical Exercise using Wiener Filtering and the Phase Vocoder. in IEEE EMBS International Conference on Engineering in Medicine and Biology. 2015. Milan, Italy: IEEE). This work showed that WFPV on average can perform better than JOSS. The main idea of WFPV is to estimate motion artifacts from accelerometer signals and then use a Weiner filter to attenuate the motion components in the PPG signal. Phase vocoder is also applied to overcome the limited resolution of the Fourier transform and to refine the initial dominant frequency estimation.

[0066] According to embodiments disclosed herein, a motion-corrupted heart-related signal, such as a PPG signal, may be reconstructed by employing a method that is based on a time-varying spectral analysis. A method for reconstructing a heart-related signal based on the time-varying spectral analysis for HR estimation may be referred to interchangeably herein as a spectral approach for filtering motion artifacts (SpaMA) method or SpaMA. A

method for reconstructing the heart-related signal based on the time-varying spectral analysis for SpO2 estimation may be referred to interchangeably herein as a spectral approach for filtering motion artifacts for oxygen saturation estimation (OxiMA) method or OxiMA.

[0067] FIG. 1 is a block diagram 100 of an example application for which embodiments disclosed herein may be applied. In FIG. 1, a subject 102 is running on a treadmill 104. The subject 102 is wearing a wrist band 106 that includes a biomedical sensor 108 that produces a heart-related signal 110. The heart-related signal 110 that is produced by the biomedical sensor 108 includes motion artifacts that are signal artifacts produced by movement of the biomedical sensor 108 relative to a sensing location (not shown). The wrist band 106 may be any suitable type of wrist band, for example, the wrist band 106 may be a smart watch.

[0068] The biomedical sensor 108 may be a PPG sensor, or any other suitable biomedical sensor, and the heart-related signal 110 may be a PPG signal, or any other suitable heart-related signal. The sensing location may a skin surface of an area on the subject's wrist where the wrist band 106 is worn, or any other suitable sensing location at which the biomedical sensor 108 senses the heart-related signal 110. For example, the sensing location may be a skin surface on the subject's forehead, and a head band including the biomedical sensor 108 or maintain the biomedical sensor 108 at the sensing location may be used instead of the wrist band 106.

[0069] Physical activity of the subject 102 may cause movement of the wrist band 106, and, thus, movement of the biomedical sensor 108, resulting in a gap between the PPG sensor and the sensing location. Ambient light may leak into the gap inducing spectrum corruption in the PPG signal. This is because the power of the PPG signal is dependent on a depth and reflection of the PPG light from the PPG sensor to the subject's skin. As such, strenuous and high intensity exercise of the subject 102, such as running or any other suitable activity, may result in movement that rises to a level causing motion artifacts in the heart-related signal 110. According to embodiments disclosed herein, the heart-related signal 110 may be reconstructed 112, producing a reconstructed heart-related signal with the motion artifacts suppressed 114. The reconstructed heart-related signal with the motion artifacts suppressed 114 may be used to accurately estimate HR, SpO2, or any other suitable heart-related estimate. As such, the reconstructed heart-related signal may be employed to detect or predict a heart-related ailment. The heart-related ailment may include at least one of a heart

rate variability (HRV) condition, atrial fibrillation condition, congestive heart failure condition, and tachycardia condition.

[0070] It should be understood that the PPG sensor is one example of a biomedical sensor, the PPG signal is one example of a heart-related signal, and that any suitable type of biomedical sensor may be employed to produce any suitable type of a heart-related signal. Further, movement of the biomedical sensor 108 relative to the sensing location may be caused by any suitable source of the movement that causes movement of the biomedical sensor 108 relative to the sensing location. It should also be understood that a subject referred to herein may be any living being, such as a person or an animal, and may be referred to interchangeably herein as a user.

[0071] FIG. 2 is a flow diagram 200 of an example embodiment of a method for reconstructing a heart-related signal output by a biomedical sensor. The example embodiment of the method of FIG. 2 may be applied to either SpaMA or OxiMA and may be applied to other applications that produce a heart-related estimate. The method may start (202) and reconstruct a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal. The reconstructing may be based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of movement (204). The method may output the reconstructed representation of the heart-related signal (206), and the method thereafter ends (208) in the example embodiment.

[0072] The method may comprise segmenting the heart-related signal into a plurality of windowed heart-related signal data segments and the motion signal into a corresponding plurality of windowed motion signal data segments and repeating the reconstructing and the outputting for each windowed heart-related signal data segment and each corresponding motion signal data segment. The time window may be a value in a range from 2 to 32 seconds. For example, the *window[k]* of raw PPG data of FIG. 3A, element 304, disclosed below, and the *window[k]* of raw accelerometer data shown in FIG. 3A, element 310, disclosed below, may each include data from the respective PPG and accelerometer signals that may be collected over a time window from 2 to 32 seconds. According to one embodiment, the time window may be 8 seconds.

[0073] The method may employ the reconstructed representation to determine a heart rate estimate. The method may employ the reconstructed representation to determine an arterial oxygen saturation (SpO2) estimate. The method may employ the reconstructed representation to detect or predict a heart-related ailment. The heart-related ailment may include at least one of a heart rate variability (HRV) condition, atrial fibrillation condition, congestive heart failure condition, and tachycardia condition.

[0074] The heart-related signal and the motion signal may be produced, concurrently.

[0075] According to some embodiments, the biomedical sensor may be at least one of: a photoplethysmogram (PPG) sensor, piezoelectric sensor, Light Emitting Diode (LED) based sensor, camera sensor, and pulse oximeter sensor. The motion sensor may be an accelerometer, or any other suitable device that produces a motion signal. If an accelerometer, the accelerometer may be a 3-axial type accelerometer, or any other suitable type of accelerometer. The biomedical sensor and the motion sensor may be co-located. For example, the wrist band 106 of FIG. 1, disclosed above, may be a smartwatch and the biomedical sensor and motion sensor may be a PPG sensor and an accelerometer, respectively, that are both disposed in the smartwatch or other suitable wearable device.

[0076] FIGS. 3A-C are flow diagrams of example embodiments of a method for reconstructing a heart-related signal output by a biomedical sensor based on embodiments disclosed in Tables 1-3, disclosed below. The method may be either a SpaMA or OxiMA method.

Table 1. Stages 1 and 2

Stage 1. Time-Varying Spectral analysis (*see* FIG. 3A)

1.1. Filter the PPG and Accelerometer signal with cutoff frequency [1, 50]/Fs/2 Hz.
1.2. Down sample the PPG and Accelerometer signal to ¼ of original sampling rate (Fs).
1.3. Compute the time frequency spectrum of both PPG and Accelerometers [0-10 Hz].

Stage 2. Movement Classification (*see* FIG. 3A)

2.1. Check each accelerometer (X, Y or Z) amplitude modulation at each window and compare to a pre-defined motion amplitude threshold. (The threshold varies depending on the type of accelerometer sensor).

Signal is clean if $AM[Acc_{x\ or\ y\ or\ z}(k)] < Motion\_Threshold$ and the signal is corrupted by motion otherwise. If the signal is clean calculate the Heart Rate from peak-to-peak intervals, otherwise go to step 2.2.

2.2. If the signal is corrupted check if the movement is pseudo-periodic (e.g. during walk, jog,

run) or non-periodic (e.g. any random movements)

The assumption is when movement is pseudo-periodic the accelerometer data should comprised of a fundamental frequency component and harmonics of the fundamental frequency at its double and third frequency band. This means the ratio of the first harmonic to the fundamental frequency should be almost 2 and the second harmonic to the fundamental should be around 3.

2.2.1. Extract the fundamental frequency component, the 1st and 2nd harmonics from (*e.g.*,VFCDM) time-frequency spectrum of accelerometers. The first three highest peaks in spectral array should represent the fundamental, 1st and 2nd harmonics as long as the movement is pseudo-periodic.

2.2.2. Calculate the ratio of the extracted 1st and 2nd fundamental frequency to the extracted fundamental frequency. If the ratios are close to 2 and 3, this indicates that the movement is most likely pseudo-periodic otherwise it is non-periodic.

2.2.3. If the movement is pseudo-periodic do the Stages 3-5 (*See* Table 2 and FIG. 3B), otherwise go to Stage 6 (*See* Table 3 and FIG. 3C).

Table 2. Stages 3-5

Stage 3. Spectral Filtering (*see* FIG. 3B)

3.1. Assume HR to be in the frequency range of [0.5Hz – 3Hz], this accounts for both low and high heart rates.
3.2. The first highest three peaks and their corresponding frequencies in the PPG filtered spectrum are assumed to have HR information.
3.3. Only the largest frequency peak (that represents the fundamental frequency of movement) of the accelerometers' spectra is used for motion artifact detection in Stage 4.

Stage 4. Motion Artifact Detection (*see* FIG. 3B)

4.1. Compare the frequencies of the three peaks in the PPG spectrum with the frequency of the largest peak in the accelerometers' spectra. If the first or second largest peaks in the PPG spectrum are similar to that of the accelerometers' peaks, then motion artifact is present in the PPG.
4.2. If motion artifact is detected from 3.1, then the corresponding frequency peak (usually the first or second largest peak) in the PPG spectrum should be discarded.

Stage 5. Heart Rate Tracking and Extraction from PPG Spectrum (*see* FIG. 3B)

Case (1): From 3.1- if the spectrum is corrupted by movement and only the first largest peak is corrupted, then the HR frequency should be the frequency of the second peak in the spectrum.
Case (2): From 3.1- if the spectrum is corrupted by movement and both the first and second largest peaks have similar frequencies to those of the accelerometers' peaks, then the HR

frequency should be the frequency of the third peak in the spectrum.
Case (3): Due to a gap between the pulse oximeter and a subject's skin, the HR frequency cannot be extracted from the spectrum and in this case the previous HR frequency is used or for offline implementation a cubic spline interpolation can be applied to fill in the missing HR information.

Table 3. Stage 6

Stage 6. Adaptive Bandpass Filtering (non-periodic movements) (*see* FIG. 3C)

When the movement is random and non-periodic it is difficult or not possible to identify HR trace from time-frequency spectrum (for example if stage 5 is not applicable). In this case which may happen more often, a new procedure is adopted that is called adaptive bandpass filtering. The assumption here is that HR does not deviate more than 10 bpm from the average of previous m HR values within 2 seconds.

6.1. Set averaging window length to m (e.g. m=5) and calculate the average of recent m estimated HR values.

$$HR_{mavg} = \frac{1}{m}\sum_{j=1}^{m} HR(k-j)$$

Where k is the current window. The window length m=5 should only be used for up to 10 seconds of consecutive motion artifact corrupted datapoints. If motion corrupted data last more than 10 seconds, m should be increased to more than 5.

6.2. Take the most recent estimated HR value and calculate bandpass filter cutoff frequency.

$$F_{CutOff} = [HR_{mavg} - 10, HR_{mavg} + 10\,]/60/Fs/2$$

Design a bandpass filter of order 4 with cutoff frequency (F_{CutOff}). Apply the filter on the PPG segment.
6.3. Calculate HR from peak-to-peak intervals of the filtered data segment obtained from 6.2. Take the average of the instantaneous HR as estimated HR value at window k.

[0077] FIG. 3A is a flow diagram (300) of an example embodiment of a method for a time-varying spectral analysis and movement classification, as disclosed in Stage 1 (time-varying spectral analysis) and Stage 2 (movement classification), respectively, in Table 1, for reconstructing the representation. The method may start (302) and the time-varying spectral analysis may be employed on a first windowed segment *window[k]* of raw PPG data (304) and a second windowed segment *window [k]* of raw accelerometer (ACC) data (310). The raw PPG data (304) and the raw ACC data (310) may be extracted from a heart-related signal that is a PPG signal and a motion signal that is an accelerometer signal, respectively.

[0078] As disclosed in Stage 1 of Table 1, the time-varying spectral analysis of FIG. 3A may include pre-processing the heart-related signal (306) to produce a pre-processed heart-related signal. The pre-processing (306) may include filtering the heart-related signal to produce a filtered heart-related signal. The pre-processing (306) may further include down-sampling the filtered heart-related signal, the down-sampling being at a sampling rate less than an original sampling rate, to produce a down-sampled, filtered heart-rate signal. The time-varying spectral analysis may further include pre-processing the motion signal (312) to produce a pre-processed motion signal. The pre-processing (312) may include filtering the motion signal to produce a filtered motion signal. The pre-processing (312) may further include down-sampling the filtered motion signal to produce a down-sampled, filtered motion signal, the down-sampling being at a sampling rate less than an original sampling rate.

[0079] As further disclosed in Stage 1 of Table 1, the time-varying spectral analysis of FIG. 3A may include computing a first time-frequency spectrum (TFS) to produce a first TFS (308) of the down-sampled, filtered heart-related signal and computing a second TFS to produce a second TFS (314) of the down-sampled, filtered motion signal. According to some embodiments, filtering and down-sampling of the heart-related signal and motion signal for computing the first TFS (308) and the second TFS (314), respectively, may be optional. The first TFS (308) (also referred to interchangeably herein as the first TFS computed) and the second TFS (314) (also referred to interchangeably herein as the second TFS computed) may be 3-dimensional spectra, the first TFS computed and the second TFS computed each including a respective time-varying amplitude or power distribution with respect to time and frequency.

[0080] For example, the first TFS computed may be a first time-varying power spectral density (PSD) and the second TFS computed may be a second time-varying PSD. A time-frequency technique, such as a variable frequency complex demodulation (VFCDM), disclosed in U.S. Patent No. 8,388,543 B2, incorporated herein in its entirety by reference, may be used for computing the first TFS (308), that is, a TFS of the PPG signal, and the second TFS (314), that is, a TFS of the accelerometer signal. However, it should be understood that any suitable time-frequency technique may be used, such as a smoothed pseudo wigner-ville method, or a wavelet based method.

[0081] As disclosed in Stage 2 of Table 1, classifying the classification of the movement (316) in FIG. 3A may include comparing an amount of amplitude modulation in the second

TFS (314) computed to an amplitude modulation threshold. The amplitude modulation threshold may be dependent on a type of the motion detector sensor, such as a type of the accelerometer. The classification of the movement may indicate whether the movement rises to a level causing motion artifacts in the heart-related signal, that is, the PPG signal, based on a result of the comparing, as disclosed in Stage 2 of Table 1.

[0082] In an event the movement classification (316) of FIG. 3A indicates that the movement does not rise to a level causing the motion artifacts (322), a peak-peak interval (PP) of the filtered heart-related signal, or alternatively, the filtered, down-sampled heart-rate signal, may be computed (318) and the reconstructed representation *HR(k)* may be based on an average value of peak-to-peak intervals (320) in the pre-processed heart-related signal, and the method thereafter ends (325) in the example embodiment.

[0083] In an event the movement classification (316) indicates that the movement does rise to the level causing the motion artifacts (323), classifying the classification of the movement may further include determining (324) whether the movement is either a pseudo-periodic movement or a periodic movement, versus a random movement, as disclosed in Stage 2 of Table 1.

[0084] With reference to Stage 2 of Table 1, in determining whether the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement, the method may further include identifying a first, second, and third frequency associated, respectively, with a first, second, and third spectral peak in the second TFS at a point in time in the second TFS. The first, second, and third peaks may have largest power or amplitude values relative to other peaks in the second TFS at the point in time. The first spectral peak may be a largest spectral peak amongst the first, second, and third spectral peaks.

[0085] In determining whether the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement, the method may compute a first ratio of the second frequency identified to the first frequency identified. The method may determine a first comparison result by comparing the first ratio computed to a first ratio value. The method may compute a second ratio of the third frequency identified to the first frequency identified and determine a second comparison result by comparing the second ratio computed to a second ratio value. The classification may further indicate the movement is either the pseudo-periodic movement or the periodic movement, versus the random

movement, based on the first comparison result and the second comparison result. The first ratio value may be 2 and the second ratio value may be 3. The classification of the movement may be periodic if the first ratio and the second ratio are exactly 2 and 3, respectively, while the classification of the movement may be pseudo-periodic if the first ratio and the second ratio are approximately 2 and 3, respectively, within a pre-determined level of accuracy.

[0086] In an event the classification of the movement is periodic or pseudo-periodic, the method of FIG. 3A may continue with the method of FIG. 3B, disclosed below. In an event the classification of the movement is random, the method of FIG. 3A continues to the method of FIG. 3C, disclosed below.

[0087] FIG. 3B is a flow diagram (330) of an example embodiment of a method for spectral filtering, motion artifact detection, and heart rate tracking and extraction, as disclosed in Stages 3, 4, and 5, respectively, of Table 2, for reconstructing the representation. The reconstructed representation may be referred to herein as a current reconstructed representation or *HR(k)*. As disclosed above with regard to FIG. 3A, in an event the classification of the movement (316) is periodic or pseudo-periodic, the method of FIG. 3A may continue with the method of FIG. 3B.

[0088] The method of FIG. 3B may start (331) and retain (332) up to a pre-determined number N of candidate spectral peaks located at a first point in time in the first TFS, that is, the first TFS from FIG. 3A. It should be understood that the method of FIG. 3B may be performed for each point in time of the first TFS and the second TFS. According to one embodiment, the pre-determined number N may be 3. The candidate spectral peaks retained may be based on having corresponding frequencies within a given frequency range. The candidate spectral peaks may be N peaks in the given frequency range that have highest amplitude or power values relative to other spectral peaks, that is, the first N highest peaks. It should be understood that the other spectral peaks have respective frequencies also within the given frequency range and are peaks located at the first point in time in the first TFS. The given frequency range may be 0.5 Hz to 3 Hz. As such, the N first highest peak in the range 0.5 Hz to 3 Hz in the first TFS may be retained at the first time point. Since no peaks in the given frequency range may be present at the first time point, the method may determine (336) whether at least one spectral peak is present.

[0089] Based on the determination (336) that no peak is present, the current reconstructed representation *HR(k)* may be based on a prior reconstructed representation *HR(k-1)* (340), the prior reconstructed representation *HR(k-1)* associated with a previous point in time, such as the previous window *k-1*, in the first TFS computed, and the method thereafter ends (354) in the example embodiment.

[0090] Based on a determination (336) that the at least one spectral peak is present, the method may discard (338) each of the candidate spectral peaks retained, that is, each peak of the *N* first highest peaks determined at (332), if the peak is associated with a same frequency as a dominant spectral peak located at a second point in time in the second TFS (314) computed as disclosed above with regard to FIG. 3A. The first point in time and the second point time may have same time values. The dominant spectral peak may have a largest power or amplitude value relative to other peaks located at the second point in time in the second TFS. The method may determine (342) whether any peaks are retained after the discarding (338). The discarding (338) may be referred to herein as a first discarding.

[0091] In an event the discarding (338) discards each of the candidate spectral peaks retained, reconstructing the current representation *HR(k)* may be based on the prior reconstructed representation, *HR(k-1)* (340), and the method thereafter ends (354) in the example embodiment.

[0092] In an event the first discarding (338) results in at least one remaining candidate spectral peak retained, reconstructing the current representation may further include second discarding (348). The second discarding (348) may discard remaining candidate spectral peaks, of the at least one remaining candidate spectral peak retained, based on whether a corresponding frequency of the at least one remaining candidate spectral peak retained is distanced (346) by at least a frequency difference threshold, such as 10bpm, from a prior reconstructed representation's frequency, that is, a frequency associated with, for example, *HR(k-1)*.

[0093] Based on each at least one remaining candidate spectral peak retained having been discarded by the second discarding (348), reconstructing the current representation may be based on the prior reconstructed representation *HR(k-1)* (350), and the method thereafter ends (354) in the example embodiment.

[0094] Based on at least one last candidate spectral peak remaining from the second discarding (348), reconstructing the current representation may be based on a selected

candidate spectral peak (352). The selected candidate spectral peak may be selected from amongst the at least one last candidate spectral peak remaining having a closest corresponding frequency to the prior reconstructed representation's frequency relative to respective frequencies of each of the at least one last candidate spectral peak remaining, and the method thereafter ends (354) in the example embodiment.

[0095] As disclosed above with regard to FIG. 3A, in an event the classification of the movement (316) is random, the method of FIG. 3A may continue with the method of FIG. 3C.

[0096] FIG. 3C is a flow diagram (330) of an example embodiment of a method for adaptive bandpass filtering of non-periodic movements, that is, random movements, for reconstructing the representation, as disclosed in Stage 6 of Table 3. The method of FIG. 3C may start (362) and compute an average value of a number *m* of prior reconstructed representations outputted prior to the reconstructing (362). The number *m* may be based on a duration of consecutive motion artifacts, detected prior to the reconstructing of the representation *HR*(*k*). For example, if motion artifacts were detected for windows *k-1*, *k-2*, and *k-3*, *m* may be understood to be 3.

[0097] The method may compute a bandpass filter cutoff frequency (366). The cutoff frequency F_c may be based on the average value computed HR_{mavg}. The method may filter the pre-processed heart-rate signal (306), disclosed in FIG. 3A, above, by applying the band pass filter computed (368) to produce a filtered, pre-processed heart-related signal. The reconstructed representation *HR(k)* may be based on an average peak-to-peak interval value (372) of the filtered, pre-processed heart-rate signal, and the method thereafter ends (374) in the example embodiment.

[0098] FIG. 4 is a block diagram of an example embodiment of a system (400). The system includes an apparatus 420 for reconstructing a heart-related signal 410c output by a biomedical sensor (not shown). The apparatus 420 includes a reconstruction unit 416 and an output unit 418. The reconstruction unit 416 may be configured to produce a reconstructed representation of the heart-related signal 414c. The reconstructing may be based on (i) a time-varying spectral analysis of the heart-related signal 410c and a motion signal 411c, the motion signal 411c output by a motion sensor (not shown) and representative of motion artifacts in the heart-related signal 410c, the motion artifacts being signal artifacts produced by movement of the biomedical sensor (not shown) relative to a sensing location (not shown),

and (ii) a classification of the movement. The output unit 418 may be configured to output the reconstructed representation of heart-related signal 414c.

[0099] The apparatus 420 may be communicatively coupled to a network 401 to receive the heart related signal 410c and the motion signal 411c. The network may be a wireless network or any other suitable network. The reconstructing and the outputting may be performed in near real-time with respect to production of the heart-related signal 410c and the motion signal 411c. Alternatively, the apparatus may be coupled to a database (not shown) storing representations of the heart related signal 410c and the motion signal 411c, and the reconstructing and the outputting may be performed in non-real-time with respect to production of the heart-related signal 410c and the motion signal 414c.

[00100] The heart-related signal 410c may include raw heart-related signal data that includes the raw heart-related signal data 410a and the raw heart-related signal data 410b produced by biometric sensors (not shown) that sense the heart-related signal data 410a and the raw heart-related signal data 410b from sensing locations (not shown) on a first user 406a and a second user 406b, respectively. The motion signal 411c may include raw motion signal data that includes the raw motion signal data 411a and the raw motion signal data 411b from motion sensors (not shown). The raw motion signal data 411a and the raw motion signal data 411b may represent motion artifacts in the heart-related signal data 410a and the raw heart-related signal data 410b, respectively.

[00101] It should be understood that the raw heart-related signal data 410a-b and the raw motion signal data 411a-b may be sent to the apparatus 420 in any suitable way. For example, the raw heart-related signal data 410a and the raw motion signal data 411a may be sent in a payload of a packet; alternatively the raw heart-related signal data 410a and the raw motion signal data 411a may be sent in payloads of different packets. Similarly, the raw heart-related signal data 410b and the raw motion signal data 411b may be sent in a payload of a packet; alternatively, the raw heart-related signal data 410b and the raw motion signal data 411b may be sent in payloads of different packets.

[00102] The user 406a may be at a gym where the user 406a is exercising, and such physical activity by the user 406a may cause motion artifacts in the raw heart-related signal data 410a. The user 406b may be in a different location, such as a hospital. The user 406b may perform movements out of boredom, such wrist shaking, causing motion artifacts in the raw heart-related signal data 410b. As such, the corresponding motion artifacts may be

suppressed in the reconstructed representations 414a and 414b of the heart-related signals 414a and 414b, respectively, according to embodiments disclosed herein. The reconstructed representations 414a and 414b, or information derived therefrom, may sent to biometric devices or other devices communicatively coupled to the network 401 the user 406a and 406 may have access to such device, respectively. Alternatively, the reconstructed representations 414a and 414b, or information derived therefrom, may sent in any suitable manner to another device communicatively coupled to the network 401 such that the reconstructed representations 414a and 414b, or information derived therefrom, may be accessible to a third party, such as doctor, or any other suitable party.

[00103] FIG. 5 is a block diagram 500 of an example embodiment of an apparatus (520) for reconstructing a heart-related signal 510 output by a biomedical sensor 508. The apparatus 520 includes a reconstruction unit 516 and an output unit 518. The reconstruction unit 516 may be configured to produce a reconstructed representation of the heart-related signal 514. The reconstructing based on (i) a time-varying spectral analysis of the heart-related signal 510 and a motion signal 511, the motion signal 511 output by a motion sensor 509 and representative of motion artifacts in the heart-related signal 510. The motion artifacts may be signal artifacts produced by movement of the biomedical sensor 508 relative to a sensing location (not shown), and (ii) a classification of the movement.

[00104] The output unit 518 may be configured to output the reconstructed representation of the heart-related signal 514. The apparatus 520 may include the biomedical sensor 508 and the motion sensor 509. The reconstructing and the outputting may be performed in real-time with respect to production of the heart-related signal 510 and the motion signal 511.

[00105] The apparatus 520 may be a wearable device, such as a smartwatch, or any other suitable device, such as a wearable personal biometric monitoring device. The apparatus 520 may have a user interface (not shown) to present the reconstructed representation of the heart-related signal 514 or information derived therefrom, such as a characteristic, notification, alarm, or any other suitable information. The reconstructed representation of heart-related signal 514 or the information derived therefrom may be presented to a user via a user interface that may be a visual or audio based user interface.

[00106] According to one embodiment, the apparatus 520 may include a heart rate unit (not shown) configured to employ the reconstructed representation of the heart-related signal 514 to determine a heart rate estimate. According to another embodiment, the apparatus 520

may include an arterial oxygen saturation (SpO2) unit (not shown) configured to employ the reconstructed representation of the heart-related signal 514 to determine a SpO2 estimate. According to yet another embodiment, the apparatus may include an ailment unit (not shown) configured to employ the reconstructed representation of the heart-related signal 514 to detect or predict a heart-related ailment, the heart-related ailment including at least one of a heart rate variability (HRV) condition, an atrial fibrillation condition, a congestive heart failure condition, and a tachycardia condition. It should be understand that any combination of the heart rate unit, SpO2 unit, and ailment unit may be included in the apparatus 520 in combination with any other units disclosed herein.

[00107] SpaMA Results

[00108] According to embodiments disclosed herein, HR reconstruction and PPG signal reconstruction may be based on a time-varying spectral analysis. As disclosed above with reference to FIGS. 3A-F, embodiments disclosed herein may be based on power spectral densities (PSDs) of both PPG and accelerometer signals for each time shift of a corresponding windowed data segment of the respective signal. According to embodiments disclosed herein, by comparing time-varying spectra of the PPG and accelerometer data, those frequency peaks resulting from motion artifacts may be suppressed from the PPG spectrum.

[00109] According to some embodiments, the method may be comprised of six stages, such as the six stages disclosed above in reference to FIGS. 3A-F. According to another embodiment the method may have five distinct stages: (1) time-varying power spectral density (PSD) calculation, (2) spectral filtering, (3) motion artifact detection, (4) HR reconstruction and (5) signal reconstruction. According to embodiments disclosed herein, the method may include computing a window-segmented power spectral density of both PPG and accelerometer signals in real-time to scale each estimate of the PSD by the equivalent noise bandwidth of the window (Stoica, P. and R.L. Moses, Introduction to Spectral Analysis. 1997: Prentice Hall).

[00110] The simplest way to approach the PSD calculation may be to employ a periodogram. However, a periodogram has drawbacks in that it is an inconsistent spectrum estimator, has high variance, and has leakage effects (Stoica, P. and R.L. Moses, Introduction to Spectral Analysis. 1997: Prentice Hall). Thus, a dominant spectral peak can lead to an estimated spectrum that contains power in frequency bands where there should be no power.

However, both problems can be solved by down-sampling the raw signal, as disclosed above with reference to FIGS. 3A-F, and then using a sufficiently small frequency step by setting a large number of frequency points. Thus, embodiments disclosed herein may resample the signal from the original sampling frequency to, for example 1/4 of it, that is, down-sample the signal, and then apply a periodogram method with frequency resolution of 0.001.

[00111] Embodiments disclosed herein may limit the spectrum to the heart rate frequency range of [0.5Hz – 3 Hz], as disclosed above with reference to FIGS. 3A-F, and take the frequency and power information of the first three peaks in the PSD at each window and signal segment. Embodiments disclosed herein may be based on an understanding that the heart rate component in a typical clean (motion free) PPG signal is always the dominant frequency component in the time-varying power spectrum, thus, the highest peak of the spectrum corresponds to the HR frequency. Thus, when movement happens the dominant component can be replaced by movement components which shift the HR to the second or third peak in the spectrum. As such, embodiments disclosed herein may compare the first N peaks, such as 3 peaks, disclosed above, and corresponding frequencies of the PPG spectrum to the first peak and frequency of the accelerometers' spectra at each window and choose the frequency components (out of three) that are different from the accelerometers' frequency.

[00112] Embodiments disclosed herein may be further based on an understanding that there is coherence between a spectral peak in the PPG and the accelerometers' spectra that signifies a motion noise artifact in the PPG signal and that peak should be discarded in the HR reconstruction. After discarding these movement peaks in the spectrum, the next highest peak that is closest to the estimated HR of the previous window may be chosen at each window. By reconstructing the HR frequency at each window, simultaneously, the PPG signal may be reconstructed by using the power, frequency and phase of the signal that corresponds to the HR frequency. That is, the time-domain signals may be reconstructed from the time-frequency domain.

[00113] The SpaMA method was applied to three different datasets and 4 types of activities. The three different datasets included: 1) training datasets from the 2015 IEEE Signal Processing Cup Database recorded from 12 subjects while performing treadmill exercise from 1 km/h to 15 km/h; 2) test datasets from the 2015 IEEE Signal Processing Cup Database recorded from 11 subjects while performing forearm and upper arm exercise; and 3) Chon Lab dataset including 10 min recordings from 10 subjects during treadmill exercise.

[00114] Electrocardiogram (ECG) signals from all three datasets provided the reference HRs which were used to determine the accuracy of the SpaMA method. The performance of the SpaMA method was calculated by computing the mean absolute error between the estimated HR from the PPG and the reference HR from the ECG. The average estimation errors using the SpaMA method on the first, second and third datasets are 0.89, 1.93 and 1.38 beats/min respectively, while the overall error on all 33 subjects is 1.86 beats/min and the performance on only treadmill experiment datasets (22 subjects) is 1.11 beats/min. Moreover, it was found that dynamics of heart rate variability (HRV) can be accurately captured using the SpaMA method where the mean Pearson's correlation coefficient was found to be 0.98 between the power spectral densities of the reference and the reconstructed heart rate time series. These results show that the SpaMA method has a potential for PPG-based HR monitoring in wearable devices for fitness tracking and health monitoring during intense physical activities.

[00115] Embodiments disclosed herein not only provide PPG signal and HR reconstruction but also the potential to do heart rate variability analysis on the results. As disclosed below, embodiments disclosed herein can outperform the JOSS technique in heart rate estimation by providing less error to the reference, which yields higher accuracy.

[00116] Embodiments disclosed herein were evaluated on three different datasets. The first two datasets were provided for the IEEE Signal Processing Cup and are publically available. The three datasets are: 1.) 12 PPG training datasets (running on treadmill) from an IEEE signal processing competition (Available from: http://www.signalprocessingsociety.org/spcup2015/index.html) which was initially used in (Zhilin, Z., P. Zhouyue, and L. Benyuan, TROIKA: A General Framework for Heart Rate Monitoring Using Wrist-Type Photoplethysmographic Signals During Intensive Physical Exercise. Biomedical Engineering, IEEE Transactions on, 2015. 62(2): p. 522-531; Zhang, Z., Photoplethysmography-Based Heart Rate Monitoring in Physical Activities via Joint Sparse Spectrum Reconstruction. Biomedical Engineering, IEEE Transactions on, 2015. PP(99): p. 1-1, 2.) 11 PPG test datasets (e.g., arm exercise) from the IEEE signal processing competition and 3.) 10 PPG recordings from the Chon lab (running on treadmill).

[00117] (1) IEEE Signal Processing Competition Training Dataset: A single-channel PPG signal, a three-axis acceleration signal, and an ECG signal simultaneously recorded from 12 Asian male subjects ranging in age from 18 to 35. For each subject, the PPG signal was

recorded from their wrist using a pulse oximeter (PO) with green LED (wavelength: 609 nm). The acceleration signal was also recorded from each subject's wrist using a three-axis accelerometer. Both the PO and the accelerometer were embedded in a wristband, which was comfortably worn. The ECG signal was recorded from the chest and it is used as the reference heart rate. All signals were sampled at 125 Hz.

[00118] (2) IEEE Signal Processing Competition Test Dataset: The dataset consists of 11 five minute recordings which were collected from 19 to 58 year old subjects performing intensive arm movements (e.g. boxing). For each subject, PPG signals were recorded with a sensing location at the wrist using a pulse oximeter with green LEDs (wavelength: 515nm). The acceleration signal was also recorded from at the sensing location at the wrist using a three-axis accelerometer. Both the PO and the accelerometer were embedded in a wristband. An ECG signal was recorded simultaneously from each subject's chest using wet ECG sensors. All signals were sampled at 125 Hz and sent to a nearby computer via Bluetooth.

[00119] (3) Chon Lab Dataset: This dataset was recorded in the Chon Lab from 10 healthy subjects (9 male/1 female), with ages ranging from 26 to 55. For each subject, the PPG signal was recorded from their forehead using a PO with red and infrared LED (wavelength: 660 and 940 nm). The acceleration signal was also recorded from each subject's forehead using a three-axis accelerometer. Both the pulse oximeter and the accelerometer were embedded in a headband and the signals were sampled at 80 Hz. The ECG signal was recorded as a reference from the chest using ECG sensors, sampled at 400Hz. During data recording, the subjects walked, jogged and ran on a treadmill with speeds of 3, 5 and 7 mph, respectively, for 9 min. At the end, all experimental subjects were asked to perform random arbitrary movements for 1 min.

[00120] For all three datasets, the data was down-sampled to 20 Hz since the estimation of heart rate is carried out in the frequency domain and this sampling rate is sufficiently high to obtain even heart rates that are as high as 240 beats/min or 4 Hz. Moreover, this down-sampling enables a focus on heart rates in the lower frequencies rather than in the physiologically irrelevant higher frequency ranges. Further details of this study's databases are given in Table 4, below. Four types of activities were involved:

- Type (1): activity involved walking or running on a treadmill for intervals of 0.5 min-1 min-1 min-1 min-0.5 min with speeds of 1-2 km/h, 6-8 km/h, 12-15 km/h, 6-

8 km/h, 12-15 km/h, 1-2 km/h, respectively. The subjects were asked to purposely move the hand with the wristband to generate motion artifacts.

- Type (2): activity included various forearm and upper arm exercise which are common arm motions (*e.g.*, shaking hands, stretching, pushing objects, running, jumping, and push-ups).
- Type (3): activity consisted of intensive forearm and upper arm movements (*e.g.*, boxing).
- Type (4): activity involved 1 min rest, 1 min walking (3 mph), 1 min rest, 2 min jogging (5 mph), 1 min rest, 2 min running (7 mph), 1 min rest, 1 min arbitrary movement. The ECG-based reference HR was recorded in order to assess the performance of the methods under test.

[00121] In summary, the first dataset includes only Type (1) activities, the second dataset includes both Type (1) and (2) activities, and the third dataset includes only Type (4) activities.

Table 4. PPG Datasets and Experiments Settings

Subject	Dataset	Activity Type	Pulse Oximeter Type	Subject's Age/Sex
1	1 (IEEE Cup)	Type (1)	Wrist: green LED (wavelength: 609nm)	18-38 y (All Male)
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13	2 (IEEE Cup)	Type (2)	Wrist: green LED (wavelength: 515nm)	19-58 y (9 Male, 1 Female)
14				
15				
16		Type (3)		
17				
18				
19				
20		Type (2)		
21		Type (3)		
22				
23		Type (2)		
24	3 (Chon Lab)	Type (4)	Forehead: Red and Infrared LED (wavelength: 660 nm, 940nm)	26-55 y (9 Male, 1 Female)
25				
26				
27				
28				
29				
30				
31				
32				
33				

[00122] An example embodiment for reconstructing a heart-related signal during intensive movements is disclose by the HR monitoring method presented below in Table 5. Details of each stage are described in subsections *i* to *v*.

Table 5. HR and PPG signal reconstruction method

Stage 1. Time-Varying Spectral analysis

1.1. Down sample the PPG and Accelerometer signal to 20 Hz.
1.2. Compute the power spectral density of both PPG and Accelerometers [0-10 Hz].

Stage 2. Spectral Filtering

2.1. Assume HR to be in the frequency range of [0.5Hz – 3Hz], this accounts for both low and high heart rates.
2.2. The first highest three peaks and their corresponding frequencies in the PPG filtered spectrum are assumed to have HR information.
2.3. Only the largest frequency peak of the accelerometers' spectra is used for MA detection in stage 3.

Stage 3. Motion Artifact Detection

3.1. Compare the frequencies of the three peaks in the PPG spectrum with the frequency of the largest peak in the accelerometers' spectra. If the first or second largest peaks in the PPG spectrum are similar to that of the accelerometers' peaks, then motion artifact is present in the PPG.
3.2. If motion artifact is detected from 3.1, then the corresponding frequency peak (usually the first or second largest peak) in the PPG spectrum should be discarded.

Stage 4. Heart Rate Tracking and Extraction from PPG Spectrum

Case (1): From 3.1- if the spectrum is corrupted by movement and only the first largest peak is corrupted, then the HR frequency should be the frequency of the second peak in the spectrum.
Case (2): From 3.1- if the spectrum is corrupted by movement and both the first and second largest peaks have similar frequencies to those of the accelerometers' peaks, then the HR frequency should be the frequency of the third peak in the spectrum.
Case (3): Due to a gap between the pulse oximeter and a subject's skin, the HR frequency cannot be extracted from the spectrum and in this case the previous HR frequency is used or for offline implementation a cubic spline interpolation can be applied to fill in the missing HR information.

Stage 5. PPG Signal Reconstruction

5.1. The PPG signal is reconstructed by using the amplitude, frequency and phase information corresponding to the HR components (extracted in stage 4) that are calculated from the spectrum at each window.

- Heart Rate Variability Analysis

By using a sample-by-sample windowing strategy, HR can be extracted, from which dynamics of heart rate variability analysis can be obtained on the motion artifact-removed reconstructed HR time series.

[00123] i. Time-Varying Spectral Analysis of PPG and Accelerometer Data

[00124] Embodiments disclosed herein may produce a time-varying spectrum by taking a T-sec window of the signal and computing the power spectral density (PSD) of the segment and then sliding the window through the whole dataset which yields a time-frequency matrix in which each array represents the power of the signal corresponding to a specific frequency and sliding time-step (shift) of S-sec. The sliding process and frequency step specify the resolution and dimension of the time-frequency matrix. According to embodiments disclosed herein, two different sliding window approaches may be used, depending on the application. For estimating either heart rates or heart rate variability, data may be shifted sample-by-sample with no overlap for the entire dataset. Such an approach enables capturing beat-to-beat dynamics of HRV which requires sample-to-sample estimation of PSD. Since some data is down-sampled data to 20 Hz in some of the database, as disclosed above, each data point may be shifted by 0.05 seconds. For estimating only the heart rates, the shift may be a data segment-by-segment shift rather than a sample-by-sample shift. This coarse-grain windowing approach has less computational cost and it can provide good tracking of heart rates, but does not apply well to HRV.

[00125] As such, according to some embodiments, a window segment length T may be set to 8 seconds and shifted by 2 seconds. The 8 second data segment and a shift of 2 seconds was chosen to compare results according to embodiments disclosed herein to other methods (TROIKA, JOSS and WFPV) which have used this chosen data segment length and time shift (Zhilin, Z., P. Zhouyue, and L. Benyuan, TROIKA: A General Framework for Heart Rate Monitoring Using Wrist-Type Photoplethysmographic Signals During Intensive Physical Exercise. Biomedical Engineering, IEEE Transactions on, 2015. 62(2): p. 522-531; Zhang, Z., Photoplethysmography-Based Heart Rate Monitoring in Physical Activities via Joint Sparse Spectrum Reconstruction. Biomedical Engineering, IEEE Transactions on, 2015. PP(99): p. 1-1). Moreover, the assumption of 8 second data length largely stems from the fact that heart rates do not change instantaneously, hence, an 8 second duration is a reasonable choice.

[00126] As a representative example, the resultant frequency components in the time-frequency matrix of recordings from subject #8 from the competition training dataset, for a window length of 8 seconds that is shifted by every 2 seconds, is shown in FIG. 6A, disclosed below.

[00127] FIGS. 6A-6C show Time-Frequency spectra of recording #8 from dataset (1).

[00128] FIG. 6A shows the PPG signal.

[00129] FIG. 6B shows the simultaneous Accelerometer-Z signal.

[00130] FIG. 6C (Top-Left) shows the TF spectrum of the PPG signal. FIG. 6C (Top-Right) shows the TF spectrum of ACC(x). FIG. 6C (Bottom-Left) shows the TF spectrum of ACC(y),. FIG. 6C (Bottom-Right) shows the TF spectrum of ACC(z); all computed from stage (1) of Table 5. The blue circles and letters represent movement elements in all four spectra.

[00131] The panels of FIG. 6A and FIG. 6B show a PPG time series and the z-axis accelerometer data, respectively. From the upper left panel of FIG. 6C, which represents the time-frequency plot of the PPG signal, it is observed that there are three dominant frequency components - one of them represents HR and the other two are similar to those of the accelerometers' spectra shown in the upper right and lower left and right panels of FIG. 6C. FIG. 6C illustrates 4 motion artifact elements (A, B, C, D) that are present in exactly the same areas among all spectra. By comparing the time-frequency (TF) spectrum of PPG to those of the accelerometers' spectra, the marked dynamics (A, B, C and D) in the PPG spectrum can be detected as sharing the same frequency dynamics as those of the accelerometer spectra marked in circles. Hence, both the top and bottom marked lines in the PPG spectrum most likely represent the motion artifacts, and the unmarked frequency represents the HR. The next section details how these motion artifact frequency dynamics may be detected and filtered according to embodiments disclosed herein.

[00132] ii. Spectral Filtering

[00133] After obtaining the power spectral density at each window, as disclosed above, embodiments disclosed herein may confine the HR frequency to the range [0.5 Hz – 3 Hz], which takes into account both at rest and high HR due to either tachycardia or exercise scenarios. Hence, for HR estimation, the strategy is to eliminate frequencies that are outside of this HR frequency range as they are most likely due to motion artifacts or harmonics of the HR frequency.

[00134] In general, HR frequency in the power spectral density of PPG at each window can have three different scenarios: (1) PPG is devoid of MA and there is no spatial gap between the sensor and the subject's skin during recording, (2) PPG is corrupted by MA and there is no spatial gap between the sensor and the subject's skin during recording and (3) There is a spatial gap between the sensor and the subject's skin during recording. For the ideal case (1), HR can be extracted and it is most likely represented as the highest peak in the PPG spectrum. For case (2), MA dynamics can result in predominately either one or two dominant peaks depending on the severity of repetitive motions, and the HR peak may be relegated to either the second or third highest peak. Non-repetitive motion artifacts will show up as a broadband spectrum without a dominant peak if they are not severe (Marmarelis, V.Z., et al., Nonlinear analysis of renal autoregulation under broadband forcing conditions. Ann Biomed Eng, 1993. 21(6): p. 591-603). The only scenario that makes it difficult to extract HR from the spectrum is scenario (3) when there is a spatial gap between the PPG sensor and the subject's skin during recording. In this scenario, assuming that the motion artifacts are short lasting, the missing HR values can be interpolated using a cubic spline approach.

[00135] FIG. 7 is an example embodiment of spectral filtering. FIG. 7 shows a representative filtered time-frequency spectral plot of a PPG signal. As disclosed above, embodiments disclosed herein may retain only the three largest frequency peaks at each time point within the defined HR range (30-180 bpm) and such retained frequency peaks are represented as blue, green and red colors, respectively. Retaining only the three largest frequency peaks at each time point may be reasonable for the first two cases, as outlined above. In the PPG time-frequency spectrum of FIG. 7, the Blue, Green and Red circles correspond to the first three highest peaks in the defined HR frequency range of (30-180 bpm), respectively, at each sliding window.

[00136] iii. Motion Artifact Detection

[00137] FIGS. 8A-8B show motion artifact detection in the PPG spectrum according to embodiments disclosed herein.

[00138] FIG. 8A shows a filtered PPG spectrum with movement and HR components. FIG. 8A is an example embodiment of a PPG spectrum which is identical to FIG. 7, but it also identifies the frequencies associated with accelerometers, as marked by the shaded areas and the letters A-D, in the top left and two bottom panels of FIG. 6C, disclosed above. The

shaded yellow elements (A, B, C, D) of FIG. 8A represent motion frequency components in the PPG spectrum, and the light blue line is the reference HR from a clean reference ECG signal. By removing the accelerometers' related frequencies in FIG. 8A, the remaining frequency dynamics which should represent HR frequency and its harmonics are shown in FIG 8B.

[00139] FIG. 8B shows a filtered PPG spectrum after removing motion artifact frequency components.

[00140] iv. Heart Rate Tracking & Extraction

[00141] A flow diagram for heart rate tracking and extraction is disclosed above, with reference to FIG. 3B. Embodiments disclosed herein may identify HR frequencies with time, such as HR frequencies from FIG. 8B. Note that in FIG. 8B, there are three peaks at each time instance (also referred to interchangeably herein as a time point). Embodiments disclosed herein may identify which of the three peaks represents the HR at each time point. For the initial time window of 8 seconds, a clean data segment may be used so that true HR can be determined. This scenario is case (1), disclosed above, in the spectral filtering section, and the detection of HR is simply the highest peak in the spectrum. Embodiments disclosed herein may estimate HR for each sliding window of data. Embodiments disclosed herein may choose a HR peak in the PPG spectrum with the knowledge of estimated HR values in previous time windows. Two main scenarios may present: (1) no peak exists in the spectrum that can represent HR, and (2) there is a spectral peak among the first three highest peaks of spectrum that belongs to the HR component.

[00142] In case (1), where HR is not detectable in the window (*e.g.*, due to spatial gap between the PO sensor and skin), in real-time implementation embodiments disclosed herein may take a previous window's HR value as the current HR (or simply use a moving average of several past HR beats or some other variant). In post-processing, or offline processing, a cubic spline interpolation may be used to fill in the missing HR information. In the more general case (2), where the HR peak is among the first three highest peaks in the spectrum, three possible scenarios can occur: (2-A) the windowed PPG signal is clean and the first highest peak in the spectrum represents the HR fundamental frequency, (2-B) the windowed PPG signal is corrupted by movement and at most two of the spectral peaks represent the accelerometers' frequency components, thus, the second or the third peak corresponds to HR, (2-C) while the HR spectral peak is detectable, the difference between its value and that of

the previous HR is more than 10 bpm, as such, embodiments disclosed herein may replace the HR by the most recent HR value from a previous window segment (or a moving average of several past HR beats or some other variant).

[00143] According to embodiments disclosed herein, criterion may be set that the HR value cannot change more than 10 BPM from a previous time window. In FIG. 8B, these cases are illustrated. For example, in most cases, the blue circle which represents the largest spectral peak is chosen but in other cases, either green or red circles are chosen for certain time points. For the HR peaks associated with either the green or red circles, embodiments disclosed herein may choose those peaks because either the first two highest peaks are related to accelerometers or the highest magnitude peak deviates more than 10 BPM from the previous HR value.

[00144] FIG. 9 shows a comparison of reconstructed HR obtained, according to embodiments disclosed herein, to reference HR obtained from simultaneous ECG recordings. In FIG. 9, the extracted HR (red color) from PPG spectra of recording#8 from the competition training dataset, according to embodiments disclosed herein, is shown in red color and the reference ECG-derived HR is shown in black color. In order to calculate the performance of HR reconstruction according to embodiments disclosed herein, the error value in each time window was calculated from the estimated HR to the reference ECG-derived HR. Two measurement indices of absolute error similar to the indices in (Krishnan, R., B. Natarajan, and S. Warren, Two-Stage Approach for Detection and Reduction of Motion Artifacts in Photoplethysmographic Data. Biomedical Engineering, IEEE Transactions on, 2010. 57(8): p. 1867-1876) were used.

$$Error(1) = \frac{1}{W}\sum_{k=1}^{w}\left|HR_{SpaMA}(k) - HR_{ref}(k)\right| \quad (1)$$

$$Error(2) = \frac{1}{W}\sum_{k=1}^{w}\frac{\left|HR_{SpaMA}(k) - HR_{ref}(k)\right|}{HR_{ref}(k)} \times 100\% \quad (2)$$

where W is the total number of windows.

[00145] v. PPG Signal Reconstruction for HRV analysis

[00146] For an HRV analysis application, the above-disclosed embodiments are identical except that the beat-by-beat shift is of data rather than the 8 second data segment shift or its variant. According to embodiments disclosed herein, the PPG signal may be reconstructed

using heart rate frequency, amplitude and phase changes, window-by-window using the sample-by-sample windowing process:

$$Rec_{Signal}(k) = A_{HR}(k) \times \sin\left(2\pi t(k) f_{HR}(k) + \varphi_{HR}(k)\right) \quad (3)$$

where $k = 1, \ldots, N$ and N is number of signal samples and total number of windows. $A_{HR}(k)$ and $\varphi_{HR}(k)$ are calculated according to the power of the signal for HR frequencies in the PSD and phase angles of complex elements in a Fast Fourier Transform (FFT) matrix that correspond to HR frequencies.

[00147] FIG. 10A is an example embodiment of PPG signal reconstruction according to embodiments disclosed herein. FIG. 10A shows a comparison between reconstructed PPG and original recording #8 from IEEE competition training dataset. The left and right panels of FIGS. 10A-B show the reconstructed PPG versus the original PPG and their HRV time series, respectively.

[00148] FIG. 10B is a zoomed-in version of FIG. 10A.

[00149] Given that embodiments disclosed herein estimate quite accurate heart rates, it is not surprising to observe similar frequency dynamics between the reference and reconstructed HRV time series, as shown in FIGS. 11A-B.

[00150] FIGS. 11A-B show comparisons of HRV spectra between the reference and the reconstructed HRV time series (*e.g.*, as shown in FIGS. 10A-B) from the MA-contaminated PPG signal for dataset #8. Note that for computing HRV, matching the amplitude of the reference HR is not a concern, as the focus is only in the dynamics of the fluctuations in the heart rates.

[00151] FIG. 11A shows a time-domain comparison of a reconstructed HR and a reference HR.

[00152] FIG. 11B shows a spectral comparison of heart rate variability between reconstructed HR and reference HR calculated from the reference ECG using Pan & Tompkins peak detection approach (Pan J, T.W., A real-time QRS detection algorithm. IEEE Trans Biomed Eng, 1985. 32(3): p. 230-236).

[00153] Results

[00154] Table 6 represents the average absolute error (E1) and the average absolute error percentage (E2) of embodiments disclosed herein as applied to all 3 datasets, respectively. Embodiments disclosed herein are compared to three methods: TROIKA, JOSS and WFPV. The results in Table 6 show that better performance from embodiments disclosed herein as

comparted to JOSS and TROIKA for all 12 subjects in the first datasets. In comparison to WFPV, embodiments disclosed herein outperform WFPV on average across all 23 subjects in both datasets (1) and (2). The total average of E1 for embodiments disclosed herein is less than 2 beats per minutes for all 33 subjects. The average of E1 across the treadmill experiment recordings (activity Type 1- IEEE dataset and Type 4- Chon Lab dataset) is around 1 beat per minute for all 22 subjects.

Table 6. SpaMA Method Performance Comparison

Subject	Dataset	Activity Type	TROIKA		JOSS		WFPV		SpaMA	
			E1	E2%	E1	E2%	E1	E2%	E1	E2%
1	1 (IEEE Cup)	Type (1)	2.87	2.18	1.33	1.19	1.23	-	**1.23**	**1.14**
2			2.75	2.37	1.75	1.66	1.26	-	1.59	1.30
3			1.91	1.50	1.47	1.27	0.72	-	**0.57**	**0.45**
4			2.25	2.00	1.48	1.41	0.98	-	**0.44**	**0.31**
5			1.69	1.22	0.69	0.51	0.75	-	**0.47**	**0.31**
6			3.16	2.51	1.32	1.09	0.91	-	**0.61**	**0.45**
7			1.72	1.27	0.71	0.54	0.67	-	**0.54**	**0.40**
8			1.83	1.47	0.56	0.47	0.91	-	**0.40**	**0.33**
9			1.58	1.28	0.49	0.41	0.54	-	**0.40**	**0.32**
10			4.00	2.49	3.81	2.43	2.61	-	2.63	1.59
11			1.96	1.29	0.78	0.51	0.94	-	**0.64**	**0.42**
12			3.33	2.30	1.04	0.81	0.98	-	1.20	0.86
mean±std			2.42±0.8	1.82±0.5	1.28±0.9	1.02±0.6	1.04±0.5	-	**0.89±0.6**	**0.65±0.4**
13	2 (IEEE Cup)	Type (2)					3.58	-	**3.41**	**4.25**
14							9.66	-	**7.29**	**9.80**
15							2.31	-	2.73	2.21
16		Type (3)					4.93	-	**3.18**	**2.11**
17							3.07	-	**3.01**	**2.52**
18							2.67	-	4.46	3.23
19							3.11	-	3.58	3.98
20		Type (2)					2.10	-	**1.94**	**1.66**
21		Type (3)					3.22	-	**2.56**	**2.02**
22							4.35	-	**3.12**	**3.28**
23		Type (2)					0.75	-	1.72	1.97
mean±std							3.61±2.2	-	**3.36±1.5**	**3.33±2.2**
Type (1,2) mean±std							2.27±2.0	-	**1.93±2.0**	**2.07±1.7**
24	3 (Chon Lab)	Type (4)							**0.88**	**0.91**
25									**1.03**	**0.83**
26									**1.10**	**0.90**
27									**1.64**	**1.54**
28									**1.41**	**1.12**
29									**0.82**	**0.70**
30									**0.63**	**0.58**
31									**4.78**	**3.87**
32									**0.95**	**0.79**
33									**0.62**	**0.52**
mean±std									**1.38±1.2**	**1.17±1.0**
Total: mean±std									**1.86±1.6**	**1.70±1.8**

[00155] FIGS. 12A, 12B, 13A, 13B, 14A, and 14B show the reconstructed HR and corresponding PSD of a sample-sample windowed HR, according to embodiments disclosed herein, in comparison to a reference HR from an ECG. The results for recording #9 from the first dataset (IEEE Competition Training dataset) and activity Type 1 (*e.g.*, running on treadmill) are shown in FIGS. 13A-B. As shown, E1 for this particular subject is as low as 0.4 bpm and the correlation between the PSD of reconstructed HR and reference HR is as high as 96%.

[00156] FIG. 12A shows a reconstructed HR vs. reference HR. FIG. 12B shows a spectral comparison of reconstructed HR and reference HR (estimated from reference ECG).

[00157] FIG. 13A illustrates the comparison between the reconstructed HR and the reference HR for Subject #14 (IEEE Competition Test Dataset) which has the highest errors. Subject #14 belongs to the second dataset (IEEE Competition Test dataset) and Type 2 activities (e.g. jumping). It can be seen that the largest error is obtained when both the physiological HR and the motion artifacts change rapidly so that the true HR cannot be reliably estimated.

[00158] FIG. 13B shows a reconstructed HR vs. reference HR for Subject 16 (IEEE Competition Test Dataset). FIG. 13B shows the comparison results of reconstructed HR and reference HR for recording #16 of the second dataset (IEEE Competition Test dataset) which has the Type 3 activities (*e.g.*, arm exercise).

[00159] FIG. 14A shows a reconstructed HR vs. reference HR for Subject #30 (Chon Lab Dataset). FIG. 14B shows a spectral comparison of reconstructed HR and reference HR (estimated from reference ECG). The results for recording #30 from the third datasets (Chon Lab datasets) and activity Type 4 (*e.g.*, running on treadmill) are shown in FIGS. 14A-B. It can be seen that the E1 for this subject is around 0.6 bpm and the correlation between the PSD of reconstructed HR and reference HR is as high as 99% for LF and 0.96 for HF frequency range. All subjects' results are provided in Table 7, disclosed below.

[00160] Table 7 represents the correlation and statistical difference using the student's t-test between PSD of estimated and reference HRV in both LF (0.04-0.15 Hz) and HF (0.15-0.4 Hz) frequency ranges. The correlation values in the table are calculated based on Pearson's linear correlation coefficient. As shown in Table 7, there was no difference between the reference and the derived HRV for LF, according to embodiments disclosed herein, and a difference was seen in only 4 out of 10 subjects for HF.

Table 7. Frequency Domain HRV analysis Comparison: PSD of SpaMA Method vs. reference

Subjects	Correlation	
	LF (LF is [0.04-0.15] Hz and HF is [0.15-0.4] Hz)	**HF**
1	0.99	0.98
2	0.99	0.96
3	0.99	0.95* (*) indicates significantly different (P-value>0.05)
4	1.00	0.99
5	1.00	0.99
6	0.99	0.96*
7	0.98	0.92*
8	0.97	0.90*
9	1.00	0.99
10	1.00	0.99
mean	0.99	0.96

[00161] Table 8 shows some of the widely-reported time-domain HRV parameters such as the mean HR, standard-deviation (SDNN) of the normal-to-normal (NN) interval, root-mean-square of successive difference (RMSSD) of the NN interval, and the number of interval differences of successive NN intervals greater than 50 ms divided by the total number of NN intervals (pNN50) estimated from embodiments disclosed herein in comparison to the reference ECG NN interval. None of these parameters were found to be significantly different between those derived according to embodiments disclosed herein and the reference HRV.

Table 8. Time Domain HRV analysis Comparison: SpaMA Method vs. reference HRV

Subjects	SDNN		meanNN		RMSSD		pNN50	
	SpaMA	Reference	SpaMA	Reference	SpaMA	Reference	SpaMA	Reference
1	2620.75	2566.47	10481.89	10480.72	33.24	18.05	0.001	0.020
2	2115.44	2079.58	9908.00	10020.00	25.93	16.32	0.011	0.019
3	3173.73	3177.68	10764.20	10829.06	89.70	56.15	0.019	0.207
4	2517.78	2533.20	10376.95	10426.26	13.54	19.58	0.001	0.030
5	2654.42	2670.32	10846.04	10990.08	11.88	18.59	0.003	0.018
6	2012.53	1974.65	9737.35	9827.63	39.64	21.17	0.004	0.025
7	3056.36	2925.19	12519.74	13134.05	27.66	30.61	0.015	0.071
8	3133.76	2756.66	10504.00	10530.00	32.57	36.38	0.002	0.003
9	2195.08	2142.53	10499.81	10470.06	8.23	13.01	0.002	0.004
10	2454.57	2406.96	12936.62	12981.21	41.52	20.28	0.006	0.024
p-value	> 0.05		> 0.05		> 0.05		> 0.05	

[00162] As such, the SpaMA method, according to embodiments disclosed herein, that may be based on time-varying spectral analysis of the PPG signal addresses Heart Rate monitoring in the real world with challenges ranging from a subject who makes sudden movements but is otherwise sedate, to intensive physical activities. Embodiments disclosed herein compare spectral changes in PPG and accelerometer signals. As disclosed above, three different datasets have been used to verify the SpaMA performance. Each dataset reflects different types of activities and movements. In all of the experiments, the reference HR was calculated from an ECG signal that was collected simultaneously with the PPG signal. The estimated HR was calculated from the spectrum of PPG in 8 second time windows. Based on the results, disclosed above, the SpaMA method may be used for tracking HR changes during severe motion artifacts with an average error of just 1.86 bpm compared to that of the reference ECG; these results are superior to three other methods tested: TROIKA, JOSS and WFPV (Zhilin, Z., P. Zhouyue, and L. Benyuan, TROIKA: A General Framework for Heart Rate Monitoring Using Wrist-Type Photoplethysmographic Signals During Intensive Physical Exercise. Biomedical Engineering, IEEE Transactions on, 2015. 62(2): p. 522-531; Zhang, Z., Photoplethysmography-Based Heart Rate Monitoring in Physical Activities via Joint Sparse Spectrum Reconstruction. Biomedical Engineering, IEEE Transactions on, 2015. PP(99): p. 1-1).

[00163] Out of 33 recordings, 23 are from a wrist pulse oximeter, and the rest of the data were recorded by a forehead pulse oximeter. The results from Table 8, disclosed above, show that the SpaMA method can be applied to monitor HR from both wrist and forehead pulse oximeters. By comparing the performance of the method for treadmill experiments (dataset 1 and dataset 3), the error is lower by almost 1 beat using a wrist pulse oximeter. However, it should be noted that from this result a conclusion that the wrist PPG provides less error than the forehead should not be drawn, as the experiments used different subjects and were two separate studies. The prior methods (TROIKA, JOSS and WFPV) were tested using only on the wrist-based PPG signals as the implementers of those methods did not have access to forehead PPG sensors. The SpaMA method, according to embodiment disclosed herein, was tested on data from both PPG sensor locations, and proved to be effective regardless of the location of the PPG sensor.

[00164] Several observations were made while analyzing the data, disclosed above. The tracking ability of the SpaMA method decreased as the frequency changes during recordings

increased. This phenomenon mostly was observed while dealing with the second set of datasets from the IEEE competition, which involved Type (2) and Type (3) activities. These types of exercises involved more abrupt movements which consequently made it more difficult to track the HR-related frequencies in the spectrum. In the three datasets that have been analyzed, recordings #10 and 14 are examples of this phenomenon.

[00165] A strength of the PPG's LED is one of the most important factors determining the SpaMA method performance. Movement induces much less spectrum corruption (shift) in the PPG if the LED is sufficiently strong. A reduction in the strength of the PPG signal can also be caused by ambient light leaking into the gap between a PPG sensor and the skin surface (Zhang, Z., Photoplethysmography-Based Heart Rate Monitoring in Physical Activities via Joint Sparse Spectrum Reconstruction. Biomedical Engineering, IEEE Transactions on, 2015. PP(99): p. 1-1). This is because the power of the signal is dependent on the depth and reflection of the light from the pulse oximeter to the subject's skin. This gap between skin and the planar substrate where the LEDs and PD are mounted may be the result of movement during physical activities or the shape of tissue that the sensors touch. Among the three datasets, low performance for recordings #16 and 31 is the result of a weak PPG signal most likely due to a gap between the sensor and skin caused by motion artifacts.

[00166] By using the sample-by-sample windowing process, SpaMA, according to embodiments disclosed herein, can be utilized for both Heart Rate monitoring and HRV analysis in both frequency- and time-domains. From the results, disclosed above, it can be observed that embodiments disclosed here are able to replicate both the low frequency (0.04-0.15Hz) and the high frequency (0.15-0.4) dynamics well, albeit better the former than the latter, when compared to a reference HRV. For time-domain HRV measures, the mean HR, SDNN, RMSSD, and pNN50 based on embodiments disclosed herein were all found to be not significantly different than the reference HRV. It has long been shown that during dynamic exercise, heart rate increases due to both a parasympathetic withdrawal and an augmented sympathetic activity (Iellamo, F., Neural mechanisms of cardiovascular regulation during exercise. Auton Neurosci, 2001. 90(1-2): p. 66-75; Bernardi, L. and M.F. Piepoli, [Autonomic nervous system adaptation during physical exercise]. Ital Heart J Suppl, 2001. 2(8): p. 831-9). The relative role of the two drives depends on the exercise intensity (Perini, R., et al., The influence of exercise intensity on the power spectrum of heart rate variability. Eur J Appl Physiol Occup Physiol, 1990. 61(1-2): p. 143-8; Sarmiento, S., et al., Heart rate

variability during high-intensity exercise. Journal of Systems Science and Complexity, 2013. 26(1): p. 104-116; Roure, R., et al., Autonomic nervous system responses correlate with mental rehearsal in volleyball training. Eur J Appl Physiol Occup Physiol, 1998. 78(2): p. 99-108). Analysis of HRV permits insight into this control mechanism (Aubert, A.E., B. Seps, and F. Beckers, Heart rate variability in athletes. Sports Med, 2003. 33(12): p. 889-919). Also, being able to do HRV analysis from PPG even during movement and physical activities would be an advantage for detecting and diagnosing many cardiovascular diseases using only PPG recordings.

[00167] The SpaMA method, according to embodiments disclosed herein, can be potentially implemented in real time. The method written in Matlab®, version R2014 and CPU 3.4 GHz takes only 110 msec per 8 second segments. Therefore, given the high accuracy of the method in estimating HR despite severe motion artifacts, the SpaMA method, according to embodiments disclosed herein, has the potential to be applicable for implementation on wearable devices such as smart watches and PPG-based fitness sensors.

[00168] As disclosed above, accurate estimation of changing arterial oxygen saturation (SpO2) from photoplethysmogram (PPG) signals during movement is a very challenging problem. This is because strenuous and high intensity movements can result in severe motion artifacts (MA), making accurate SpO2 estimation from PPG signals difficult. As such, embodiment disclosed herein may applied the methods for reconstructing a PPG signal, as disclosed above, and include an additional stage of SpO2 estimation.

[00169] According to one embodiment, OxiMA may be comprised of the 6 stages disclosed above, with reference to FIGS. 3A-F, and include Stage 7, that is SpO2 Estimation.

[00170] According to another embodiment, OxiMA may be comprised of 6 stages: (1) Time-frequency Spectral Analysis, (2) Signal Decomposition, (3) Spectral Filtering, (4) Heart Rate (HR) extraction and tracking, (5) Signal Reconstruction, (6) SpO2 Estimation.

[00171] OxiMA

[00172] According to some embodiments, OxiMA may decompose the PPG signal into its frequency components by using a complex demodulation-based technique and may choose the components with frequencies close to the HR frequency for reconstructing the clean PPG signal. Next, SpO2 may be estimated from the reconstructed PPG signal. Such a method is applied to 22 minute datasets recorded from 10 subjects. A Nellcor OxiMax transmission sensor was used to collect analog PPG signals, while reference SpO2 and HR were collected

simultaneously from the FDA approved Masimo SET Radical RDS-1 pulse oximeter. The performance of the OxiMA method according to embodiments disclosed herein, was determined by computing the mean absolute error between the estimated HR/SpO2 from the PPG and reference HR [Masimo]/SpO2[Masimo] oximeter. The results show the average estimation error using OxiMA are only 2.4 beats/minute for HR and 1.8% for SpO2, respectively. As such, the OxiMA method has great potential for MA reduction for both SpO2 and HR monitoring.

[00173] Vital signs and clinical symptoms have been shown to be poor predictors of hypoxia, and in order to rationalize oxygen therapy, measurement of arterial oxygen saturation by pulse oximetry is being increasingly recommended (Laman, M., et al., Can clinical signs predict hypoxaemia in Papua New Guinean children with moderate and severe pneumonia? Ann Trop Paediatr, 2005. 25(1): p. 23-7) Arterial oxygen saturation (SpO2) reflects the relative amount of oxyhemoglobin in the arterial blood. The most common method to measure SpO2 is based on pulse oximetry, whereby oxidized hemoglobin and reduced hemoglobin have significantly different optical spectra.

[00174] Specifically, at a red wavelength of about 660 nm, there is a significant difference in light absorbance between reduced (Hb) and oxidized hemoglobin (HbO2). A measurement of the percent oxygen saturation of blood is defined as the ratio of oxyhemoglobin to the total concentration of hemoglobin present in the blood. Pulse oximetry assumes that the fluctuations of the PPG signal are caused by changes in arterial blood volume associated with each heartbeat, where the magnitude of the fluctuations depends on the amount of arterial blood rushing into the peripheral vascular bed, the optical absorption of the blood, skin and tissue, and the wavelengths used to illuminate the blood. The photoplethysmogram (PPG) can be used to derive not only the SpO2 and heart rate (HR) data, but also other vital physiological information (Laman, M., et al., Can clinical signs predict hypoxaemia in Papua New Guinean children with moderate and severe pneumonia? Ann Trop Paediatr, 2005. 25(1): p. 23-7; Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263; Tamisier, R., et al., A new model of chronic intermittent hypoxia in humans: effect on ventilation, sleep, and blood pressure. J Appl Physiol (1985), 2009. 107(1): p. 17-24; Jubran, A., Pulse oximetry. Crit Care, 1999. 3(2): p. R11-r17). As disclosed above, utilizing a pulse oximeter

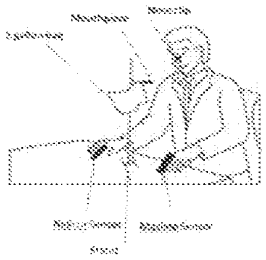
as a multi-purpose vital sign monitor has clinical appeal, since it is familiar to clinicians and comfortable for the patient (Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263).

[00175] In healthy persons, SpO2 is typically near 98%. A lower reading indicates a level of hypoxia. SpO2 readings below 95% are usually a cause for concern, indicating the need for supplemental oxygen therapy. In certain individuals, such as those with chronic respiratory or cardiac diseases, SpO2 readings below 95% may be considered normal. However, in general, SpO2 readings between 90%-95% represent mild hypoxia, while 85%-90% indicates serious hypoxia, and readings below 85% are considered critical hypoxia (Tamisier, R., et al., A new model of chronic intermittent hypoxia in humans: effect on ventilation, sleep, and blood pressure. J Appl Physiol (1985), 2009. 107(1): p. 17-24).

[00176] As disclosed below, the OxiMA method according to embodiments disclosed herein, provides HR reconstruction with accurate SpO2 estimation even during movement. The most recent methods as noted above (e.g., TROIKA and JOSS) do not show their ability to obtain SpO2 estimates as they were mainly designed for HR calculations in the presence of intense motion artifacts.

[00177] The OxiMA method was evaluated on a lab controlled dataset that was recorded during voluntary induced hypoxia. In an IRB approved study which recruited 10 subjects, one set of data was collected from each subject for a duration of 22 min. Reference arterial SpO2 and HR were collected from the FDA approved Masimo SET Radical RDS-1 pulse oximeter (mounted on the left hand), while a Nellcor OxiMax sensor (mounted on the right hand) was used to collect analog PPG signals, simultaneously (Table 9).

TABLE 9
PPG DATASETS AND EXPERIMENTS SETTINGS

Scenario	Sensor Type	Age/Sex Ethnicity
Oxygen Saturation Variations 	[Actual PPG] Finger Pulse Oximeter Nellcor [Ref SpO_2] Finger Pulse Oximeter [Ref HR] SilverRest ECG Electrode	23-58 yr (10 Males) 3 Asian 2 Hispanic 3 American 2 White

[00178] Each subject sat in a chair and was asked to re-breathe into a 1-gallon bag four times for approximately two minutes each time. During the first and third time the subject rebreathed into the bag, subjects were asked to remain still. During the second and fourth time the subject rebreathed into the bag, subjects were asked to introduce motion artifacts into the measurement by shaking their right hand. Each subject wore a disposable nose clip to prevent accidental breathing of room air. The Masimo reference sensor placed in the left hand remained motionless for the entire duration of the study. Subjects had at least two minutes of rest between successive breathing maneuvers, with more time if requested. The protocol for this experiment is presented in Table 10. Worcester Polytechnic Institute IRB approved the study protocol and informed consent was required by all subjects prior to data recording.

[00179] This sequence of data recording allowed us to test the efficacy of the OxiMA method while a subject experienced different levels of short lasting hypoxia during motion artifacts. For reference, other clinical studies showed that SpO2 levels in patients suffering from mild to moderate sleep apnea can drop to about 80% for short periods of time until the patient is awakened without irreversible physiological effects (Maeda, Y., M. Sekine, and T. Tamura, Relationship between measurement site and motion artifacts in wearable reflected photoplethysmography. J Med Syst, 2011. 35(5): p. 969-76).

[00180] Methodology

[00181] The protocol for testing performance of the OxiMA method is presented in Table 10.

TABLE 10
EXPERIMENT PROTOCOL

End Time (min)	Event
2	Rest (baseline)
4	Bag breathing (motion)
5	Rest (oxygen recovery)
7	Rest
9	Bag breathing (motion)
10	Rest (oxygen recovery)
12	Rest
14	Bag breathing (no motion)
15	Rest (oxygen recovery)
17	Rest
19	Bag breathing (motion)
20	Rest (oxygen recovery)
22	Rest

[00182] Details of each stage of the OxiMA method as applied in the experiment are disclosed below.

[00183] Time-Varying Spectral Analysis of PPG and Accelerometer Data

[00184] To compute the time-frequency spectrum, a variable frequency complex demodulation technique was employed. Table 11, disclosed below, presents the OxiMA method, according to one embodiment.

[00185] The time-varying spectrum is estimated by taking a T-sec window of the PPG signal and computing the VFCDM time-frequency of the segment and then sliding the window through the whole dataset. There is no overlapping between the sliding time windows. The window segment length T was set to 8 seconds and was shifted by 8 seconds. The assumption of 8 second data length largely stems from the fact that SpO2 and heart rates do not change instantaneously; hence, an 8 second duration is a reasonable choice.

TABLE 11
OXIMA METHOD: HR AND SPO2 RECONSTRUCTION

Stage 1. VFCDM Time-Frequency Spectrum
1.1. Downsample the PPG signal to ¼ of the original sampling frequency.
1.2. Compute the VFCDM based time-frequency spectrum (TFS)

Stage 2. Signal Decomposition
2.1. Decompose the PPG signal into its frequency components according to frequency bands in the TFS

Stage 3. Spectral Filtering
3.1. Assume HR to be in the frequency range of [0.5Hz – 3Hz], to account for both low and high HR values.
3.2. The first highest two peaks and their corresponding frequencies in the PPG filtered spectrum are assumed to have HR information.

Stage 4. Heart Rate Tracking and Extraction from PPG Spectrum
Case (1): From 3.1- if the spectrum is corrupted by movement and only the first largest peak is corrupted, then the HR frequency should be the frequency of the second peak in the spectrum.
Case (2): Due to the sensor-skin interface interruption, which could be a result of gap between the pulse oximeter and a subject's skin or slight sensor alignment variations relative to skin, the HR frequency cannot be extracted from the spectrum and in this case the previous HR frequency is used or for offline implementation a cubic spline interpolation can be applied to fill in the missing HR information.

Stage 5. PPG Signal Reconstruction
5.1. The PPG signal is reconstructed by using the summation of VFCDM components with frequency close to the HR frequency at each window.

Stage 6. Oxygen Saturation Estimation
6.1. Calculate the SpO2 estimations from reconstructed infrared and red PPG signals using the following empirical calibration equation [2]

$$SpO_2(\%) = (110 - 25R)$$

where,

$$R = \frac{AC_{Red}/DC_{Red}}{AC_{IR}/DC_{IR}}$$

[00186] FIGS. 15A-B show the resultant VFCDM time-frequency spectrum of recordings from subject #5, as a representative example.

[00187] The panels in FIGS. 15A-B show infrared PPG time series data. FIG. 15B represents the time-frequency plot of the infrared PPG signal. The next section details how the PPG data is decomposed into its frequency components using VFCDM.

[00188] Signal Decomposition

[00189] The original PPG signal was decomposed into sinusoidal modulations using a VFCDM method, as disclosed in Table 12 below.

$$x(t) = \sum_{i=1}^{N} Component\{i\} = \sum_{i=1}^{N} dc_i(t)A_i(t)cos\big(2\pi f_i(t) + \phi_i(t)\big) \quad (4)$$

[00190] By assuming N=12 fixed frequency bands each with a distinct central frequency, the PPG and accelerometer signals may be decomposed using the VFCDM method of Table 12 which yields 12 components.

TABLE 12
VFCDM METHOD

Consider a sinusoidal signal $x(t)$ to be a narrow band oscillation with a time-varying center frequency $f(\tau)$, instantaneous amplitude $A(t)$, phase $\phi(t)$, and the direct current component $dc(t)$:

$$\boldsymbol{x(t) = dc(t) + A(t)\cos\left(\int_0^t 2\pi f(\tau)d\tau + \phi(t)\right)}$$

Step (1) For a given center frequency, we can extract the instantaneous amplitude information $A(t)$ and phase information $\phi(t)$ by multiplying (1) by $e^{-j\int_0^t 2\pi f(\tau)d\tau}$ which results in the following:

$$z(t) = x(t)e^{-j\int_0^t 2\pi f(\tau)d\tau} = dc(t)e^{-j\int_0^t 2\pi f(\tau)d\tau} + \frac{A(t)}{2}e^{j\phi(t)} + \frac{A(t)}{2}e^{-j\left(\int_0^t 4\pi f(\tau)d\tau + \phi(t)\right)}$$

Step (2) From (2), if $z(t)$ is filtered with an ideal low-pass filter (LPF) with a cutoff frequency $f_c < f_0$, where f_0 is the center frequency of interest. Then the filtered signal $z_{lp}(t)$ will contain only the component of interest $z_{lp}(t) = \frac{A(t)}{2}e^{j\phi(t)}$.

Step (3) By changing the center frequency followed by using the variable frequency approach as well as the LPF, the signal, $x(t)$, will be decomposed into the sinusoid modulations, d_i, by the CDM technique as follows:

$$\boldsymbol{x(t) = \sum_i d_i = dc(t) + \sum_i A_i(t)\cos\left(\int_0^t 2\pi f_i(\tau)d\tau + \phi_i(t)\right)}$$

Step (4) The instantaneous frequency and amplitude of d_i can be calculated using the Hilbert transform

$$A(t) = 2|z_{lp}(t)| = [X^2(t) + Y^2(t)]^{1/2}$$
$$X(t) = real(z_{lp}(t))$$
$$Y(t) = imag\left(z_{lp}(t)\right) = H[X(t)] = \frac{1}{\pi}\int \frac{X(t')}{t-t'}dt'$$
$$\phi(t) = \arctan\left(\frac{imag\left(z_{lp}(t)\right)}{real\left(z_{lp}(t)\right)}\right) = \arctan\left(\frac{Y(t)}{X(t)}\right) \qquad f(t) = f_0 + \frac{1}{2\pi}\frac{d\phi(t)}{dt}$$

[00191] FIG. 16 shows the twelve components corresponding to the IR and Red signal for subject #5. Among the twelve frequency bands, bands 1 to 5 correspond to frequency range of [0.5 Hz to 3 Hz], which is typically the HR frequency range accounting for both normal and elevated heart rates. Embodiments disclosed herein select a component of these 5 components to reconstruct the signal that preserves the HR and is less corrupted by the

motion artifacts. For the selection, an accurate HR may be estimated by selecting the components that match closest to the actual HR frequency in order to reconstruct a less noisy PPG signal than the original motion corrupted data.

[00192] Spectral Filtering

[00193] After obtaining the power spectral density at each window, HR frequency may be assumed to be confined in the range [0.5 Hz – 3 Hz], which takes into account both at rest and high HR values due to either tachycardia or exercise scenarios. Next, for HR estimation, the strategy is to keep only frequencies that correspond to the first and second peak at each column of time-frequency matrix, as disclosed above, with reference to FIG. 3B.

[00194] In general, HR frequency in the VFCDM based power spectral density of the PPG at each window can have three different scenarios: (1) PPG is devoid of MA and there is no sensor-skin interface problems like a spatial gap between the sensor and the subject's skin during recording, (2) PPG is corrupted by MA and there is no spatial gap between the sensor and the subject's skin during recording and (3) There is a spatial gap between the sensor and the subject's skin during recording. For the ideal case (1), HR can be extracted and it is most likely represented as the highest peak in the PPG spectrum. For case (2), MA dynamics can result in the dominant peak and HR frequency peak's magnitude become smaller than the MA frequency peak in the spectrum. The only scenario that makes it difficult to extract HR from the spectrum is scenario (3) when there is a spatial gap between the PPG sensor and the subject's skin during recording. In this scenario, assuming that the motion artifacts are short lasting, the missing HR values can be interpolated using the cubic spline approach.

[00195] FIGS. 17A-C are plots of the above three scenarios. In FIG. 17A and FIG. 17B, the true HR frequency is close to the first and second peak respectively, while in FIG. 17C, the true HR frequency is far from the dominant peaks in the spectrum. As long as the PPG data is clean, an assumption may be made that the HR frequency belongs to the frequency component with the highest power (peak) at the each column of the TFS matrix. On the other hand, when the data becomes corrupted by MA, it might shift the HR frequency to the next highest peak in the spectrum or might lose the dominant HR frequency.

[00196] Embodiments disclosed herein employ a TFS filtering step to search for N first highest spectral peaks and their associated frequencies in each column of the TFS. Hence, the original TFS of FIG. 15B can be filtered to select only N, for example, 2, in the example embodiments, highest spectral peaks.

[00197] FIG. 18A shows a representative filtered time-frequency spectral plot of PPG recording from subject #5. This portion of the OxiMA method involves retaining only the two largest frequency peaks at each time point within the defined HR range (30-180 bpm) and they are represented as blue and green traces, respectively.

[00198] Heart Rate Tracking and Extraction

[00199] After filtering the TFS, the HR may be extracted. The HR tracking method may be summarized as: Assume there is only knowledge of the initial HR, the HR at each window is extracted by comparing the peaks to the previous HR value.

[00200] As disclosed above with reference to FIG. 3B, if the largest peak is within the 10 bpm range from the previous value of HR, it is chosen; if not, the second largest peak is checked for compliance of this scenario. If the HR value deviates by more than 10 bpm, the HR from the previous window may be adopted by the method.

[00201] FIG. 18B illustrates the tracking of HR based on OxiMA method, disclosed above.

[00202] FIGS. 19A and 19B represent comparisons, of the estimated 8 second moving averaged HR from the OxiMA method, to the reference HR, and the HR calculated from the motion-corrupted PPG signal, compared to the reference HR from the ECG, respectively. In order to calculate the performance of the OxiMA method for HR reconstruction, the error value in each time window was calculated from the estimated HR to the reference ECG-derived HR. Two measurement indices of absolute and normalized errors similar to the indices in (Wang, H., et al., A high resolution approach to estimating time-frequency spectra and their amplitudes. Ann Biomed Eng, 2006. 34(2): p. 326-3) were used.

$$Error(1) = \frac{1}{W}\sum_{k=1}^{w}\left|HR_{OxiMA}(k) - HR_{ref}(k)\right| \quad (5)$$

$$Error(2) = \frac{1}{W}\sum_{k=1}^{w}\frac{\left|HR_{OxiMA}(k) - HR_{ref}(k)\right|}{HR_{OxiMA}(k)} \times 100\% \quad (6)$$

where, W is the total number of windows.

[00203] PPG signal reconstruction

[00204] Now that HR values at each time window are estimated from the time-frequency spectrum, the signal reconstruction phase of the OxiMA method may be performed. An assumption may be made that the signal components corresponding to the HR frequency are more robust against motion and, thus, a less corrupted signal can be reconstructed using the summation of these components.

[00205] By calculating the components from the Signal Decomposition, using Eq (4) and the time-frequency spectrum of the PPG, at each 8-sec window a signal component may be chosen that has a frequency close to estimated HR frequency and that component may be employed to reconstruct infrared and red PPG data at each window. This yields a less motion-corrupted data that can be used for oxygen saturation estimation, as disclosed in FIG. 20A and FIG. 20B.

[00206] Oxygen Saturation Estimation

[00207] In order to calculate SpO2 from PPG signals, red and infrared PPG signals with clearly separable DC and AC components are required. Let the pulsatile components of the red and infrared PPG signals be denoted as AC_{Red} and AC_{IR}, respectively, then the "ratio-of-ratio" R is estimated (Thakor, N.V. and Y.S. Zhu, Applications of adaptive filtering to ECG analysis: noise cancellation and arrhythmia detection. IEEE Trans Biomed Eng, 1991. 38(8): p. 785-94; Diniz, P., Adaptive filtering: algorithms and practical implementation. 2008: . Springer Science, Business Media L.L.C) as

$$\boldsymbol{R = \frac{AC_{Red}/DC_{Red}}{AC_{IR}/DC_{IR}}} \qquad (7)$$

[00208] Accordingly, SpO2 may be computed by substituting the R value in an empirical linear approximated relation given by $SpO_2(\%) = (110 - 25R)$.

[00209] FIG. 20C represents the reconstructed SpO2 values obtained from OxiMA in comparison to the reference SpO2 values and the estimated values before reconstruction.

[00210] OxiMA Results

[00211] Table 13 represents the average absolute error (E1) and the average absolute error percentage (E2) of HR and SpO2 estimations of the OxiMA method on the varying hypoxia level dataset.

TABLE 13
OXIMA METHOD PERFORMANCE COMPARISON (HR ESTIMATIONS)

Subject	Actual HR estimation error		OxiMA HR estimation error	
	E1	E2%	E1	E2%
1	3.84	4.83	**1.53**	**2.10**
2	6.84	9.57	**2.72**	**3.97**
3	8.15	9.59	**1.69**	**2.29**
4	4.55	5.39	**2.61**	**3.18**
5	10.53	11.96	**4.04**	**4.60**
6	4.46	5.52	**2.04**	**2.66**
7	12.41	19.65	**2.81**	**4.37**
8	3.84	4.35	**2.10**	**2.46**
9	3.80	4.13	**2.57**	**2.83**
10	3.65	4.20	**1.85**	**2.41**
mean±std	6.20±3.2	7.91±5.0	2.40±0.73	3.09±0.90

[00212] The OxiMA method is compared to the HR and SpO2 estimations prior to the reconstruction method, where both pre- and post-reconstruction estimations are compared to the reference HR and reference SpO2 values obtained from the Masimo pulse oximeter.

[00213] The results presented in Table 13 show that OxiMA on average improves the HR and SpO2 estimations by 100% and 105%, respectively when compared to those estimations without the reconstruction method. Improvement rates are calculated as follow:

$$\boldsymbol{ImRate1}(\%) = \frac{\mathbf{1}}{\boldsymbol{W}}\sum_{\boldsymbol{k=1}}^{\boldsymbol{W}}\frac{|\boldsymbol{Error1_{OxiMA}(k)-Error1_{Act}(k)}|}{\boldsymbol{Error1_{OxiMA}(k)}} \times \mathbf{100}\% \quad (8)$$

$$\boldsymbol{ImRate2}(\%) = \frac{\mathbf{1}}{\boldsymbol{W}}\sum_{\boldsymbol{k=1}}^{\boldsymbol{W}}\frac{|\boldsymbol{Error2_{OxiMA}(k)-Error2_{Act}(k)}|}{\boldsymbol{Error2_{OxiMA}(k)}} \times \mathbf{100}\% \quad (9)$$

[00214] FIGS. 21A-C and FIGS. 22A-B show the reconstructed SpO2 and HR in comparison to the reference HR from ECG recordings for subject #5. The largest error

among all recordings was found to be from this recording, as shown in Tables 13 and 14. The larger error could be due to rapid movements or skin-sensor gap during the recordings.

TABLE 14
OXIMA METHOD PERFORMANCE COMPARISON (SpO_2 ESTIMATIONS)

Subject	Actual SpO_2 estimation error		OxiMA SpO_2 estimation error	
	E1	E2%	E1	E2%
1	2.51	2.63	**0.86**	**0.90**
2	7.14	9.63	**2.45**	**3.10**
3	6.21	6.59	**1.61**	**1.67**
4	1.89	2.46	**0.95**	**1.16**
5	7.13	7.80	**3.25**	**3.47**
6	2.85	2.99	**1.10**	**1.14**
7	5.83	9.09	**2.57**	**4.52**
8	3.51	4.63	**1.73**	**2.22**
9	1.81	2.10	**1.50**	**1.61**
10	4.85	5.91	**1.93**	**2.07**
mean±std	4.37±2.1	5.38±2.8	1.79±0.8	2.19±1.2

[00215] As such, the E1 (HR) for this particular subject is as low as 4.05 bpm while the E1 (SpO2) is as low as 3.25%. It can be seen from Table 15, disclosed below, that HR and SpO2 both improved by 160% and 119%, respectively, post reconstruction method.

TABLE 15
OXIMA METHOD PERFORMANCE COMPARISON (SpO_2 ESTIMATIONS)

Subject	HR Improvement Rate		SpO_2 Improvement Rate	
	ImRate1%	ImRate2%	ImRate1%	ImRate2%
1	150.90	130.00	191.86	192.22
2	151.47	141.05	191.43	210.64
3	323.08	318.78	285.71	294.61
4	74.33	69.50	98.95	112.07
5	160.17	160.66	119.38	124.78
6	118.63	107.52	159.09	162.28
7	377.22	372.54	126.85	101.10
8	82.86	76.83	102.89	108.55
9	47.86	45.94	20.67	30.43
10	97.30	74.27	151.30	185.5
mean±std	158.38±108.2	149.71±109.9	144.81±70.5	152.2±73.2

V. Conclusions

[00216] As such, the OxiMA method that may be based on time-varying spectral analysis of the PPG signal combats motion artifacts that can degrade the accuracy of SpO2 and HR estimations. According to embodiments disclosed herein, the OxiMA method may decompose the PPG signal into many frequency bands using a VFCDM method (Chon, K.H.,

S. Dash, and J. Kihwan, Estimation of Respiratory Rate From Photoplethysmogram Data Using Time–Frequency Spectral Estimation. Biomedical Engineering, IEEE Transactions on, 2009. 56(8): p. 2054-2063), or any other suitable time-frequency technique, such as a wavelet analysis (Chon, K.H., S. Dash, and J. Kihwan, Estimation of Respiratory Rate From Photoplethysmogram Data Using Time–Frequency Spectral Estimation. Biomedical Engineering, IEEE Transactions on, 2009. 56(8): p. 2054-2063). According to embodiments disclosed herein, those components that are within the heart rate ranges including both extreme ranges of the low and high heart rates may be decomposed and used to reconstruct the PPG signal based on those components. As such, frequencies that are not within the prescribed HR ranges may be removed. From this reconstructed time series HR may be estimated and SpO2 may be estimated, as disclosed above.

[00217] The dataset used to verify the OxiMA method's performance was collected from 10 subjects during hypoxic experiments. The results show accurate estimation of both HR and SpO2 even during the presence of severe motion artifacts where the average error was only 2.4 bpm. More importantly, the average improvements in these estimates are astoundingly high for both HR (149%) and SpO2 (152%) when the reconstruction method applied, according to embodiments disclosed herein. Other methods for estimates of HR during severe motion artifacts for PPG signal Zhilin, Z., P. Zhouyue, and L. Benyuan, TROIKA: A General Framework for Heart Rate Monitoring Using Wrist-Type Photoplethysmographic Signals During Intensive Physical Exercise. Biomedical Engineering, IEEE Transactions on, 2015. 62(2): p. 522-531; Zhang, Z., Photoplethysmography-Based Heart Rate Monitoring in Physical Activities via Joint Sparse Spectrum Reconstruction. Biomedical Engineering, IEEE Transactions on, 2015. PP(99): p. 1-1; Salehizadeh, S., et al., A Novel Time-Varying Spectral Filtering Algorithm for Reconstruction of Motion Artifact Corrupted Heart Rate Signals During Intense Physical Activities Using a Wearable Photoplethysmogram Sensor. Sensors, 2015. 16(1): p. 10) produced good results (Kalman, R.E., A New Approach to Linear Filtering and Prediction Problems Transactions of the ASME – Journal of Basic Engineering, 1960. Series D (82)). However, these methods are only confined to HR estimation and not SpO2. Specifically, previous PPG reconstruction methods, such as (Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263; Kim, B.S.

and S.K. Yoo, Motion artifact reduction in photoplethysmography using independent component analysis. IEEE Trans Biomed Eng, 2006. 53(3): p. 566-8), have been tested under MA conditions but not with concomitant hypoxia. The results, disclosed abele, illustrate the efficacy of a method which provides accurate estimates of both SpO2 and HR even when there are significant MA and concomitant low oxygen saturation values.

[00218] Observations were made while analyzing the OxiMA data. The tracking ability of the OxiMA method decreased as the frequency changes during recordings increased. This is mostly likely because OxiMA tracks a dominant frequency through an 8-second window. Since each subjects' motion varied throughout each hypoxic maneuver, the dominant frequency can change within the observed window. The strength of the PPG's LED is one of the most important factors determining the performance. A reduction in the strength of the PPG signal can be caused by ambient light leaking into the gap between a PPG sensor and the skin surface (Zhang, Z., Photoplethysmography-Based Heart Rate Monitoring in Physical Activities via Joint Sparse Spectrum Reconstruction. Biomedical Engineering, IEEE Transactions on, 2015. PP(99): p. 1-1). This is because the power of the signal is dependent on the depth and reflection of the light from the pulse oximeter sensor to the subject's skin. This gap between the skin and the sensor may be the result of movement during physical activities or the shape of tissue that the sensors touch. In the datasets that have been analyzed, recordings #5 and #7 are examples of the above two scenarios.

[00219] Additionally, the local blood perfusion of the monitored region affects the signal-to-noise ratio of the PPG signal. When performing the hypoxic maneuvers, subjects' HR and breathing rate normally increase as oxygen saturation decreases. These physiologic changes cause more distinct pulsations in the digits, which increase the signal-to-noise ratio.

[00220] The OxiMA method can be easily implemented in real-time. Execution time of the method has been found to be only 180 msec on data divided into 8 second segments using Matlab® R2014a and CPU 3.6GHz. Therefore, given the high accuracy of the OxiMA method in estimating HR and SpO2 despite severe motion artifacts, this method has the potential to be applicable for implementation on wearable devices such as smart watches and PPG-based fitness sensors.

[00221] FIG. 23 is a block diagram of an example of the internal structure of a computer 2300 in which various embodiments of the present disclosure may be implemented. The computer 2300 contains a system bus 2302, where a bus is a set of hardware lines used for

data transfer among the components of a computer or processing system. The system bus 2302 is essentially a shared conduit that connects different elements of a computer system (*e.g.*, processor, disk storage, memory, input/output ports, network ports, *etc.*) that enables the transfer of information between the elements. Coupled to the system bus 2302 is an I/O device interface 2304 for connecting various input and output devices (*e.g.*, keyboard, mouse, displays, printers, speakers, *etc.*) to the computer 2300. A network interface 2306 allows the computer 2300 to connect to various other devices attached to a network. Memory 2308 provides volatile storage for computer software instructions 2310 and data 2312 that may be used to implement embodiments of the present disclosure. Disk storage 2314 provides non-volatile storage for computer software instructions 2310 and data 2312 that may be used to implement embodiments of the present disclosure. A central processor unit 2318 is also coupled to the system bus 2302 and provides for the execution of computer instructions.

[00222] Further example embodiments disclosed herein may be configured using a computer program product; for example, controls may be programmed in software for implementing example embodiments. Further example embodiments may include a non-transitory computer-readable medium containing instructions that may be executed by a processor, and, when loaded and executed, cause the processor to complete methods described herein. It should be understood that elements of the block and flow diagrams, such as the reconstruction unit 416, output unit 418, reconstruction unit 516, output unit 518, heart rate unit, arterial oxygen saturation (SpO2) unit, and ailment unit, disclosed above, may be implemented in software, hardware, such as via one or more arrangements of circuitry of FIG. 23, disclosed above, or equivalents thereof, firmware, a combination thereof, or other similar implementation determined in the future. In addition, the elements of the block and flow diagrams described herein may be combined or divided in any manner in software, hardware, or firmware. If implemented in software, the software may be written in any language that can support the example embodiments disclosed herein. The software may be stored in any form of computer readable medium, such as random access memory (RAM), read only memory (ROM), compact disk read-only memory (CD-ROM), and so forth. In operation, a general purpose or application-specific processor or processing core loads and executes software in a manner well understood in the art. It should be understood further that the block and flow diagrams may include more or fewer elements, be arranged or oriented differently, or be represented differently. It should be understood that implementation may

dictate the block, flow, and/or network diagrams and the number of block and flow diagrams illustrating the execution of embodiments disclosed herein.

[00223] The teachings of all patents, published applications and references cited herein are incorporated by reference in their entirety.

[00224] While this invention has been particularly shown and described with references to example embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the invention encompassed by the appended claims.

CLAIMS

What is claimed is:

1. A method for reconstructing a heart-related signal output by a biomedical sensor, the method comprising:

reconstructing a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal, the reconstructing based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of the movement; and

outputting the reconstructed representation of the heart-related signal.

2. The method of Claim 1, wherein the motion artifacts are suppressed in the reconstructed representation of the heart-related signal.

3. The method of Claim 1, wherein:

the time-varying spectral analysis includes pre-processing the heart-related signal to produce a pre-processed heart-related signal; and

in an event the classification indicates that the movement does not rise to a level causing the motion artifacts, the reconstructed representation is based on an average value of peak-to-peak intervals in the pre-processed heart-related signal.

4. The method of Claim 3, wherein the pre-processing includes filtering the heart-related signal to produce a filtered heart-related signal.

5. The method of Claim 4, wherein the pre-processing further includes down-sampling the filtered heart-related signal, the down-sampling being at a sampling rate less than an original sampling rate.

6. The method of Claim 1, wherein the time-varying spectral analysis includes:

computing a first time-frequency spectrum (TFS) of the heart-related signal; and

computing a second TFS of the motion signal.

7. The method of Claim 6, wherein the first TFS computed and the second TFS computed are 3-dimensional spectra, the first TFS computed and the second TFS computed each including a respective time-varying amplitude or power distribution with respect to time and frequency.

8. The method of Claim 6, wherein the first TFS computed is a first time-varying power spectral density (PSD) and the second TFS computed is a second time-varying PSD.

9. The method of Claim 6, wherein the reconstructed representation is a current reconstructed representation and wherein, based on the classification indicating that the movement does rise to a level causing the motion artifacts and is a pseudo-periodic movement or a periodic movement, the reconstructing includes:

determining whether at least one spectral peak is present having a corresponding frequency within a given frequency range at a point in time in the first TFS computed, the current reconstructed representation being reconstructed for the point in time; and

wherein, based on a determination that the at least one spectral peak is not present, the current reconstructed representation is based on a prior reconstructed representation, the prior reconstructed representation associated with a previous point in time in the first TFS computed.

10. The method of Claim 9, wherein the given frequency range is 0.5 Hz to 3 Hz.

11. The method of Claim 6, wherein the reconstructing includes:

retaining up to a pre-determined number of candidate spectral peaks located at a first point in time in the first TFS computed, the candidate spectral peaks retained based on having corresponding frequencies within a given frequency range and

highest amplitude or power values relative to other spectral peaks located at the first point in time, the other spectral peaks having respective frequencies within the given frequency range; and

discarding each of the candidate spectral peaks retained that is associated with a same frequency as a dominant spectral peak located at a second point in time in the second TFS computed, the first point in time and the second point in time having same time values.

12. The method of Claim 11, wherein the given frequency range is 0.5 Hz to 3 Hz.

13. The method of Claim 11, wherein the representation is a current representation, wherein the reconstructed representation is a current reconstructed representation, and wherein, in an event the discarding discards each of the candidate spectral peaks retained, reconstructing the current representation is based on a prior reconstructed representation, the prior reconstructed representation associated with a previous point in time in the first TFS computed, the previous point in time being an earlier point in time with respect to the first point in time.

14. The method of Claim 11, wherein the discarding is a first discarding and wherein the representation is a current representation and, wherein, in an event the first discarding results in at least one remaining candidate spectral peak retained, reconstructing the current representation further includes:

second discarding, wherein the second discarding discards remaining candidate spectral peaks, of the at least one remaining candidate spectral peak retained, based on whether a corresponding frequency of the at least one remaining candidate spectral peak retained is distanced by at least a frequency difference threshold from a prior reconstructed representation's frequency, the prior reconstructed representation associated with a previous point in time in the first TFS computed, the previous point in time being an earlier point in time with respect to the first point in time.

15. The method of Claim 14, wherein:

based on each of the at least one remaining candidate spectral peak retained having been discarded by the second discarding, reconstructing the current representation is based on the prior reconstructed representation; and

based on at least one last candidate spectral peak remaining, the at least one last candidate spectral peak remaining not discarded by the second discarding, reconstructing the current representation is based on a selected candidate spectral peak selected from amongst the at least one last candidate spectral peak remaining having a closest corresponding frequency to the prior reconstructed representation's frequency relative to respective frequencies of each of the at least one last candidate spectral peak remaining.

16. The method of Claim 11, wherein the dominant spectral peak has a largest power or amplitude value relative to other peaks located at the second point in time in the second TFS.

17. The method of Claim 11, wherein the retaining and the discarding are based on:

the classification indicating that the movement is a pseudo-periodic movement or a periodic movement; and

determining that at least one spectral peak with a corresponding frequency in the given frequency range is present at the first point in time.

18. The method of Claim 6, wherein the time-varying spectral analysis further includes pre-processing the heart-related signal and the motion signal for the computing of the first TFS and the second TFS.

19. The method of Claim 6, wherein the pre-processing includes filtering the heart-related signal and the motion signal to produce a filtered heart-related signal and a filtered motion signal, respectively.

20. The method of Claim 19, wherein the pre-processing further includes down-sampling both the filtered heart-related signal and the filtered motion signal, the down-sampling being at a sampling rate less than an original sampling rate.

21. The method of Claim 6, further including:

classifying the classification of the movement by comparing an amount of amplitude modulation in the second TFS computed to an amplitude modulation threshold, wherein the classification indicates whether the movement rises to a level of causing the motion artifacts based on a result of the comparing.

22. The method of Claim 21, wherein the amplitude modulation threshold is dependent on a type of the motion detector sensor.

23. The method of Claim 21, wherein, in an event the result indicates that the movement does rise to the level causing the motion artifacts, classifying the classification of the movement further includes determining whether the movement is either a pseudo-periodic movement or a periodic movement, versus a random movement.

24. The method of Claim 23, wherein, in determining whether the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement includes, the method further includes:

identifying a first, second, and third frequency associated, respectively, with a first, second, and third spectral peak in the second TFS at a point in time in the second TFS, the first, second, and third peaks having largest power or amplitude values relative to other peaks in the second TFS at the point in time, the first spectral peak being a largest spectral peak amongst the first, second, and third spectral peaks;

computing a first ratio of the second frequency identified to the first frequency identified and determining a first comparison result by comparing the first ratio computed to a first ratio value; and

computing a second ratio of the third frequency identified to the first frequency identified and determining a second comparison result by comparing the second ratio computed to a second ratio value, wherein the classification further indicates that the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement, based on the first comparison result and the second comparison result.

25. The method of Claim 24, wherein the first ratio value is 2 and the second ratio value is 3.

26. The method of Claim 1, wherein the time-varying signal analysis includes pre-processing the heart-related signal to produce a pre-processed heart-related signal and, in an event the classification of the movement indicates random movement, the reconstructing includes:

computing an average value of a number of prior reconstructed representations outputted prior to the reconstructing, the number based on a duration of consecutive motion artifacts, detected prior to the reconstructing;

computing a bandpass filter cutoff frequency based on the average value computed;

filtering the pre-processed heart-related signal by applying the band pass filter computed to produce a filtered, pre-processed heart-related signal; and

wherein the reconstructed representation is based on an average peak-to-peak interval value of the filtered, pre-processed heart-related signal.

27. The method of Claim 1, wherein the heart-related signal and the motion signal are produced, concurrently.

28. The method of Claim 1, further comprising:

segmenting the heart-related signal into a plurality of windowed heart-related signal data segments and the motion signal into a corresponding plurality of windowed motion signal data segments; and

repeating the reconstructing and the outputting for each windowed heart-related signal data segment and each corresponding motion signal data segment.

29. The method of Claim 28, wherein the time window is a value in a range from 2 to 32 seconds.

30. The method of Claim 1, wherein the biomedical sensor is at least one of: a photoplethysmogram (PPG) sensor, piezoelectric sensor, Light Emitting Diode (LED) based sensor, camera sensor, and pulse oximeter sensor, and wherein the motion sensor is an accelerometer.

31. The method of Claim 1, wherein the biomedical sensor and the motion sensor are co-located.

32. The method of Claim 1, further comprising employing the reconstructed representation to determine a heart rate estimate.

33. The method of Claim 1, further comprising employing the reconstructed representation to determine an arterial oxygen saturation (SpO2) estimate.

34. The method of Claim 1, further comprising employing the reconstructed representation to detect or predict a heart-related ailment, the heart-related ailment including at least one of a heart rate variability (HRV) condition, atrial fibrillation condition, congestive heart failure condition, and tachycardia condition.

35. The method of Claim 1, wherein the reconstructing and the outputting are performed in real-time with respect to production of the heart-related signal and the motion signal.

36. The method of Claim 1, wherein the reconstructing and the outputting are performed in non-real-time with respect to production of the heart-related signal and the motion signal.

37. An apparatus for reconstructing a heart-related signal output by a biomedical sensor, the apparatus comprising:

a reconstruction unit configured to reconstruct a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal, the reconstructing based on (i) a time-varying spectral analysis of the heart-related signal

and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of the movement; and

an output unit configured to output the reconstructed representation of the heart-related signal.

38. The apparatus of Claim 37, wherein the motion artifacts are suppressed in the reconstructed representation of the heart-related signal.

39. The apparatus of Claim 37, wherein:

the time-varying spectral analysis includes pre-processing the heart-related signal to produce a pre-processed heart-related signal; and

in an event the classification indicates that the movement does not rise to level causing the motion artifacts, the reconstructed representation is based on an average value of peak-to-peak intervals in the pre-processed heart-related signal.

40. The apparatus of Claim 39, wherein the pre-processing includes filtering the heart-related signal to produce a filtered heart-related signal.

41. The apparatus of Claim 40, wherein the pre-processing further includes down-sampling at a sampling rate less than an original sampling rate, the filtered heart-related signal, the down-sampling being at a sampling rate less than an original sampling rate.

42. The apparatus of Claim 37, wherein the time-varying spectral analysis includes:

computing a first time-frequency spectrum (TFS) of the heart-related signal; and

computing a second TFS of the motion signal.

43. The apparatus of Claim 42, wherein the first TFS computed and the second TFS computed are 3-dimensional spectra, the first TFS computed and the second TFS

computed each including a respective time-varying amplitude or power distribution with respect to time and frequency.

44. The apparatus of Claim 42, wherein the first TFS computed is a first time-varying power spectral density (PSD) and the second TFS computed is a second time-varying PSD.

45. The apparatus of Claim 42, wherein the reconstructed representation is a current reconstructed representation and wherein, based on the classification indicating that the movement does rise to a level causing the motion artifacts and is a pseudo-periodic movement or a periodic movement, to reconstruct the representation includes:

determining whether at least one spectral peak is present having a corresponding frequency within a given frequency range at a point in time in the first TFS computed, the current reconstructed representation being reconstructed for the point in time; and

wherein, based on a determination that the at least one spectral peak is not present, the reconstructed current representation is based on a prior reconstructed representation, the prior reconstructed representation associated with a previous point in time in the first TFS computed.

46. The apparatus of Claim 45, wherein the given frequency range is 0.5 Hz to 3 Hz.

47. The apparatus of Claim 42, wherein to reconstruct the representation includes:

retaining up to a pre-determined number of candidate spectral peaks located at a first point in time in the first TFS computed, the candidate spectral peaks retained based on having corresponding frequencies within a given frequency range and highest amplitude or power values relative to other spectral peaks located at the first point in time, the other spectral peaks having respective frequencies within the given frequency range; and

discarding each of the candidate spectral peaks retained that is associated with a same frequency as a dominant spectral peak located at a second point in time in the second TFS computed, the first point in time and the second point in time having same time values.

48. The apparatus of Claim 47, wherein the given frequency range is 0.5 Hz to 3 Hz.

49. The apparatus of Claim 47, wherein the representation is a current representation, wherein the reconstructed representation is a current reconstructed representation, and wherein, in an event the discarding discards each of the candidate spectral peaks retained, reconstructing the current representation is based on a prior reconstructed representation, the prior reconstructed representation associated with a previous point in time in the first TFS computed, the previous point in time being an earlier point in time with respect to the first point in time.

50. The apparatus of Claim 47, wherein the discarding is a first discarding and wherein the representation is a current representation and, wherein, in an event the first discarding results in at least one remaining candidate spectral peak retained, reconstructing the current representation further includes:

second discarding, wherein the second discarding discards remaining candidate spectral peaks, of the at least one remaining candidate spectral peak retained, based on whether a corresponding frequency of the at least one remaining candidate spectral peak retained is distanced by at least a frequency difference threshold from a prior reconstructed representation's frequency, the prior reconstructed representation associated with a previous point in time in the first TFS computed, the previous point in time being an earlier point in time with respect to the first point in time.

51. The apparatus of Claim 50, wherein:

based on each of the at least one remaining candidate spectral peak retained having been discarded by the second discarding, reconstructing the current representation is based on the prior reconstructed representation; and

based on at least one last candidate spectral peak remaining, the at least one last candidate spectral peak remaining not discarded by the second discarding, reconstructing the current representation is based on a selected candidate spectral peak selected from amongst the at least one last candidate spectral peak remaining having a closest corresponding frequency to the prior reconstructed representation's frequency relative to respective frequencies of each of the at least one last candidate spectral peak remaining.

52. The apparatus of Claim 47, wherein the dominant spectral peak has a largest power or amplitude value relative to other peaks located at the second point in time in the second TFS.

53. The apparatus of Claim 47, wherein the retaining and the discarding are based on:

the classification of the movement indicating that the movement is a pseudo-periodic movement or a periodic movement; and

determining that at least one spectral peak with a corresponding frequency in the given frequency range is present at the first point in time.

54. The apparatus of Claim 42, wherein the time-varying spectral analysis further includes pre-processing the heart-related signal and the motion signal for the computing of the first TFS and the second TFS.

55. The apparatus of Claim 42, wherein the pre-processing includes filtering the heart-related signal and the motion signal to produce a filtered heart-related signal and a filtered motion signal, respectively.

56. The apparatus of Claim 55, wherein the pre-processing further includes down-sampling both the filtered heart-related signal and the filtered motion signal, the down-sampling being at a sampling rate less than an original sampling rate.

57. The apparatus of Claim 42, further including a classification unit, the classification unit configured to:

classify the classification of the movement by comparing an amount of amplitude modulation in the second TFS computed to an amplitude modulation threshold, wherein the classification indicates whether the movement rises to a level causing the motion artifacts based on a result of the comparing.

58. The apparatus of Claim 57, wherein the amplitude modulation threshold is dependent on a type of the motion detector sensor.

59. The apparatus of Claim 57, wherein, in an event the result indicates that the movement does rise to the level causing the motion artifacts, the classification unit is further configured to classify the classification of the movement by determining whether the movement is either a pseudo-periodic movement or a periodic movement, versus a random movement.

60. The apparatus of Claim 59, wherein to determine whether the movement is either the pseudo-periodic movement or the periodic movement versus a random movement includes:

identifying a first, second, and third frequency associated, respectively, with a first, second, and third spectral peak in the second TFS at a point in time in the second TFS, the first, second, and third peaks having largest power or amplitude values relative to other peaks in the second TFS at the point in time, the first spectral peak being a largest spectral peak amongst the first, second, and third spectral peaks;

computing a first ratio of the second frequency identified to the first frequency identified and determining a first comparison result by comparing the first ratio computed to a first ratio value; and

computing a second ratio of the third frequency identified to the first frequency identified and determining a second comparison result by comparing the second ratio computed to a second ratio value, wherein the classification further indicates that the movement is either the pseudo-periodic movement or the periodic

movement, versus the random movement, based on the first comparison result and the second comparison result.

61. The apparatus of Claim 60, wherein the first ratio value is 2 and the second ratio value is 3.

62. The apparatus of Claim 59, wherein the time-varying signal analysis includes pre-processing the heart-related signal to produce a pre-processed heart-related signal and, in an event the classification of the movement indicates random movement, the reconstructing includes:

computing an average value of a number of prior reconstructed representations outputted prior to the reconstructing, the number based on a duration of consecutive motion artifacts, detected prior to the reconstructing;

computing a bandpass filter cutoff frequency based on the average value computed;

filtering the pre-processed heart-related signal by applying the band pass filter computed to produce a filtered, pre-processed heart-related signal; and

wherein the reconstructed representation is based on an average peak-to-peak interval value of the filtered, pre-processed heart-related signal.

63. The apparatus of Claim 37, wherein the heart-related signal and the motion signal are produced, concurrently.

64. The apparatus of Claim 37, further comprising segmentation unit configured to:

segment the heart-related signal into a plurality of windowed heart-related signal data segments and the motion signal into corresponding plurality of windowed motion signal data segments, wherein the reconstruction unit and the output unit reconstruct the representation and output the reconstructed representation, respectively, based on each windowed heart-related signal data segment and each corresponding motion signal data segment.

65. The apparatus of Claim 64, wherein the time window is a value in a range from 2 to 32 seconds.

66. The apparatus of Claim 37, wherein the biomedical sensor is at least one of: a photoplethysmogram (PPG) sensor, piezoelectric sensor, Light Emitting Diode (LED) based sensor, camera sensor, and pulse oximeter sensor, and wherein the motion sensor is an accelerometer.

67. The apparatus of Claim 37, wherein the apparatus includes the biomedical sensor and the motion sensor.

68. The apparatus of Claim 37, further comprising a heart rate estimator configured to employ the reconstructed representation to determine a heart rate estimate.

69. The apparatus of Claim 37, further comprising an arterial oxygen saturation (SpO2) unit configured to employ the reconstructed representation to determine a SpO2 estimate.

70. The apparatus of Claim 37, further comprising an ailment unit configured to employ the reconstructed representation to detect or predict a heart-related ailment, the heart-related ailment including at least one of a heart rate variability (HRV) condition, an atrial fibrillation condition, a congestive heart failure condition, and a tachycardia condition.

71. The apparatus of Claim 37, wherein the reconstruction unit and the output unit are configured to reconstruct and to output, respectively, in real-time with respect to production of the heart-related signal and the motion signal.

72. The apparatus of Claim 37, wherein the reconstruction unit and the output unit are configured to reconstruct and to output, respectively, in non-real-time with respect to production of the heart-related signal and the motion signal.

73. A non-transitory computer-readable medium having encoded thereon a sequence of instructions which, when loaded and executed by a processor, causes the processor to reconstruct a heart-related signal output by a biomedical sensor, the processor reconstructing the heart-related signal by:

reconstructing a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal, the reconstructing based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of the movement; and

outputting the reconstructed representation of the heart-related signal.

Petitioner Ex-1004, 0866

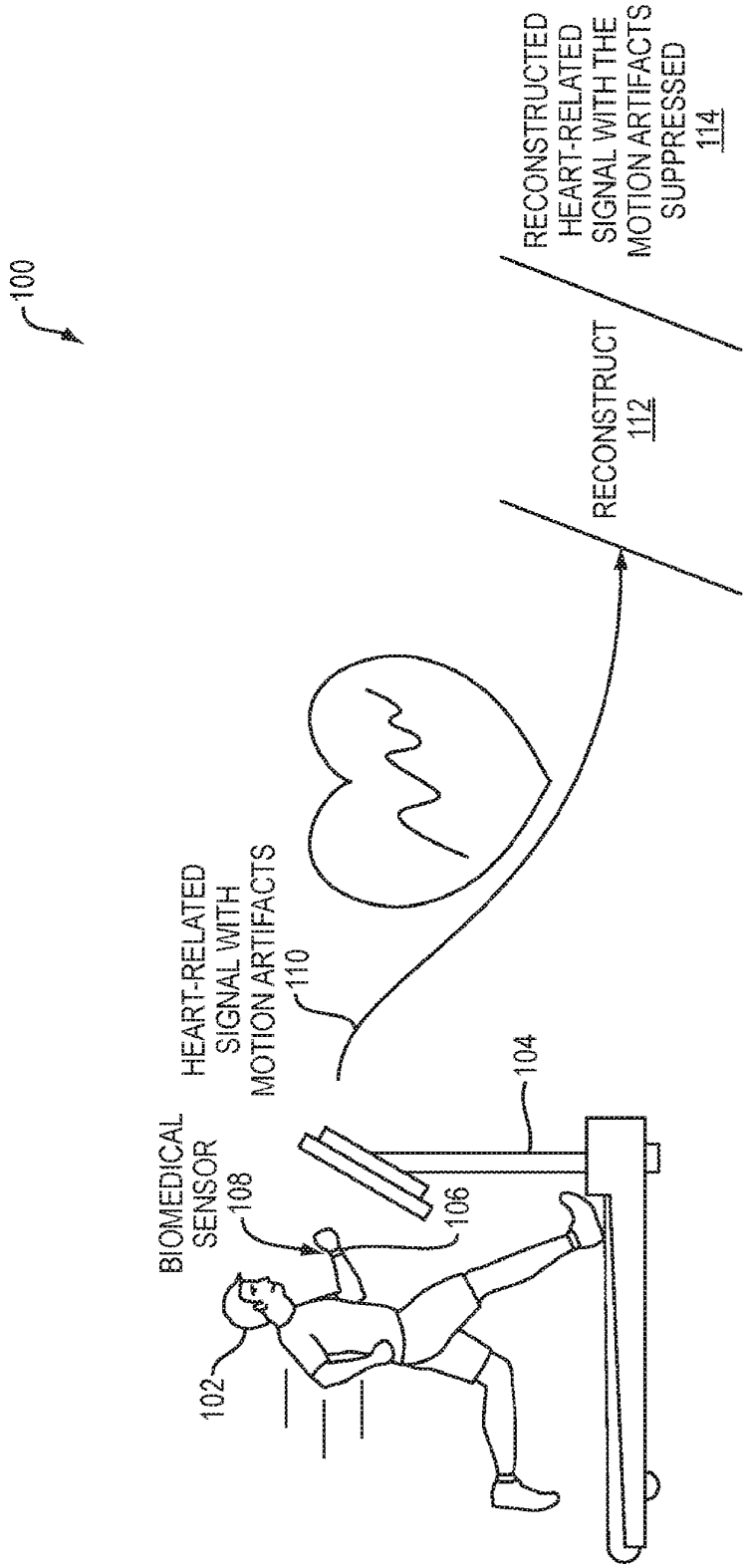


FIG. 1

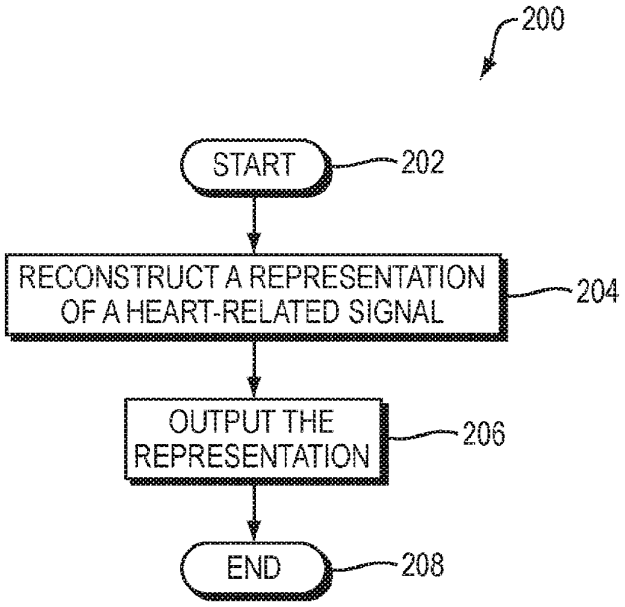

200
START
202
RECONSTRUCT A REPRESENTATION OF A HEART-RELATED SIGNAL
204
OUTPUT THE REPRESENTATION
206
END
208

FIG. 2

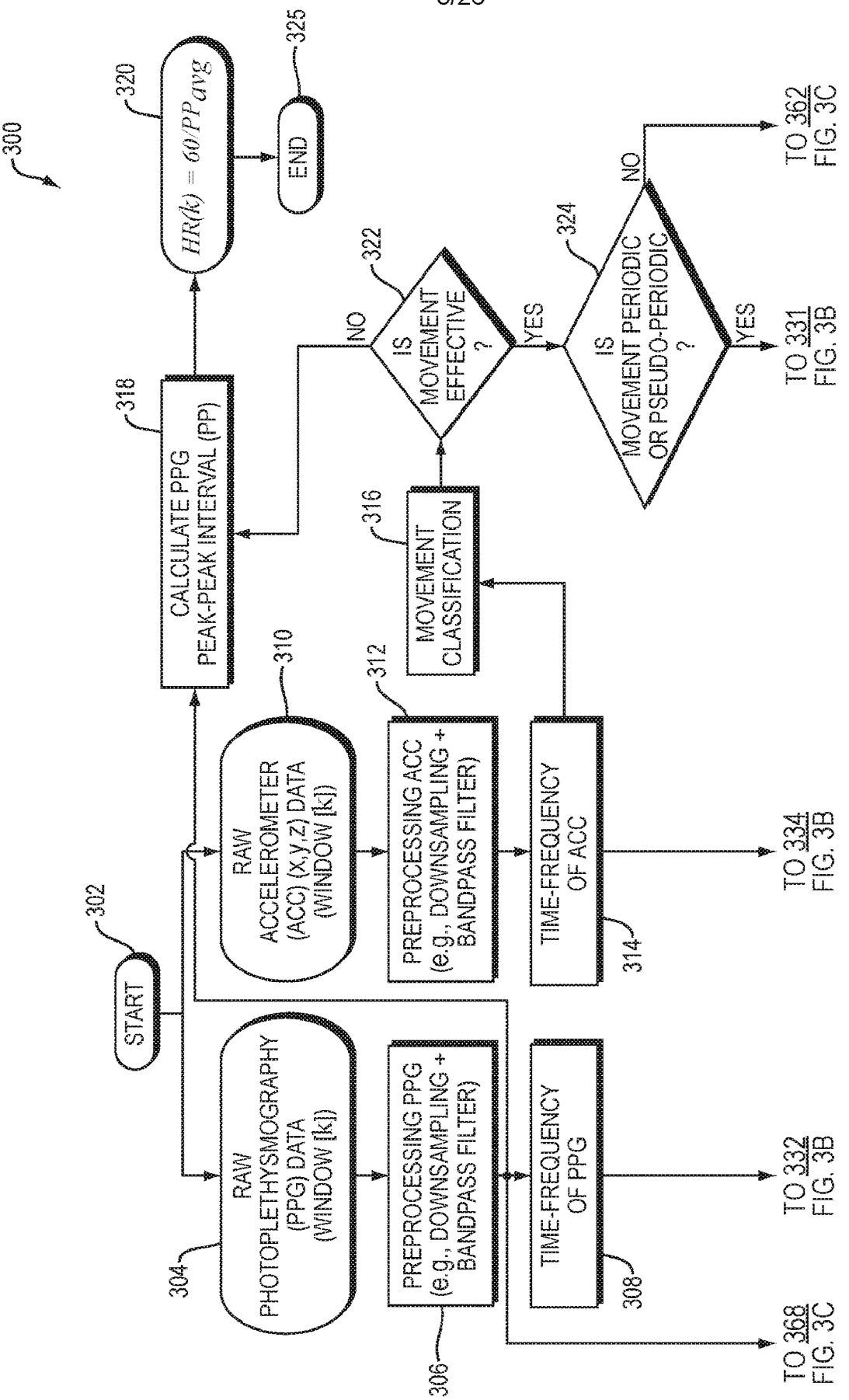


FIG. 3A

Petitioner Ex-1004, 0868

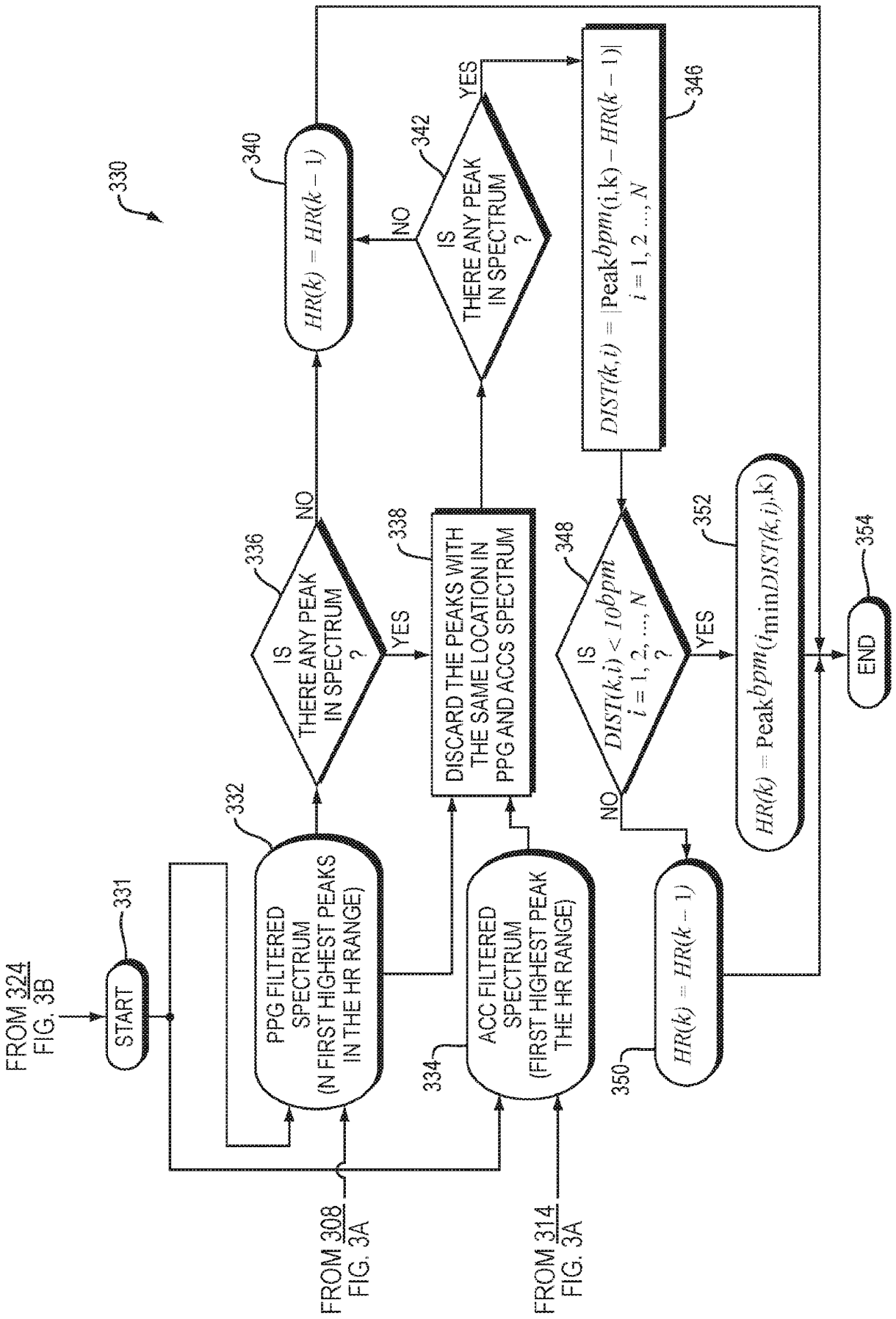


FIG. 3B

Petitioner Ex-1004, 0869

Petitioner Ex-1004, 0870

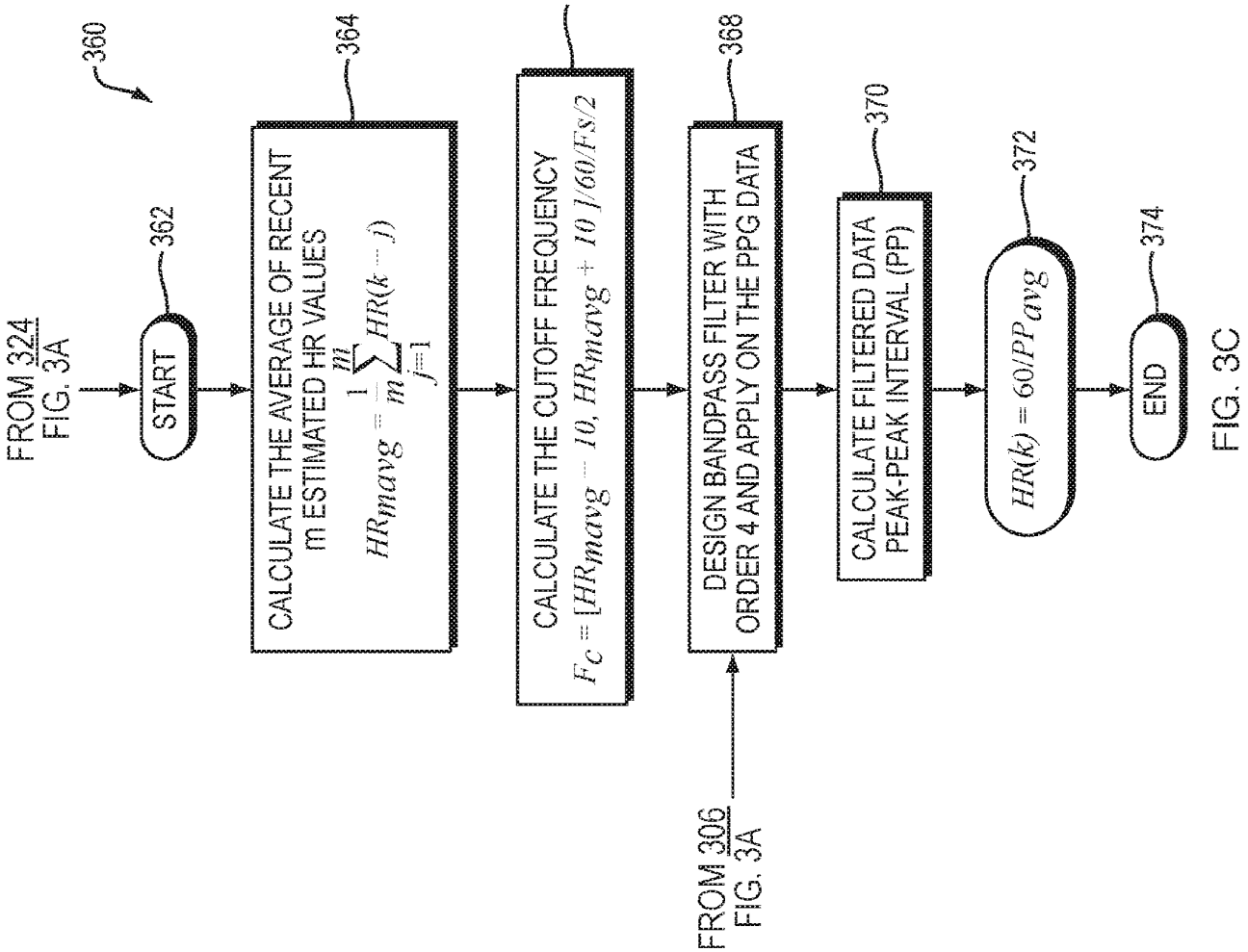


FIG. 3C

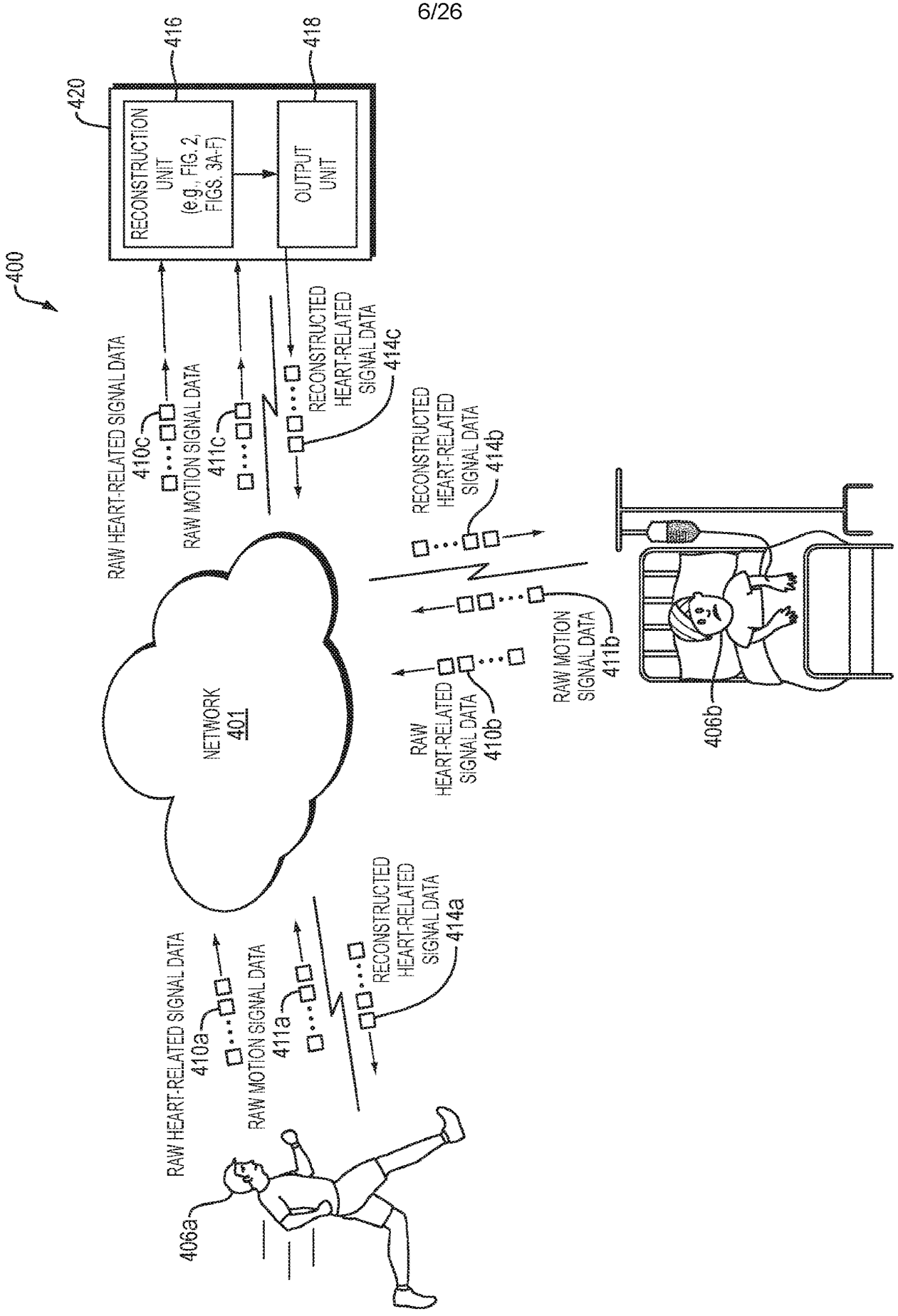


FIG. 4

Petitioner Ex-1004, 0871

Petitioner Ex-1004, 0872

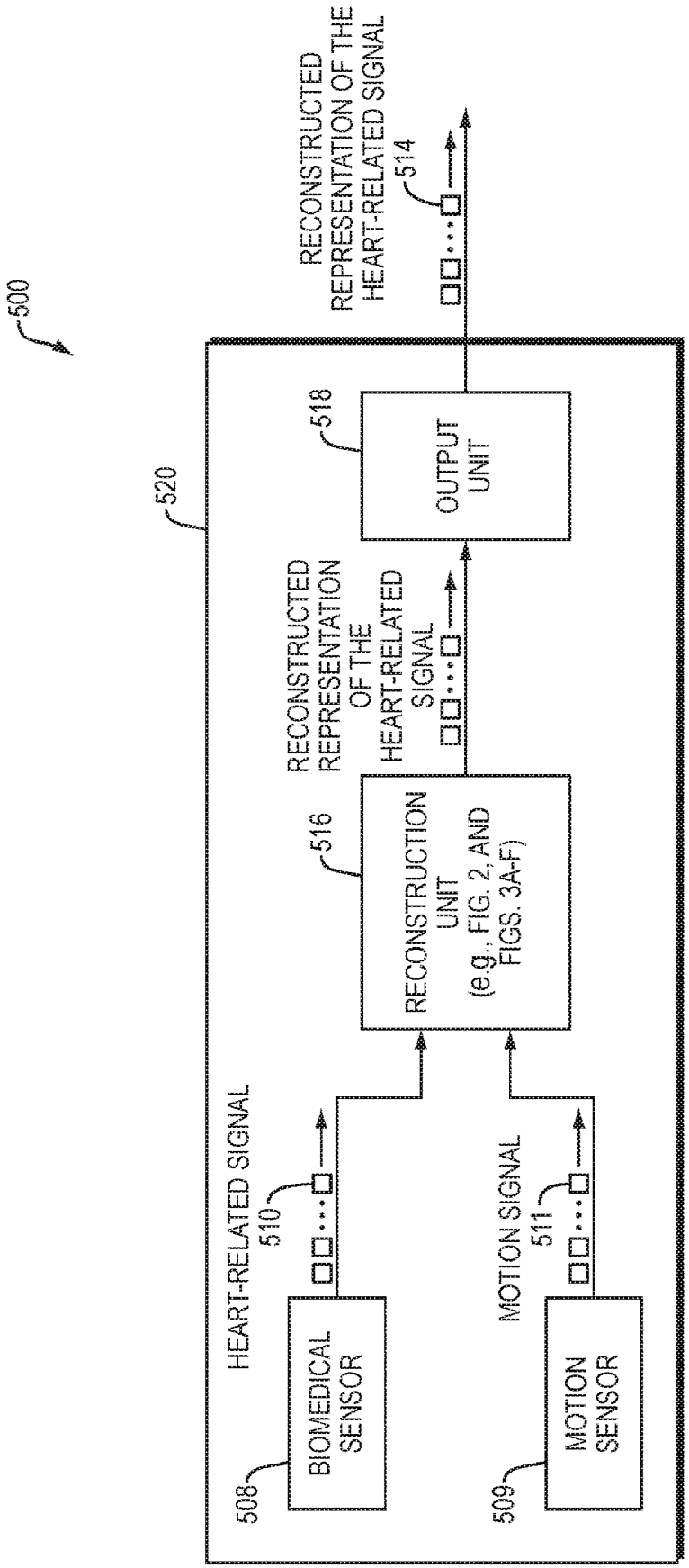


FIG. 5

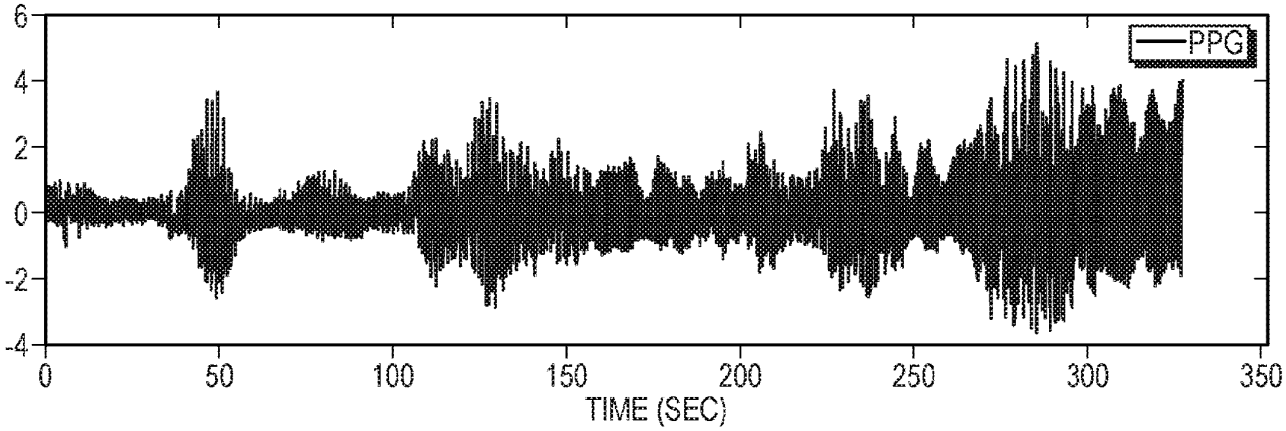


FIG. 6A

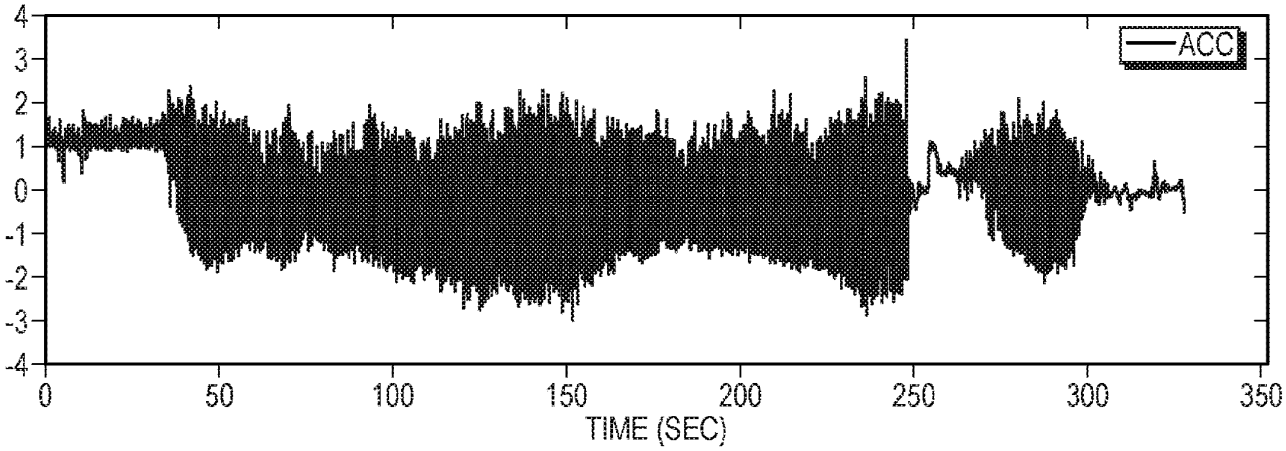


FIG. 6B

Petitioner Ex-1004, 0873

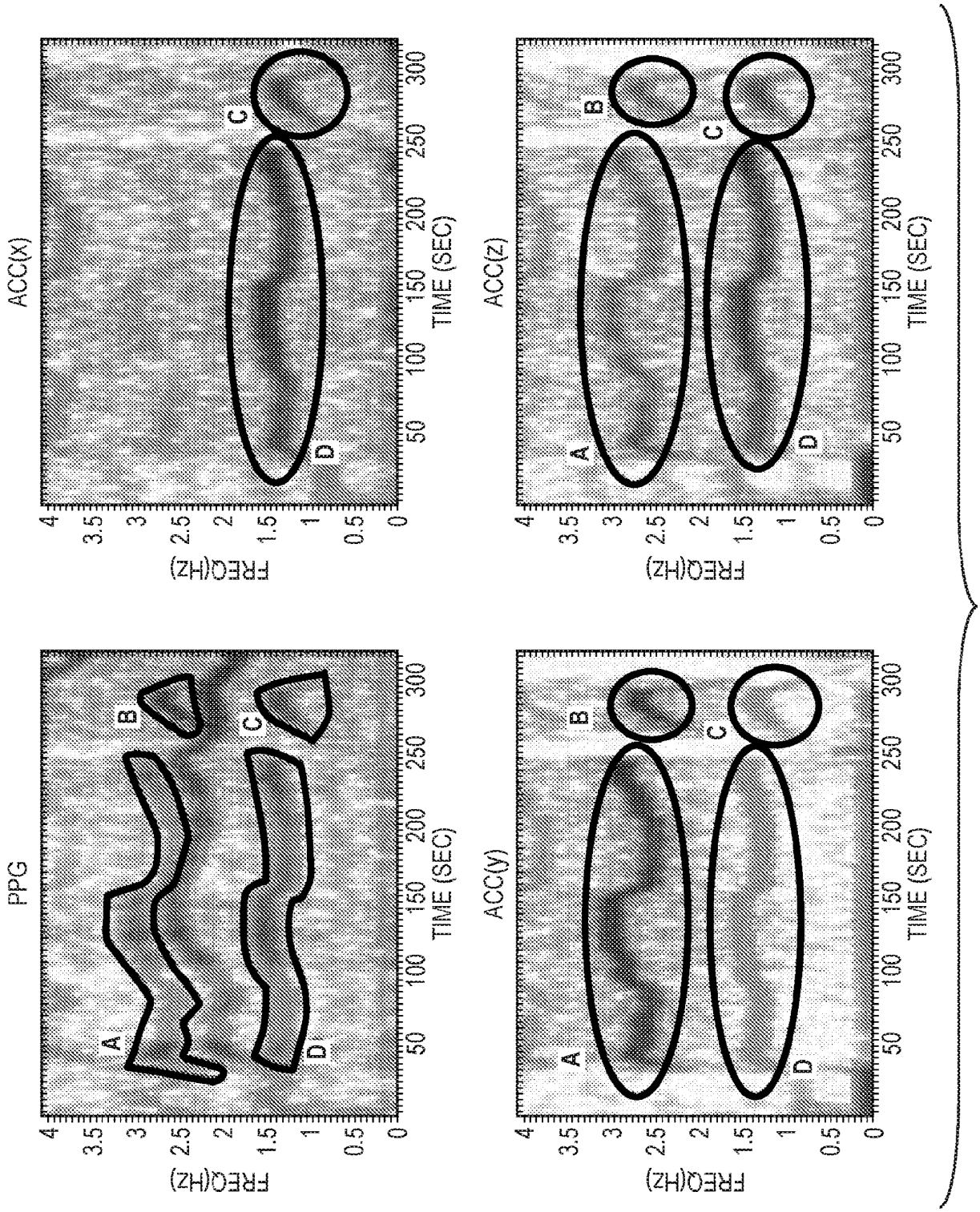


FIG. 6C

Petitioner Ex-1004, 0874

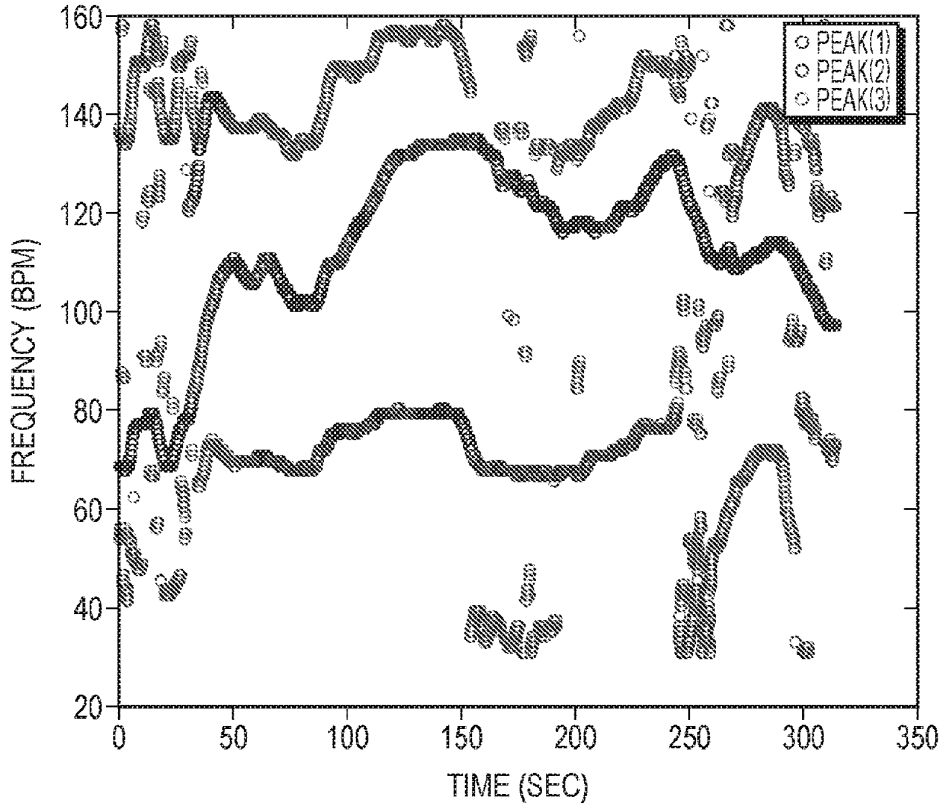

PEAK(1)
PEAK(2)
PEAK(3)
FREQUENCY (BPM)
160
140
120
100
80
60
40
20
0
50
100
150
200
250
300
350
TIME (SEC)

FIG. 7

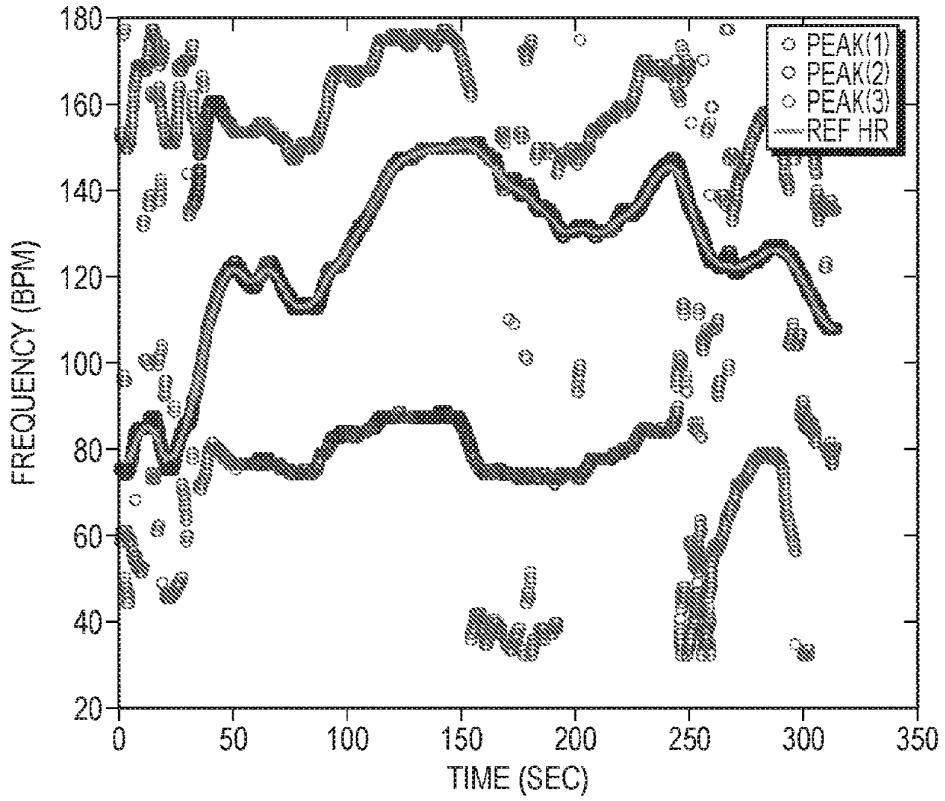

FREQUENCY (BPM)
TIME (SEC)
PEAK(1)
PEAK(2)
PEAK(3)
REF HR
180
160
140
120
100
80
60
40
20
0
50
100
150
200
250
300
350

FIG. 8A

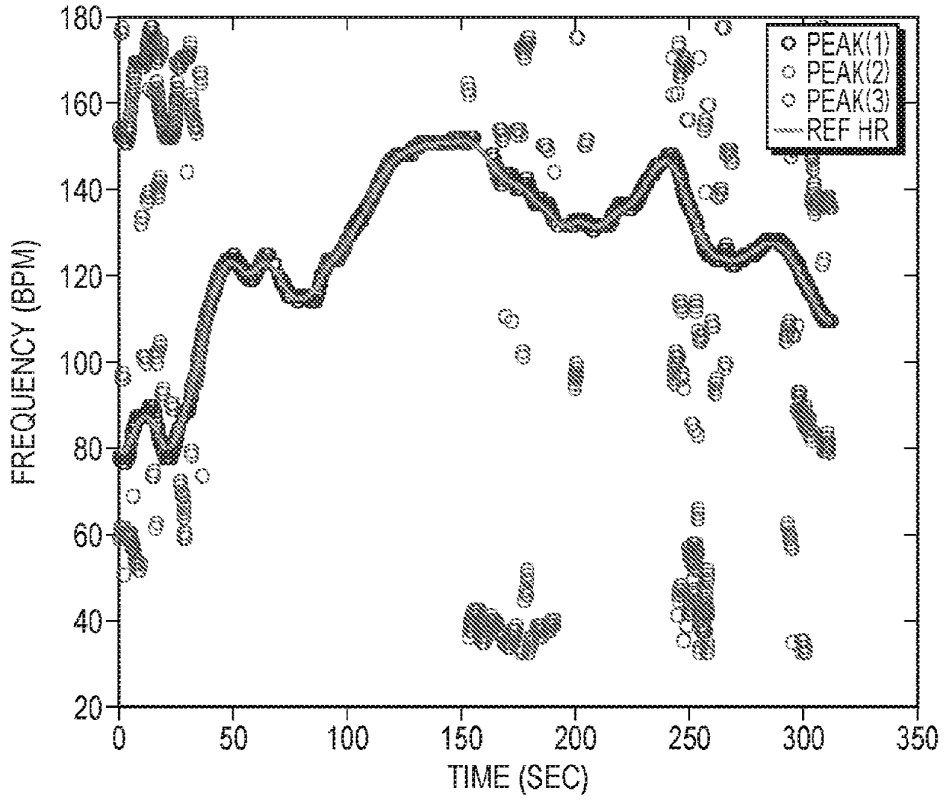

FREQUENCY (BPM)
TIME (SEC)
PEAK(1)
PEAK(2)
PEAK(3)
REF HR
180
160
140
120
100
80
60
40
20
0
50
100
150
200
250
300
350

FIG. 8B

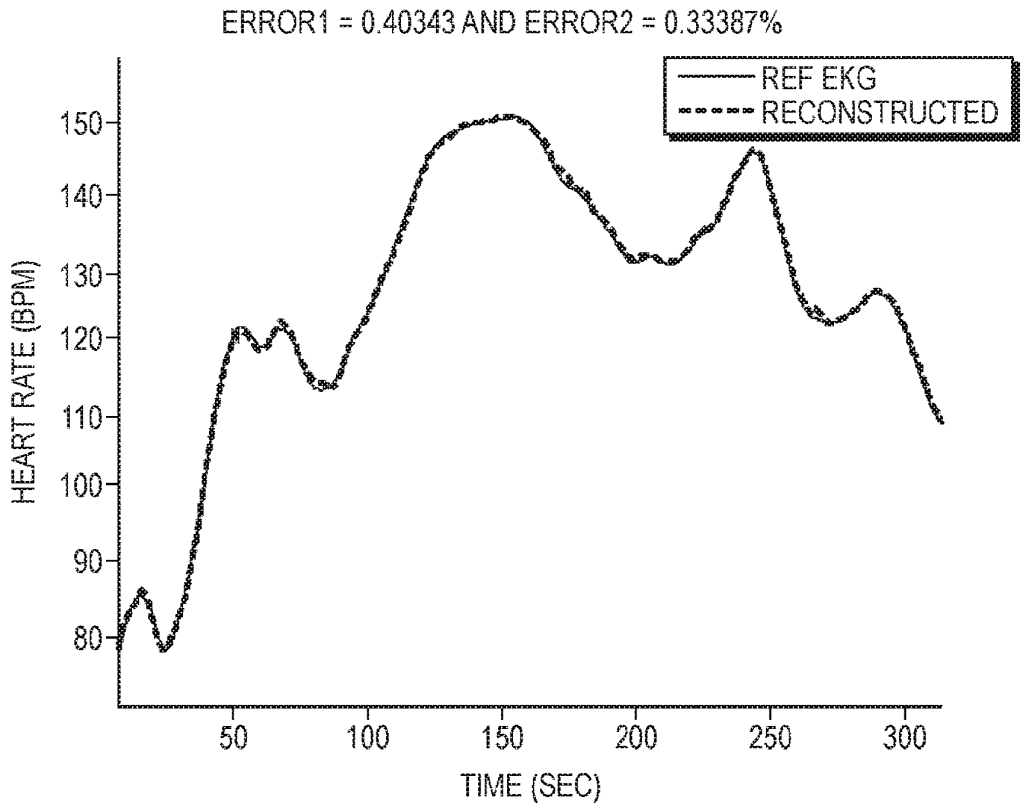


FIG. 9

Petitioner Ex-1004, 0877

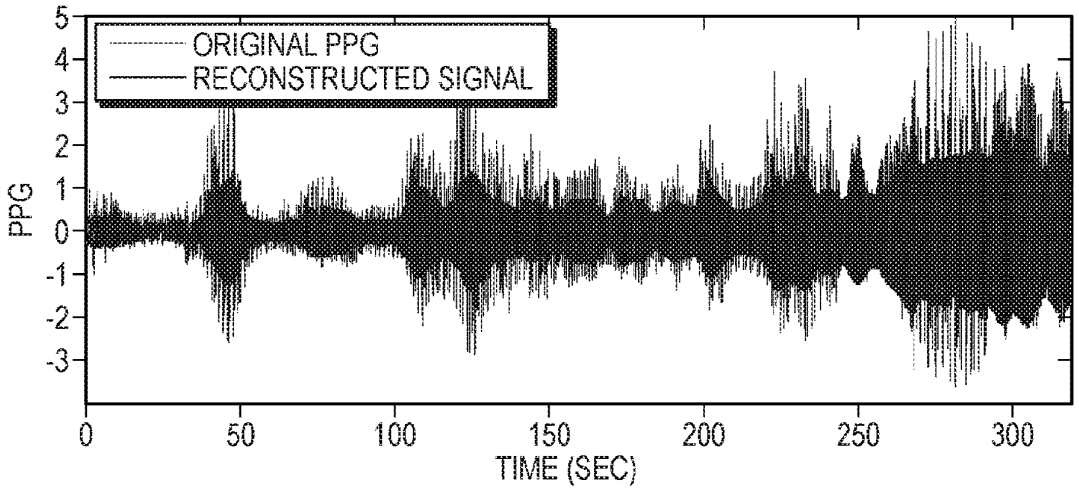


FIG. 10A

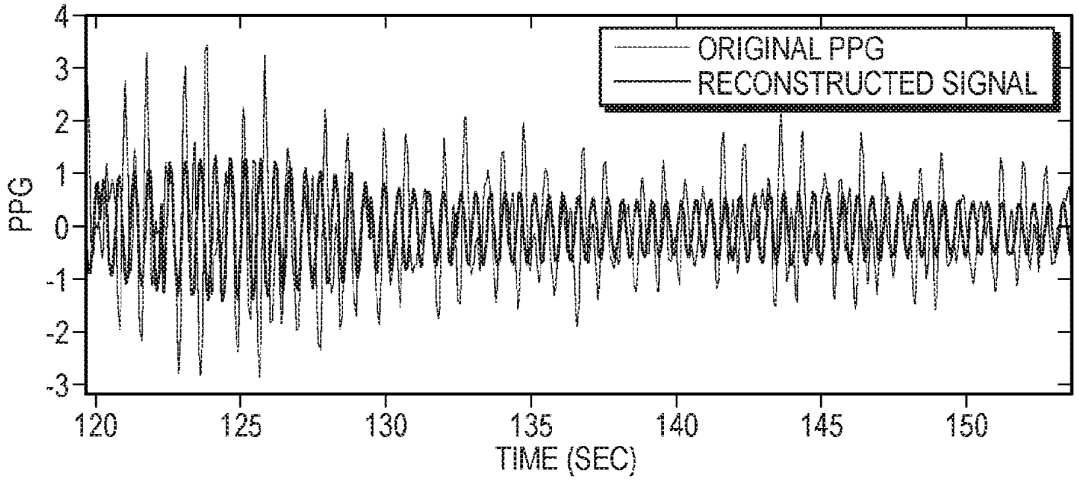


FIG. 10B

Petitioner Ex-1004, 0878

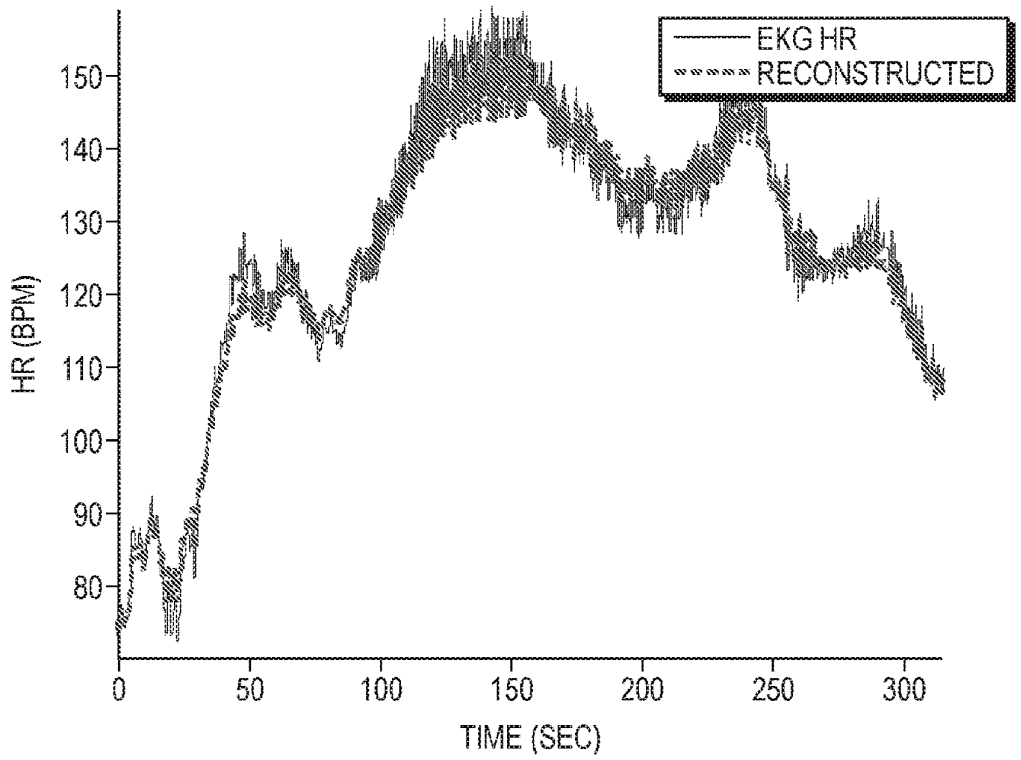


FIG. 11A

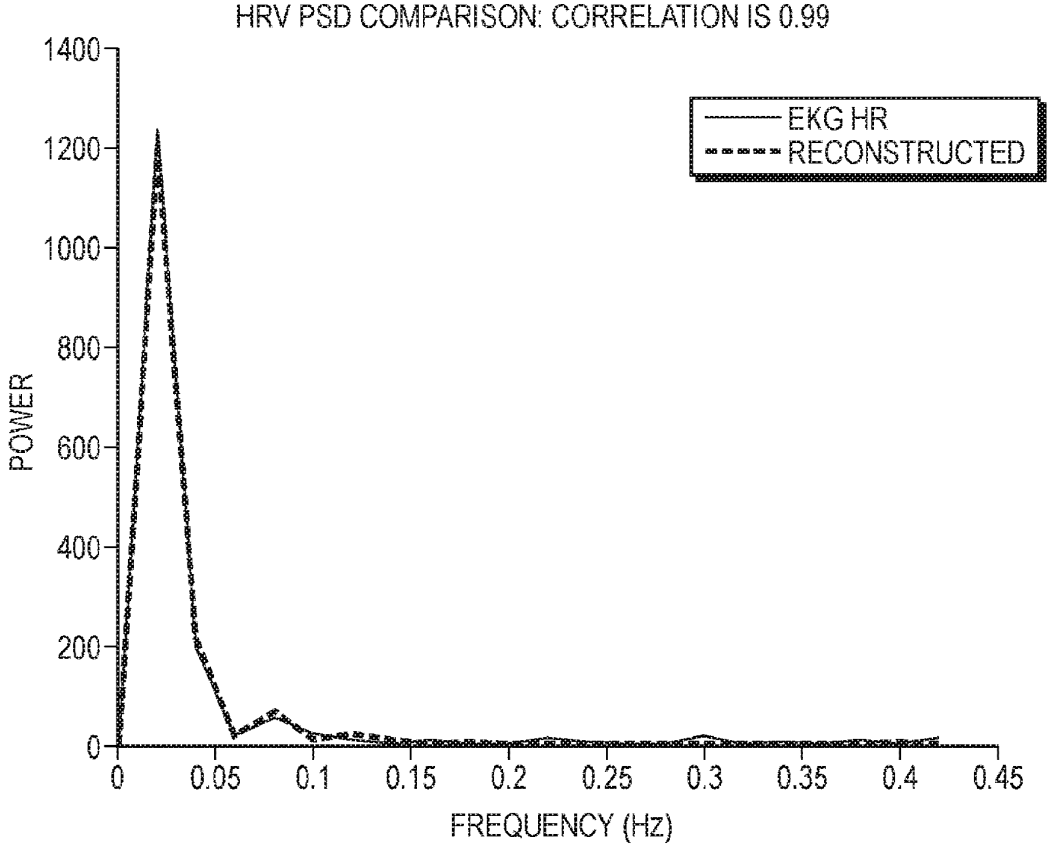


FIG. 11B

Petitioner Ex-1004, 0879

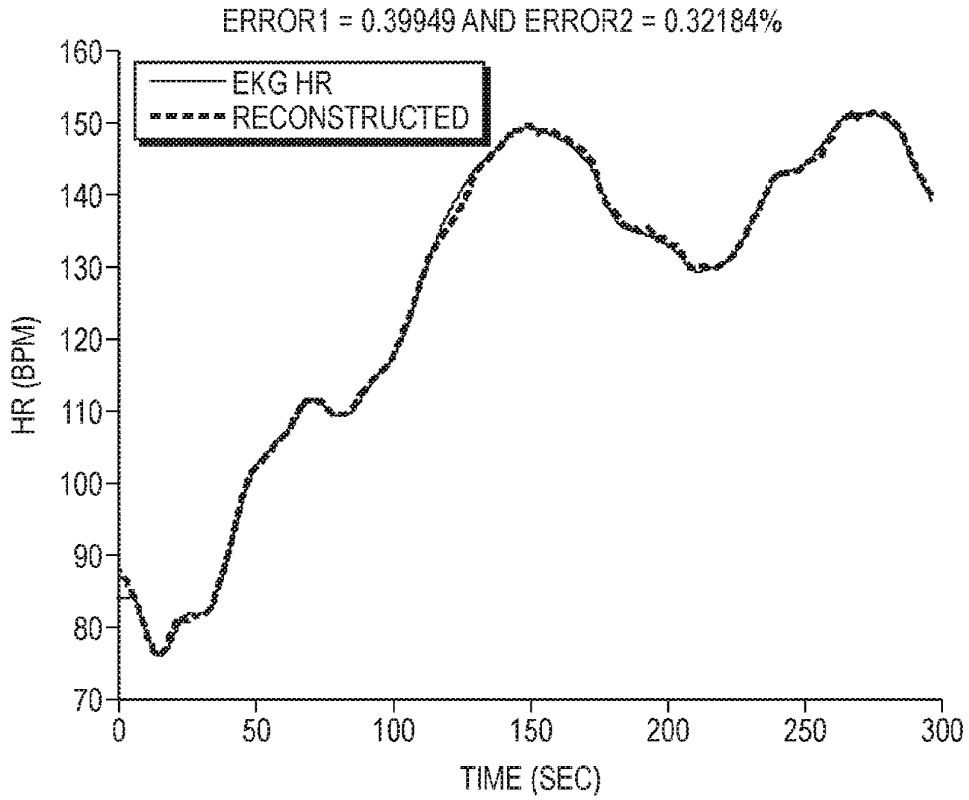


FIG. 12A

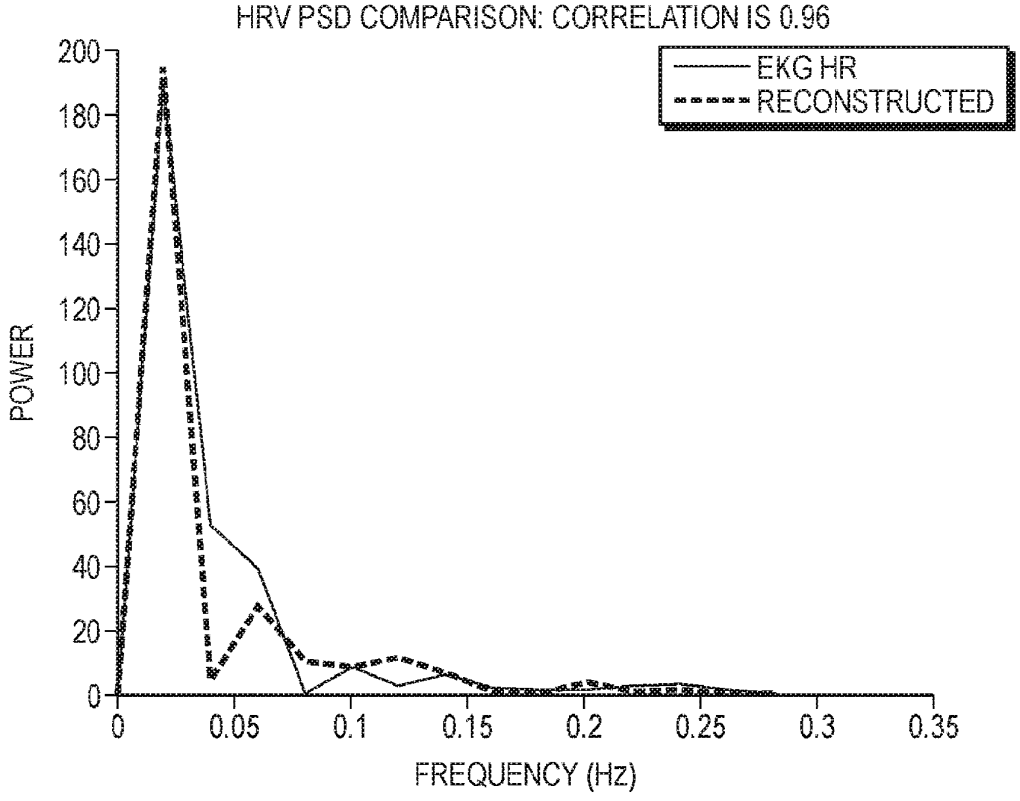


FIG. 12B

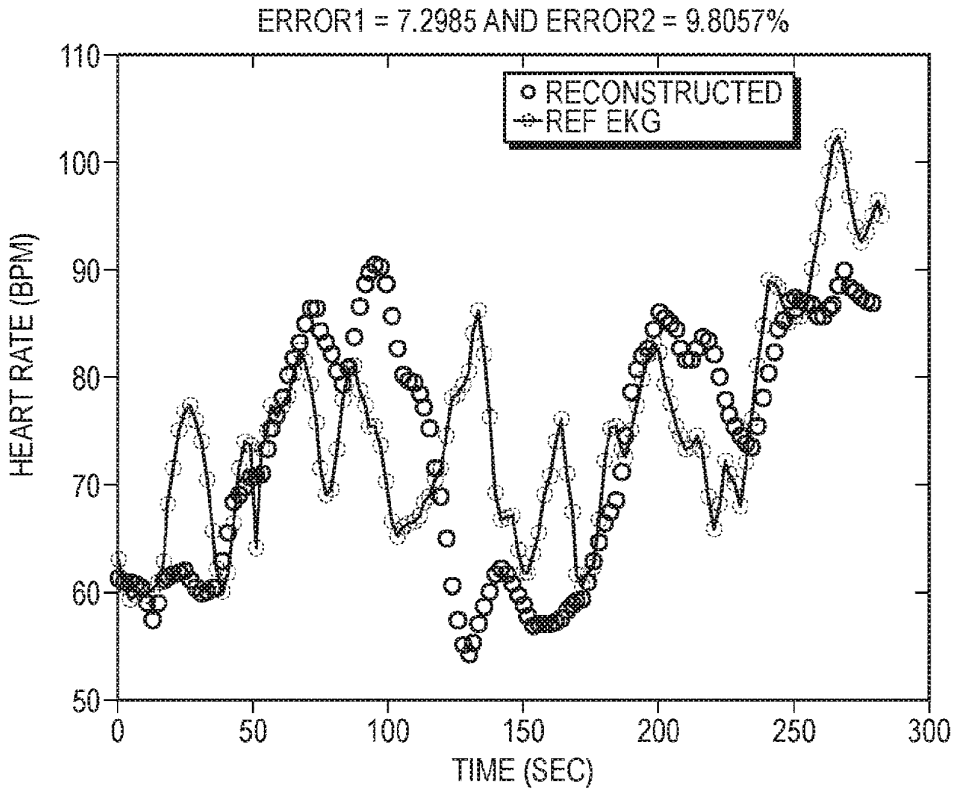


FIG. 13A

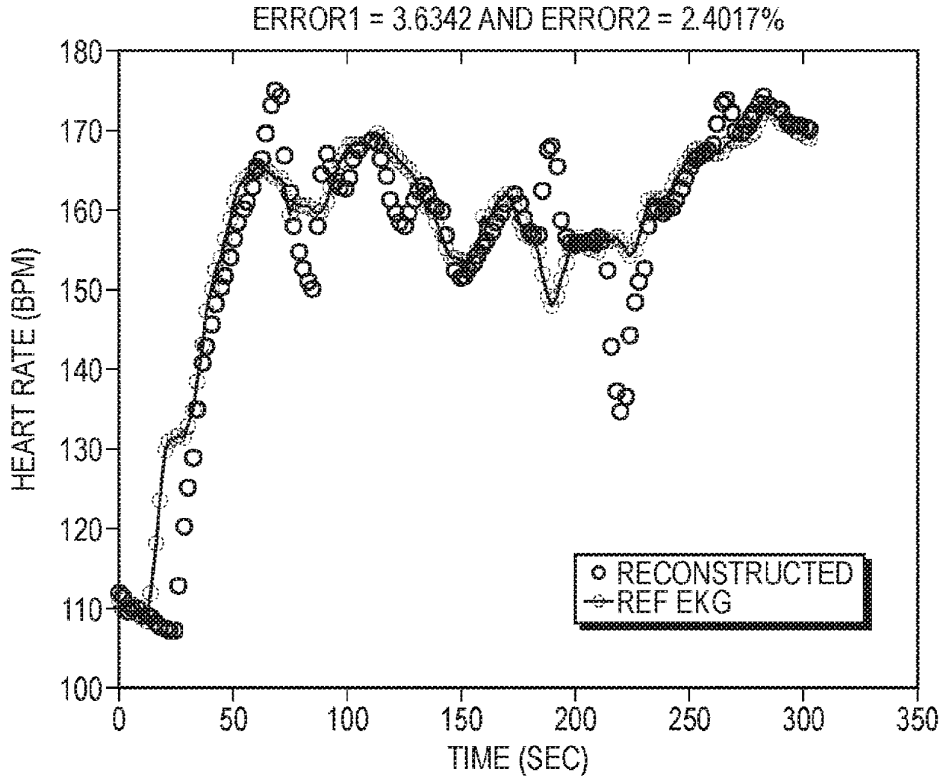


FIG. 13B

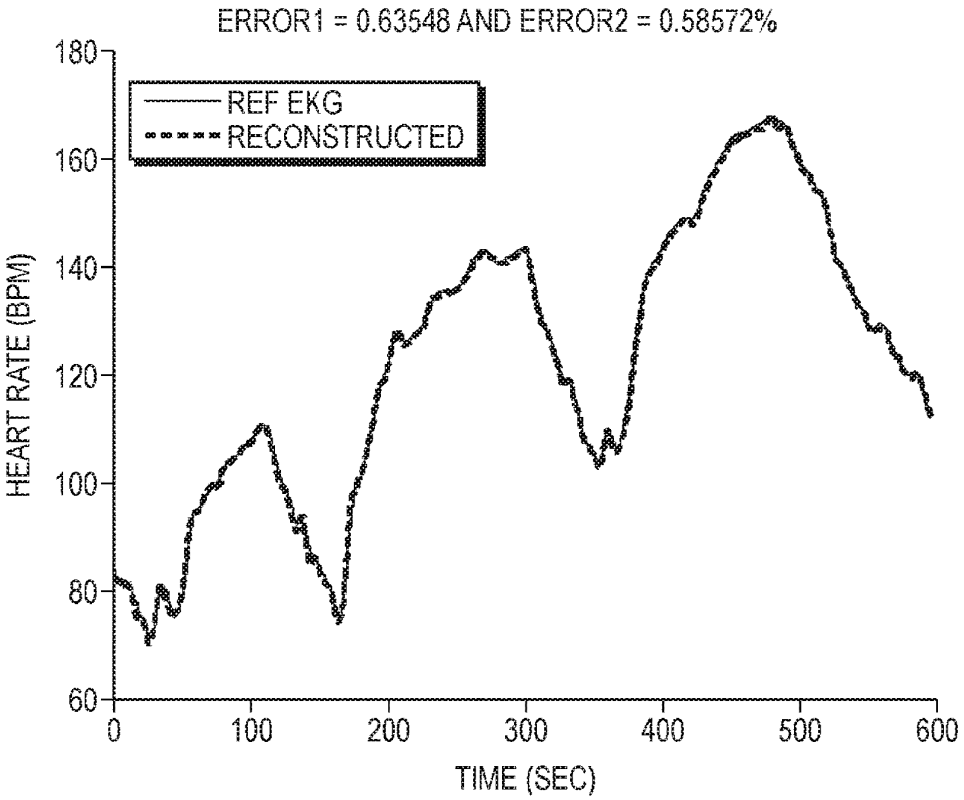


FIG. 14A

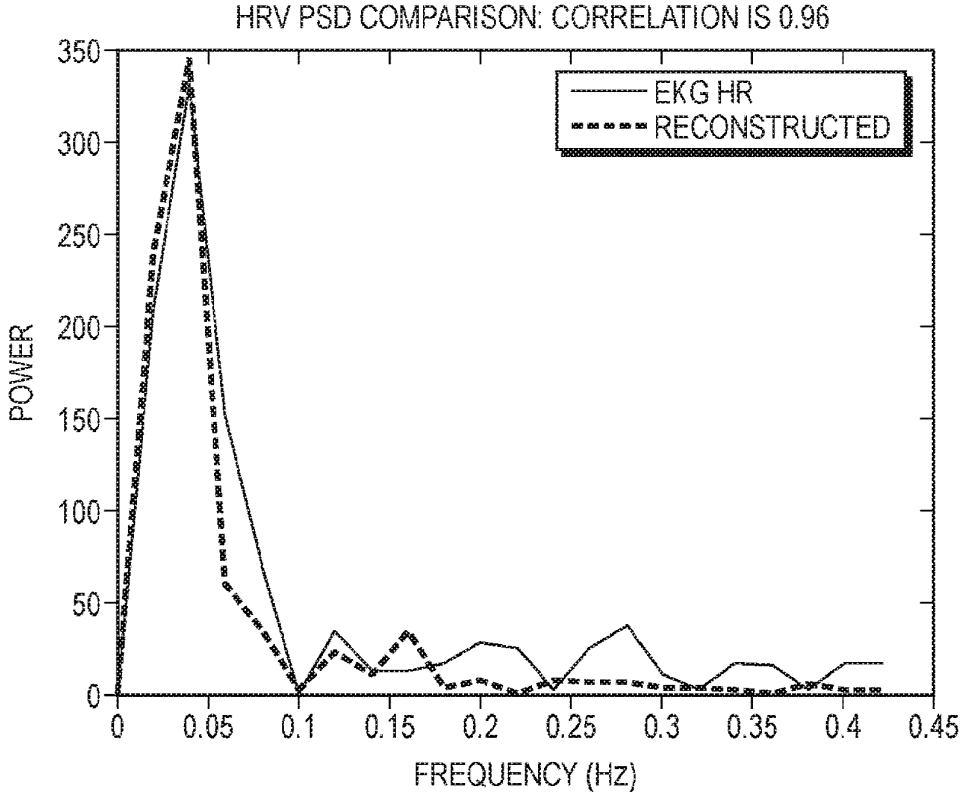


FIG. 14B

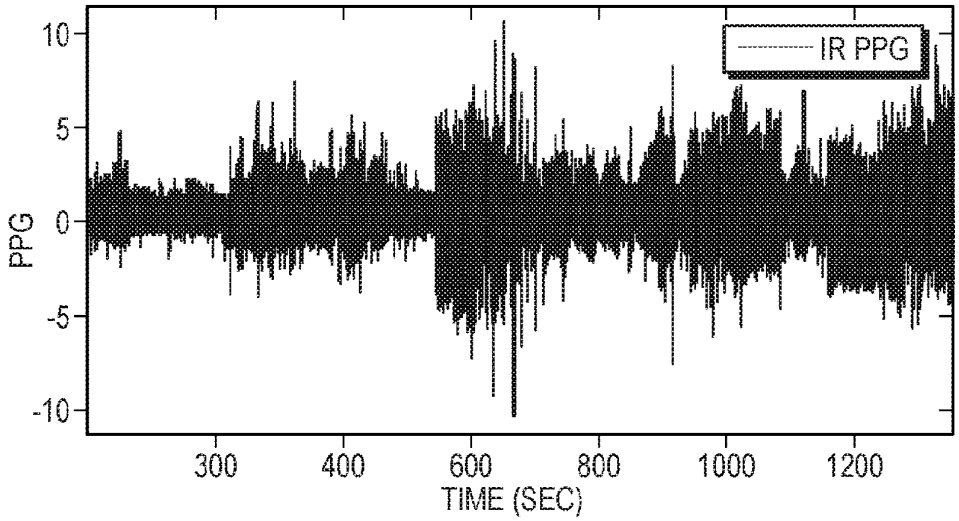


FIG. 15A

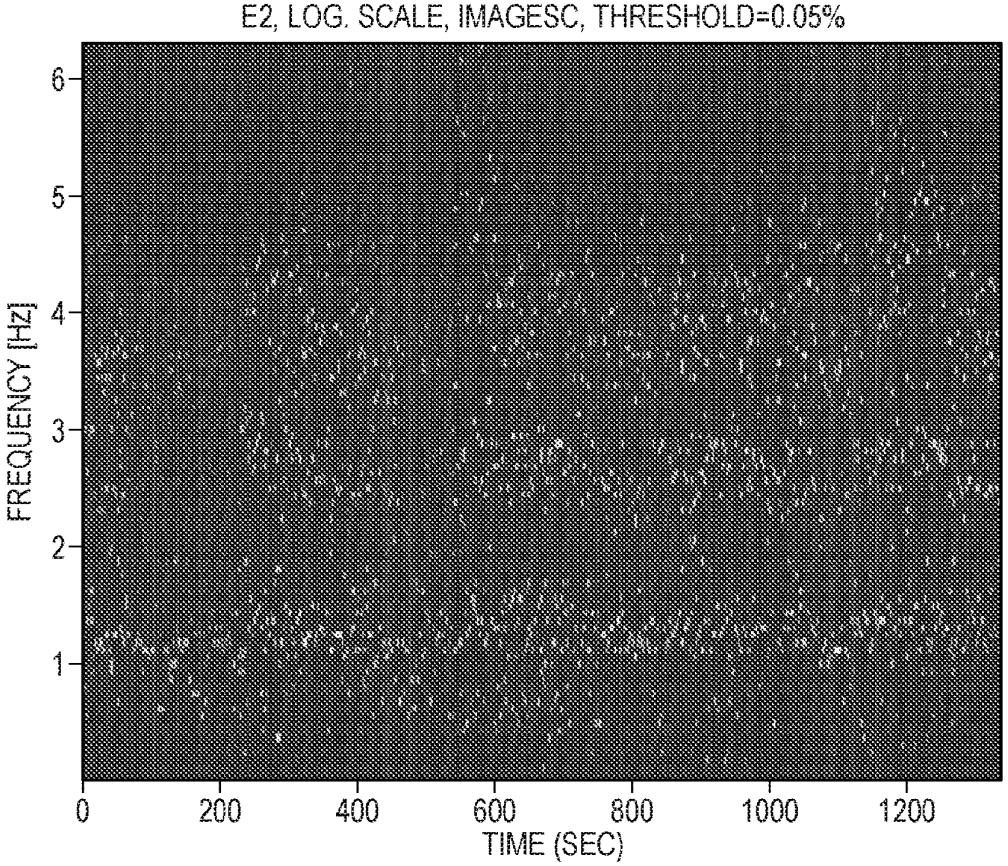


FIG. 15B

Petitioner Ex-1004, 0883

Petitioner Ex-1004, 0884

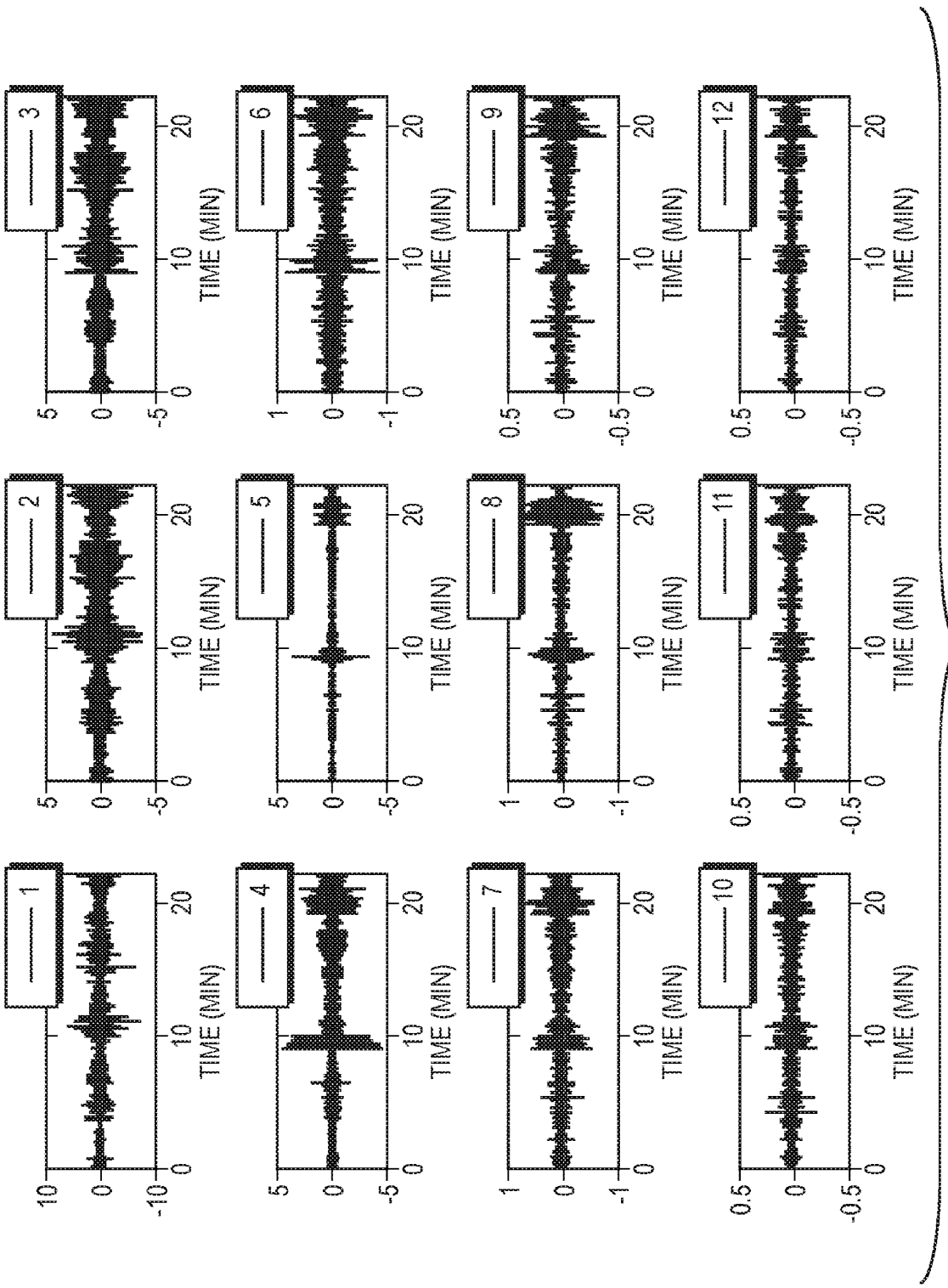


FIG. 16

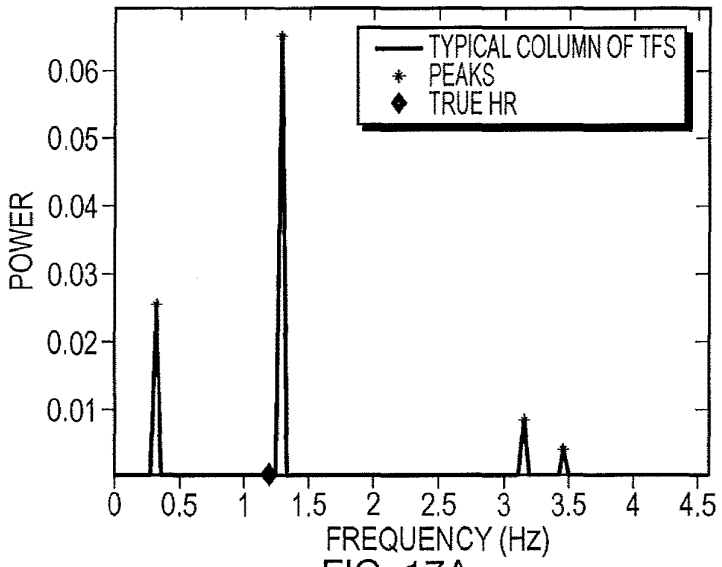


FIG. 17A

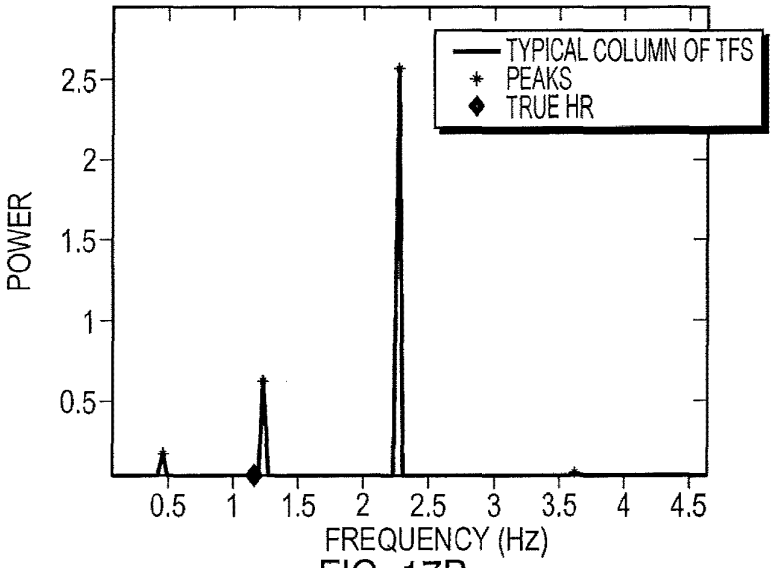


FIG. 17B

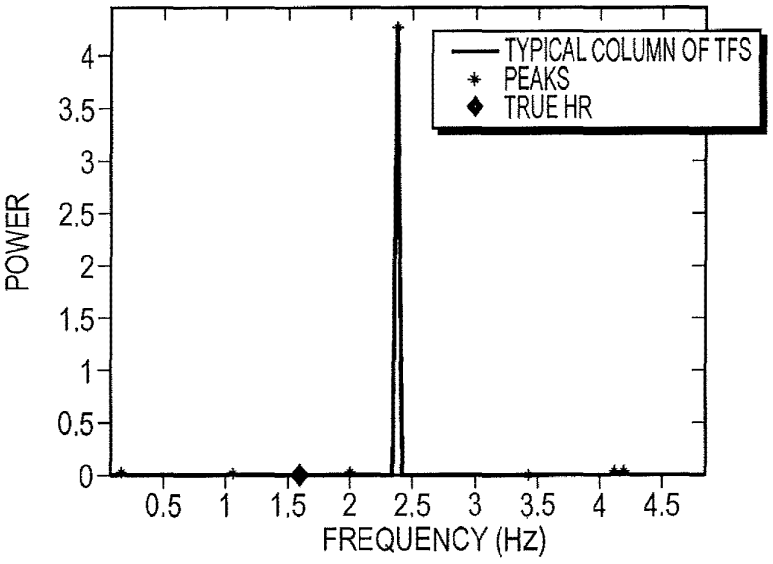


FIG. 17C

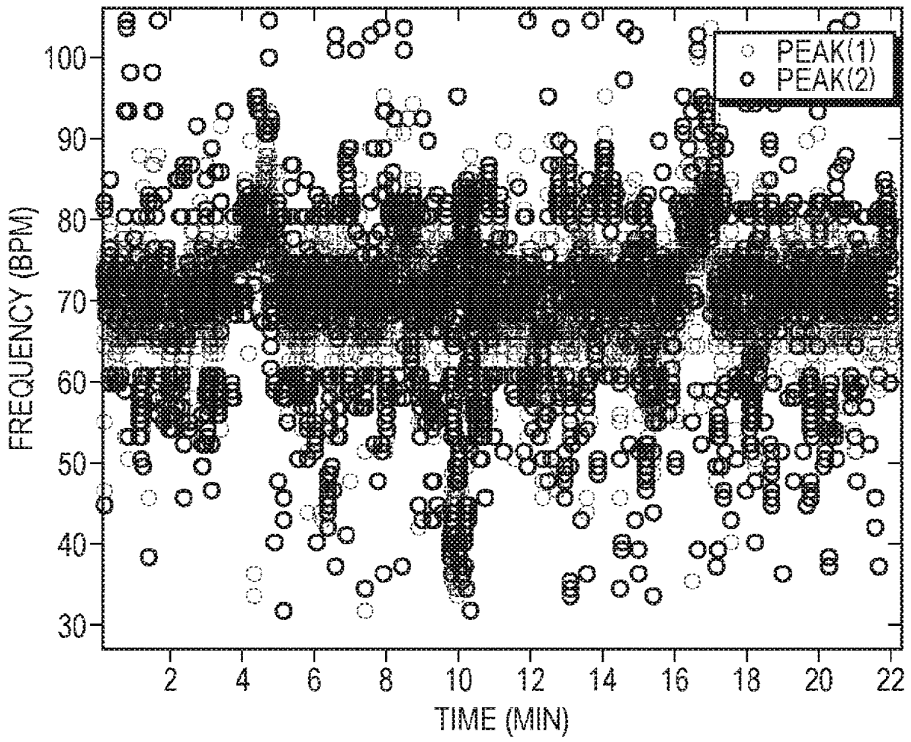


FIG. 18A

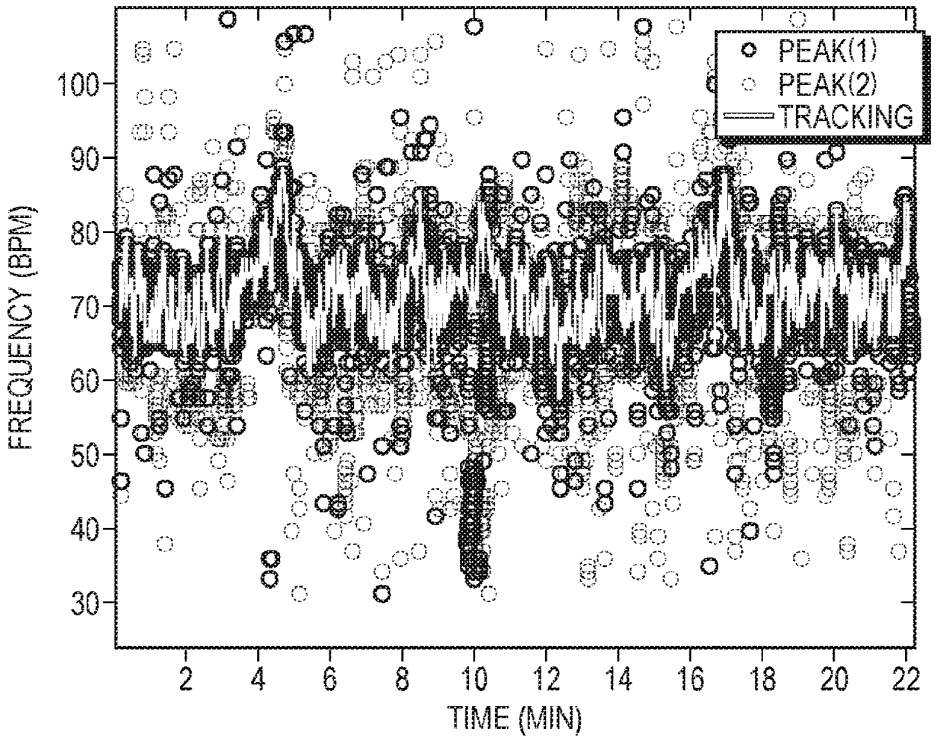


FIG. 18B

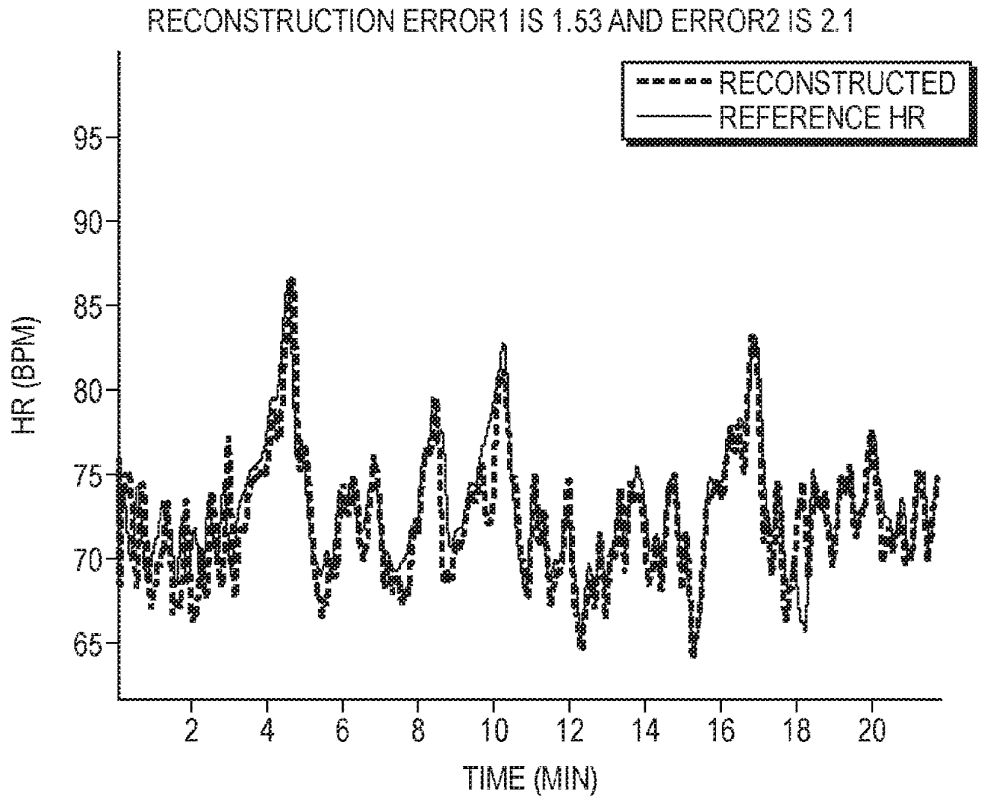


FIG. 19A

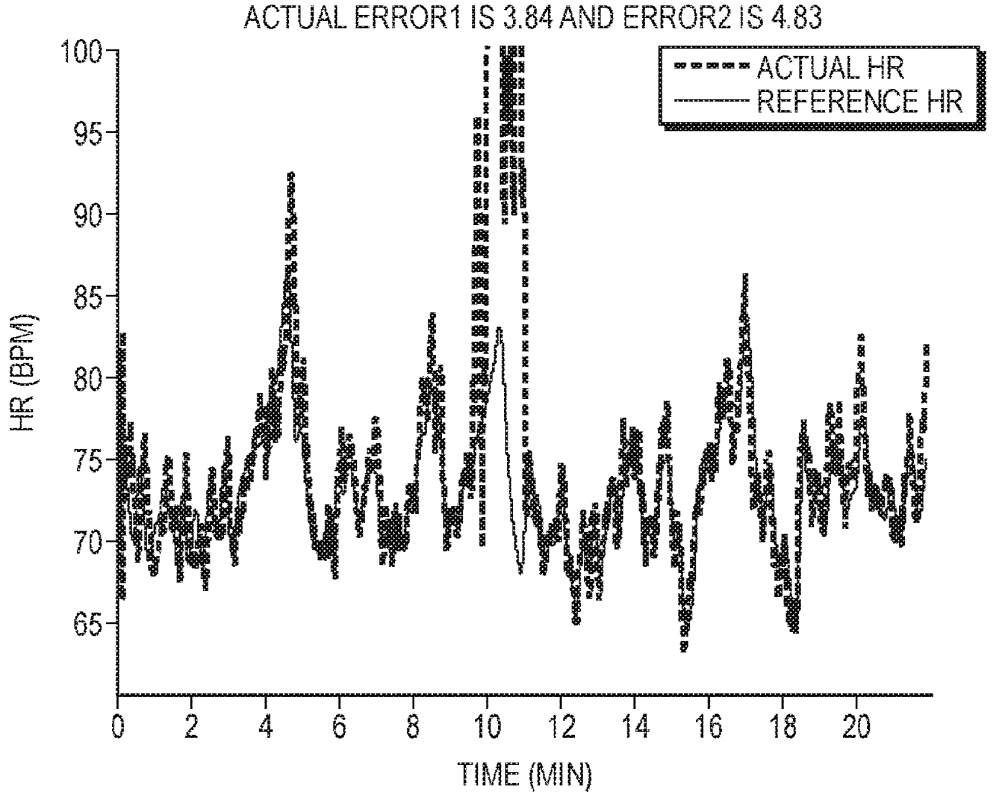


FIG. 19B

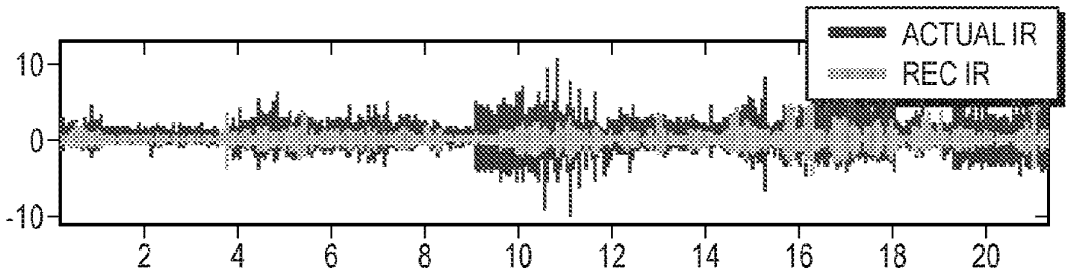
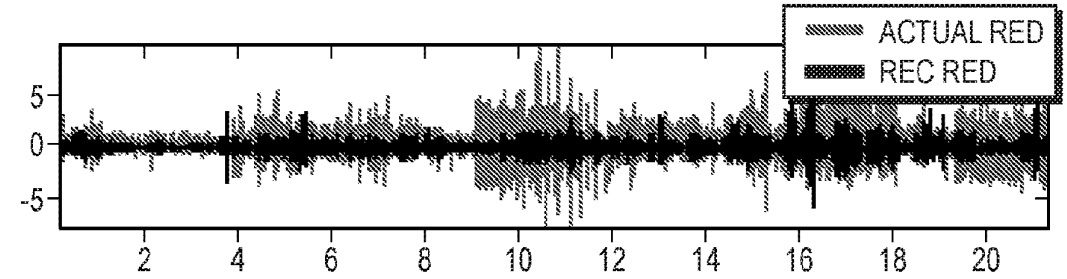


FIG. 20A



ACTUAL ERROR IS 2.8557 AND VFCDM ERROR IS 1.1013

FIG. 20B

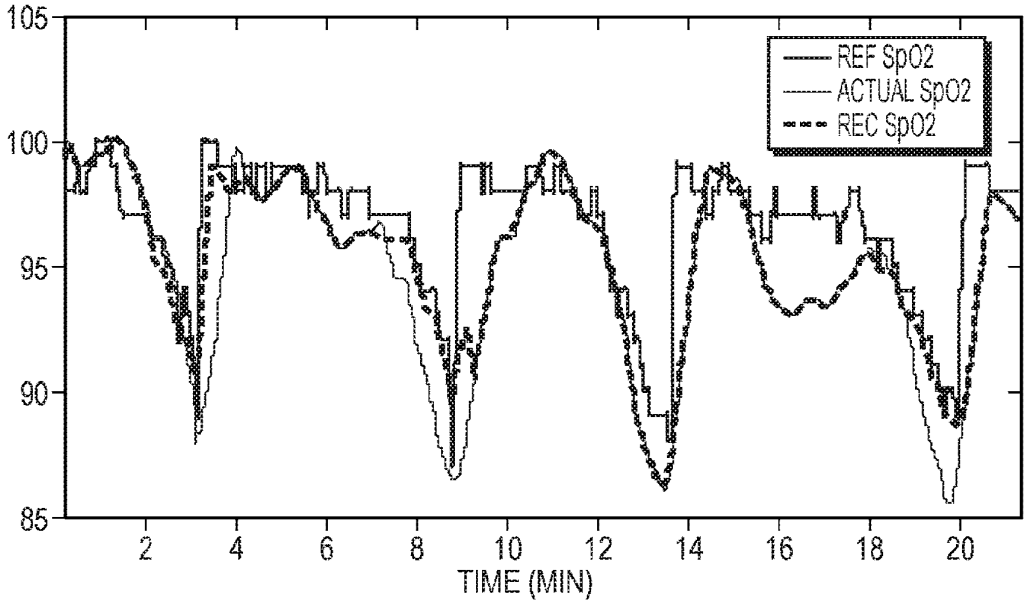


FIG. 20C

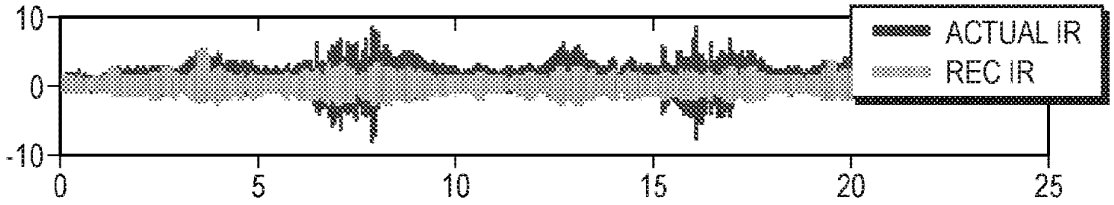


FIG. 21A

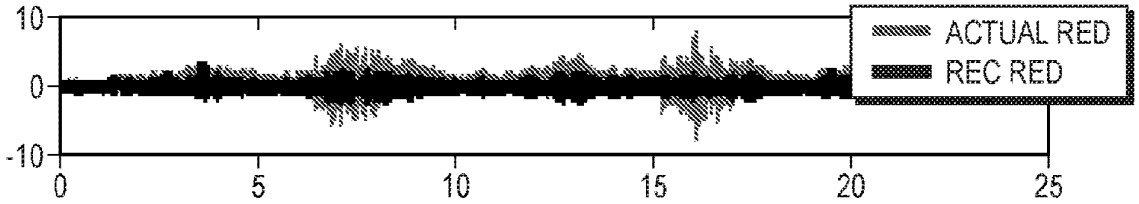


FIG. 21B

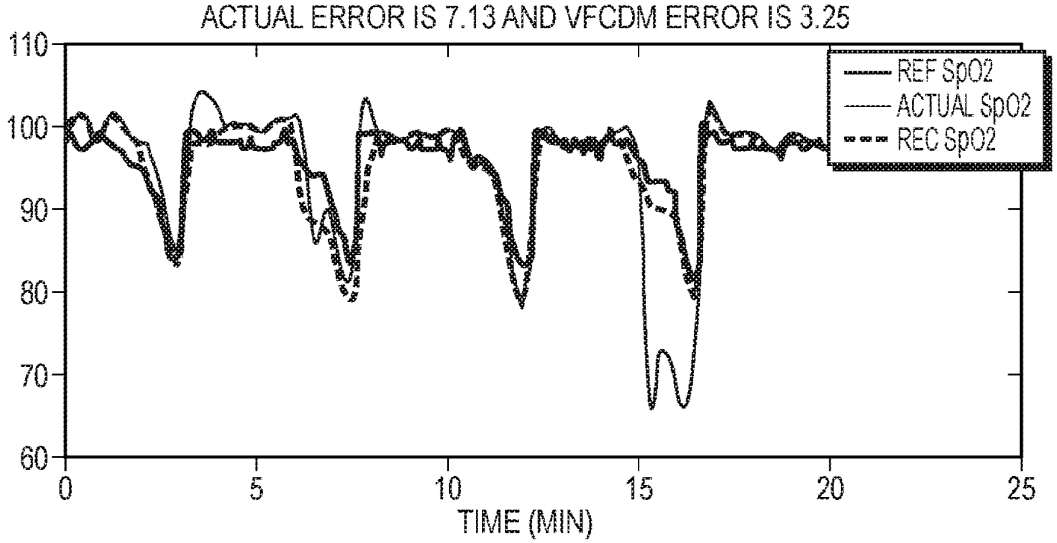


FIG. 21C

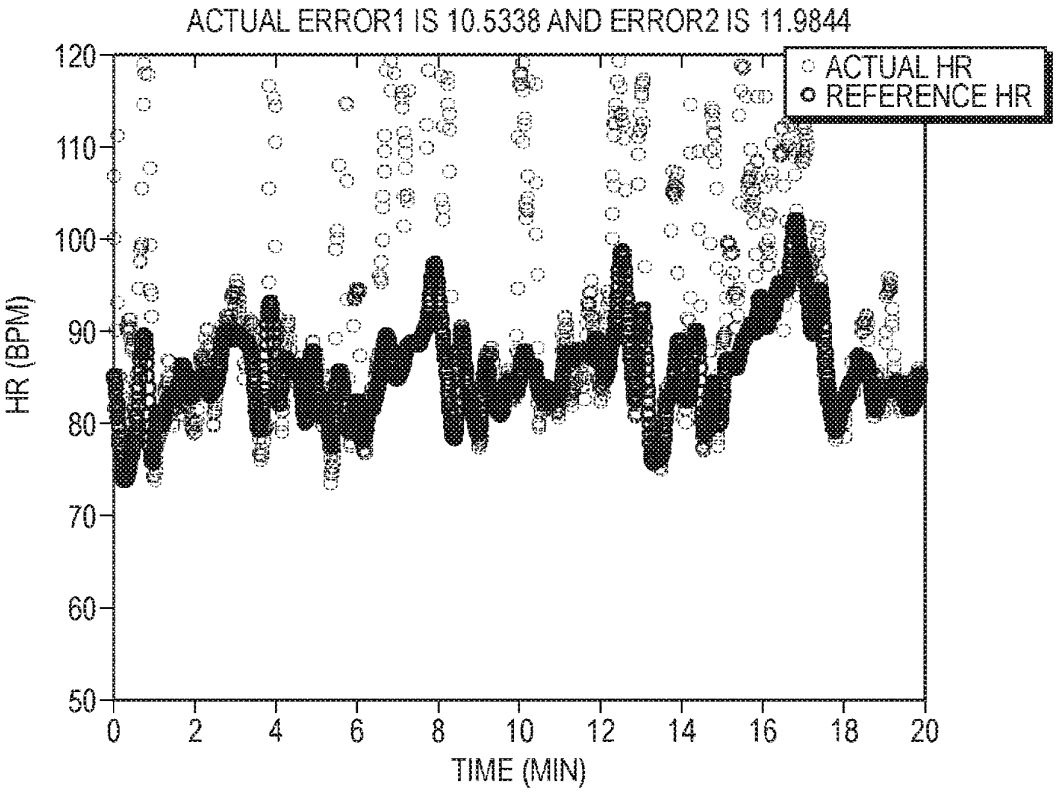


FIG. 22A

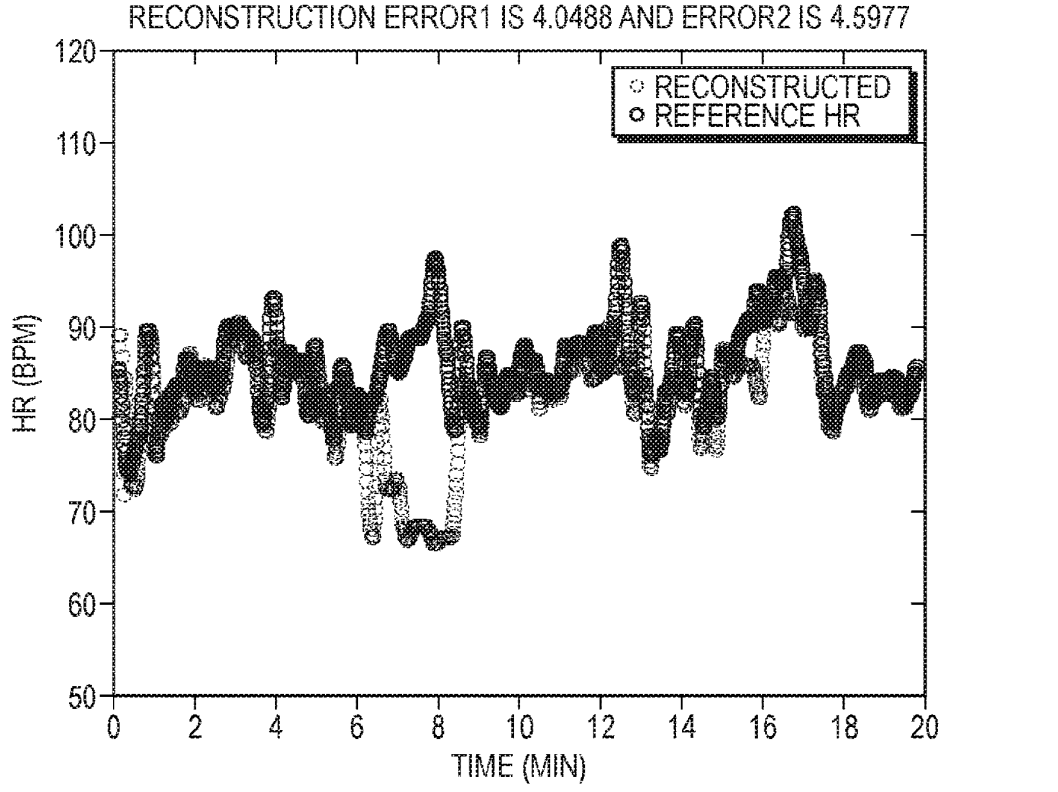


FIG. 22B

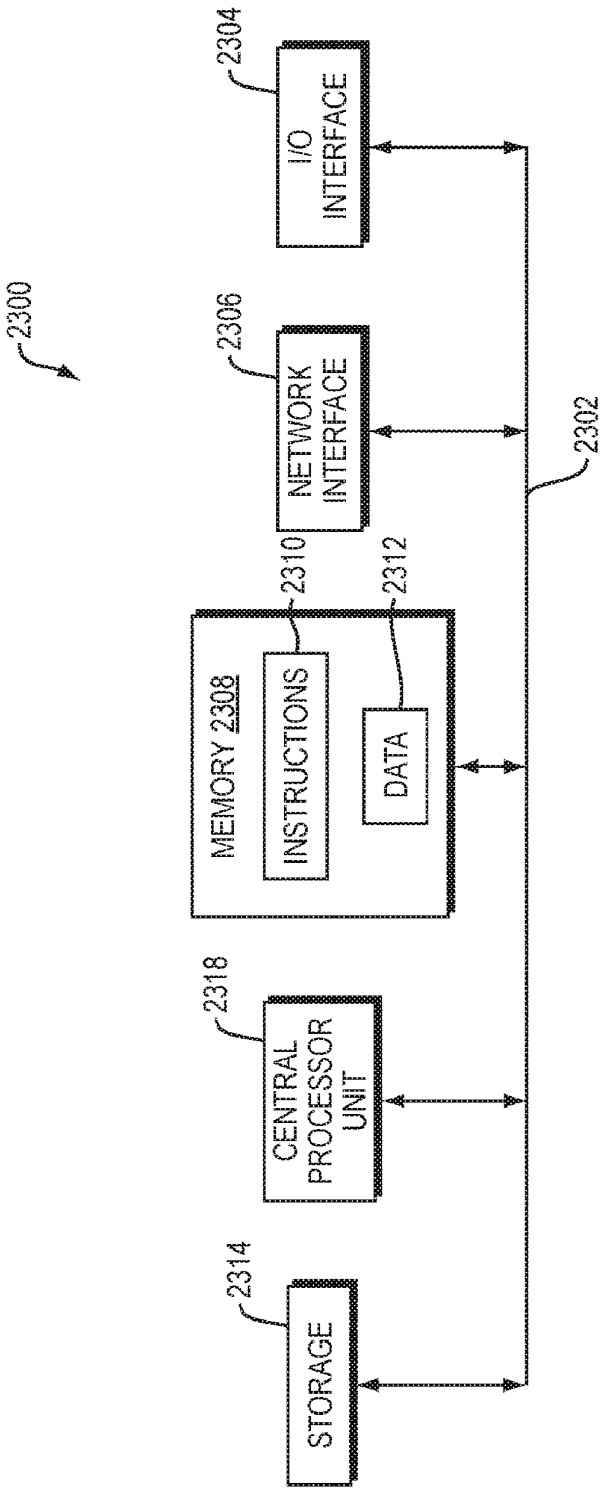

2300
2304
I/O INTERFACE
2306
NETWORK INTERFACE
2302
2310
2312
MEMORY 2308
INSTRUCTIONS
DATA
2318
CENTRAL PROCESSOR UNIT
2314
STORAGE

FIG. 23

PATENT COOPERATION TREATY

From the INTERNATIONAL SEARCHING AUTHORITY

PCT

NOTIFICATION OF TRANSMITTAL OF THE INTERNATIONAL SEARCH REPORT AND THE WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY, OR THE DECLARATION

(PCT Rule 44.1)

To:
Solomon, Mark B
HAMILTON, BROOK, SMITH & REYNOLDS, P.C.
530 Virginia Road
P.O. Box 9133
Concord MA 01742-9133
ETATS-UNIS D'AMERIQUE

RECEIVED
HAMILTON, BROOK, SMITH & REYNOLDS, P.C.
MAR 31 2017
ATTORNEY/IFC/AL
Docketed ___ Already Docketed
Not Required DOCKETED
Initials 1st ___ Initials 2nd ___

Applicant's or agent's file reference 4147.1020004	Date of mailing *(day/month/year)* 16 March 2017 (16-03-2017) **FOR FURTHER ACTION** See paragraphs 1 and 4 below
International application No. PCT/US2016/036734	International filing date *(day/month/year)* 9 June 2016 (09-06-2016)
Applicant UNIVERSITY OF CONNECTICUT	

1. [X] The applicant is hereby notified that the international search report and the written opinion of the International Searching Authority have been established and are transmitted herewith.

   Filing of amendments and statement under Article 19:
   The applicant is entitled, if he so wishes, to amend the claims of the International Application (see Rule 46):

   When? The time limit for filing such amendments is normally two months from the date of transmittal of the International Search Report.

   How? Directly to the International Bureau of WIPO, 34 chemin des Colombettes 1211 Geneva 20, Switzerland, Fascimile No.: (41-22) 338.82.70

   For more detailed instructions, see *PCT Applicant's Guide*, International Phase, paragraphs 9.004 - 9.011.

2. [ ] The applicant is hereby notified that no international search report will be established and that the declaration under Article 17(2)(a) to that effect and the written opinion of the International Searching Authority are transmitted herewith.

3. [ ] **With regard to any protest** against payment of (an) additional fee(s) under Rule 40.2, the applicant is notified that:

   [ ] the protest together with the decision thereon has been transmitted to the International Bureau together with any applicant's request to forward the texts of both the protest and the decision thereon to the designated Offices.

   [ ] no decision has been made yet on the protest; the applicant will be notified as soon as a decision is made.

4. **Reminders**

   The applicant may **submit comments on an informal basis on the written opinion of the International Searching Authority** to the International Bureau. These comments will be made available to the public after international publication. The International Bureau will send a copy of such comments to all designated Offices unless an international preliminary examination report has been or is to be established.

   Shortly after the expiration of **18 months from the priority date, the international application will be published** by the International Bureau. If the applicant wishes to avoid or postpone publication, a notice of withdrawal of the international application, or of the priority claim, must reach the International Bureau before the completion of the technical preparations for international publication (Rules 90*bis*.1 and 90*bis*.3).

   Within **19 months** from the priority date, but only in respect of some designated Offices, a demand for international preliminary examination must be filed if the applicant wishes to postpone the entry into the national phase **until 30 months** from the priority date (in some Offices even later); otherwise, the applicant must, **within 20 months** from the priority date, perform the prescribed acts for **entry into the national phase** before those designated Offices. In respect of other designated Offices, the time limit of **30 months** (or later) will apply even if no demand is filed within 19 months. For details about the applicable time limits, Office by Office, see www.wipo.int/pct/en/texts/time_limits.html and the *PCT Applicant's Guide*, National Chapters.

   Within **19 months from the priority date, the applicant may request that a supplementary international search be carried out** by a different International Searching Authority that offers this service (Rule 45*bis*.1). The procedure for requesting supplementary international search is described in the *PCT Applicant's Guide*, International Phase, paragraphs 8.006-8.032.

Name and mailing address of the International Searching Authority European Patent Office, P.B. 5818 Patentlaan 2 NL-2280 HV Rijswijk Tel. (+31-70) 340-2040 Fax: (+31-70) 340-3016	Authorized officer AMBROSCH, Jeannette Tel: +31 (0)70 340-2915

PATENT COOPERATION TREATY

PCT

INTERNATIONAL SEARCH REPORT

(PCT Article 18 and Rules 43 and 44)

Applicant's or agent's file reference	**FOR FURTHER ACTION**	see Form PCT/ISA/220 as well as, where applicable, item 5 below.
4147.1020004		
International application No.	International filing date *(day/month/year)*	(Earliest) Priority Date *(day/month/year)*
PCT/US2016/036734	9 June 2016 (09-06-2016)	9 June 2015 (09-06-2015)
Applicant		
UNIVERSITY OF CONNECTICUT		

This international search report has been prepared by this International Searching Authority and is transmitted to the applicant according to Article 18. A copy is being transmitted to the International Bureau.

This international search report consists of a total of 4 sheets.

[X] It is also accompanied by a copy of each prior art document cited in this report.

1. **Basis of the report**
   a. With regard to the **language,** the international search was carried out on the basis of:
      [X] the international application in the language in which it was filed
      [ ] a translation of the international application into _____, which is the language of a translation furnished for the purposes of international search (Rules 12.3(a) and 23.1(b))
   b. [ ] This international search report has been established taking into account the **rectification of an obvious mistake** authorized by or notified to this Authority under Rule 91 (Rule 43.6*bis*(a)).
   c. [ ] With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, see Box No. I.

2. [ ] **Certain claims were found unsearchable** (See Box No. II)

3. [ ] **Unity of invention is lacking** (see Box No III)

4. With regard to the **title,**
   [X] the text is approved as submitted by the applicant
   [ ] the text has been established by this Authority to read as follows:

5. With regard to the **abstract,**
   [X] the text is approved as submitted by the applicant
   [ ] the text has been established, according to Rule 38.2, by this Authority as it appears in Box No. IV. The applicant may, within one month from the date of mailing of this international search report, submit comments to this Authority

6. With regard to the **drawings,**
   a. the figure of the **drawings** to be published with the abstract is Figure No. 1
      [X] as suggested by the applicant
      [ ] as selected by this Authority, because the applicant failed to suggest a figure
      [ ] as selected by this Authority, because this figure better characterizes the invention
   b. [ ] none of the figures is to be published with the abstract

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2016/036734

A. CLASSIFICATION OF SUBJECT MATTER
INV. A61B5/00 A61B5/024 A61B5/0245 A61B5/11 A61B5/0205
ADD. A61B5/1455 A61B5/046 A61B5/0464

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
A61B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2014/275854 A1 (VENKATRAMAN SUBRAMANIAM [US] ET AL) 18 September 2014 (2014-09-18) paragraphs [0005], [0030], [0045], [0052], [0132], [0136], [0140], [0148], [0153], [0154], [0163], [0177] paragraphs [0202], [0203], [0212], [0247], [0249], [0292], [0398]	1-73

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
9 March 2017	16/03/2017

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Meyer, Wolfgang

1

Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2016/036734

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2011/026669 A1 (SUISSE ELECTRONIQUE MICROTECH [CH]; VETTER ROLF [CH]; CORREVON MARC [C) 10 March 2011 (2011-03-10) page 1, line 21 - page 2, line 8 page 3, lines 26, 28, 29 page 4, lines 12, 18, 24, 25 page 5, line 1 - line 14 page 7, line 11 page 8, lines 6, 8, 9, 18, 19 page 9, lines 23, 24 page 12, line 1 page 14, line 13 page 14, line 25 - page 15, line 13 page 15, lines 8, 9 page 17, line 11	1-6,9, 10,12, 13, 18-22, 24,25, 27-34, 37-42, 45,46, 48,49, 54-58, 60,61, 63-70
A	WO 2012/123828 A1 (KONINKL PHILIPS ELECTRONICS NV [NL]; GOPAL SAMY MATHAN KUMAR [DE]; YIN) 20 September 2012 (2012-09-20) page 5, lines 33, 34	5,20,41, 56
A	EP 1 757 224 A2 (NIHON KOHDEN CORP [JP]) 28 February 2007 (2007-02-28) paragraph [0087]	24,25, 60,61
A	US 2014/275852 A1 (HONG JUNG OOK [US] ET AL) 18 September 2014 (2014-09-18) the whole document	1-73
A	US 2008/167564 A1 (HETE BENARD F [US] ET AL) 10 July 2008 (2008-07-10) the whole document	1-73
A	EP 1 297 784 A1 (CSEM CT SUISSE ELECTRONIQUE [CH]) 2 April 2003 (2003-04-02) the whole document	1-73

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2016/036734

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2014275854 A1	18-09-2014	US 2014275854 A1	18-09-2014
		US 2014276119 A1	18-09-2014
		US 2014288436 A1	25-09-2014
		US 2014288438 A1	25-09-2014
		US 2015196256 A1	16-07-2015
		US 2017027523 A1	02-02-2017
WO 2011026669 A1	10-03-2011	EP 2473094 A1	11-07-2012
		US 2012190948 A1	26-07-2012
		WO 2011026669 A1	10-03-2011
WO 2012123828 A1	20-09-2012	CN 103429150 A	04-12-2013
		EP 2683296 A1	15-01-2014
		JP 2014511250 A	15-05-2014
		RU 2013145520 A	20-04-2015
		US 2013345585 A1	26-12-2013
		WO 2012123828 A1	20-09-2012
EP 1757224 A2	28-02-2007	AT 493930 T	15-01-2011
		EP 1757224 A2	28-02-2007
		JP 4830693 B2	07-12-2011
		JP 2007083021 A	05-04-2007
		US 2007049811 A1	01-03-2007
US 2014275852 A1	18-09-2014	US 2014275852 A1	18-09-2014
		US 2014288390 A1	25-09-2014
		US 2014288391 A1	25-09-2014
		US 2014288392 A1	25-09-2014
		US 2015025393 A1	22-01-2015
		US 2015025394 A1	22-01-2015
		US 2015201853 A1	23-07-2015
		US 2015201854 A1	23-07-2015
US 2008167564 A1	10-07-2008	EP 2111152 A2	28-10-2009
		US 2008167564 A1	10-07-2008
		WO 2008086472 A2	17-07-2008
EP 1297784 A1	02-04-2003	AT 481922 T	15-10-2010
		EP 1297784 A1	02-04-2003
		US 2003065269 A1	03-04-2003

Information on Search Strategy - Pilot phase (see OJ 2015, A86)
The type of information contained in this sheet may change during the pilot for improving the usefulness of this new service.

Application Number
PCT/US2016/036734

TITLE: METHOD AND APPARATUS FOR REMOVING MOTION ARTIFACTS FROM BIOMEDICAL SIGNALS

APPLICANT: UNIVERSITY OF CONNECTICUT

IPC CLASSIFICATION: A61B5/00, A61B5/024, A61B5/0245, A61B5/11, A61B5/0205, A61B5/1455, A61B5/046, A61B5/0464

EXAMINER: Meyer, Wolfgang

CONSULTED DATABASES: WPI, NPL, TXTE

CLASSIFICATION SYMBOLS DEFINING EXTENT OF THE SEARCH:

IPC:

CPC: A61B5/721, A61B5/7207, A61B5/02405, A61B5/02438, A61B5/0245, A61B5/7253, A61B5/7239, A61B5/6824, A61B5/02416, A61B2503/10, A61B2505/07, A61B2505/09, A61B5/112

FI/F-TERMS:

KEYWORDS OR OTHER ELEMENTS FEATURING THE INVENTION:
Classification of movement; motion noise, movement noise; biosignal; PPG; accelerometer; noise removal; time-varying spectral analysis; time-frequency spectrum; wavelet; heart rate; heart rate variability; peak selection and discarding; harmonics analysis

EPO FORM P04A42

PATENT COOPERATION TREATY

From the
INTERNATIONAL SEARCHING AUTHORITY

To:

see form PCT/ISA/220

PCT

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

(PCT Rule 43*bis*.1)

Date of mailing
(day/month/year) see form PCT/ISA/210 (second sheet)

Applicant's or agent's file reference
see form PCT/ISA/220

FOR FURTHER ACTION
See paragraph 2 below

International application No.	International filing date *(day/month/year)*	Priority date *(day/month/year)*
PCT/US2016/036734	09.06.2016	09.06.2015

International Patent Classification (IPC) or both national classification and IPC
INV. A61B5/00 A61B5/024 A61B5/0245 A61B5/11 A61B5/0205 ADD. A61B5/1455 A61B5/046 A61B5/0464

Applicant
UNIVERSITY OF CONNECTICUT

1. This opinion contains indications relating to the following items:

- ☒ Box No. I Basis of the opinion
- ☐ Box No. II Priority
- ☐ Box No. III Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
- ☐ Box No. IV Lack of unity of invention
- ☒ Box No. V Reasoned statement under Rule 43*bis*.1(a)(i) with regard to novelty, inventive step and industrial applicability; citations and explanations supporting such statement
- ☐ Box No. VI Certain documents cited
- ☒ Box No. VII Certain defects in the international application
- ☒ Box No. VIII Certain observations on the international application

2. **FURTHER ACTION**

If a demand for international preliminary examination is made, this opinion will usually be considered to be a written opinion of the International Preliminary Examining Authority ("IPEA") except that this does not apply where the applicant chooses an Authority other than this one to be the IPEA and the chosen IPEA has notifed the International Bureau under Rule 66.1*bis*(b) that written opinions of this International Searching Authority will not be so considered.

If this opinion is, as provided above, considered to be a written opinion of the IPEA, the applicant is invited to submit to the IPEA a written reply together, where appropriate, with amendments, before the expiration of 3 months from the date of mailing of Form PCT/ISA/220 or before the expiration of 22 months from the priority date, whichever expires later.

For further options, see Form PCT/ISA/220.

Name and mailing address of the ISA:	Date of completion of this opinion	Authorized Officer
European Patent Office P.B. 5818 Patentlaan 2 NL-2280 HV Rijswijk - Pays Bas Tel. +31 70 340 - 2040 Fax: +31 70 340 - 3016	see form PCT/ISA/210	Meyer, Wolfgang Telephone No. +31 70 340-0

Box No. I Basis of the opinion

1. With regard to the **language**, this opinion has been established on the basis of:

   ☒ the international application in the language in which it was filed.

   ☐ a translation of the international application into , which is the language of a translation furnished for the purposes of international search (Rules 12.3(a) and 23.1 (b)).

2. ☐ This opinion has been established taking into account the **rectification of an obvious mistake** authorized by or notified to this Authority under Rule 91 (Rule 43*bis*.1(a))

3. ☐ With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, this opinion has been established on the basis of a sequence listing:

   a. ☐ forming part of the international application as filed:

      ☐ in the form of an Annex C/ST.25 text file.

      ☐ on paper or in the form of an image file.

   b. ☐ furnished together with the international application under PCT Rule 13*ter*.1(a) for the purposes of international search only in the form of an Annex C/ST.25 text file.

   c. ☐ furnished subsequent to the international filing date for the purposes of international search only:

      ☐ in the form of an Annex C/ST.25 text file (Rule 13*ter*.1(a)).

      ☐ on paper or in the form of an image file (Rule 13*ter*.1(b) and Administrative Instructions, Section 713).

4. ☐ In addition, in the case that more than one version or copy of a sequence listing has been filed or furnished, the required statements that the information in the subsequent or additional copies is identical to that forming part of the application as filed or does not go beyond the application as filed, as appropriate, were furnished.

5. Additional comments:

Box No. V Reasoned statement under Rule 43*bis*.1(a)(i) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1. Statement

Novelty (N)	Yes:	Claims	5, 20, 24, 25, 41, 56, 61
	No:	Claims	1-4, 6-19, 21-23, 26-40, 42-55, 57-60, 62-73
Inventive step (IS)	Yes:	Claims	
	No:	Claims	1-73
Industrial applicability (IA)	Yes:	Claims	1-73
	No:	Claims	

2. Citations and explanations

see separate sheet

Box No. VII Certain defects in the international application

The following defects in the form or contents of the international application have been noted:

see separate sheet

Box No. VIII Certain observations on the international application

The following observations on the clarity of the claims, description, and drawings or on the question whether the claims are fully supported by the description, are made:

see separate sheet

Re Item V

Reasoned statement with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1 Reference is made to **the following documents**:

D1 US 2014/275854 A1 (VENKATRAMAN SUBRAMANIAM [US] ET AL) 18 September 2014 (2014-09-18)

D2 WO 2011/026669 A1 (SUISSE ELECTRONIQUE MICROTECH [CH]; VETTER ROLF [CH]; CORREVON MARC [C) 10 March 2011 (2011-03-10)

D3 WO 2012/123828 A1 (KONINKL PHILIPS ELECTRONICS NV [NL]; GOPAL SAMY MATHAN KUMAR [DE]; YIN) 20 September 2012 (2012-09-20)

D4 EP 1 757 224 A2 (NIHON KOHDEN CORP [JP]) 28 February 2007 (2007-02-28)

Novelty (Article 33(2) PCT)

2 Furthermore, the below-mentioned lack of clarity notwithstanding, the subject-matter of **claims 1-4, 6-19, 21-23, 26-40, 42-55, 57-59 and 62-73** is not new in the sense of Article 33(2) PCT, and the criteria of Article 33(1) PCT are therefore not met.

2.1 With regard to **independent method claim 1** document **D1** discloses:

A method (*par. 5: "methods"*) for reconstructing a heart-related signal (*par. 5: "of determining a user's heart rate"*) output by a biomedical sensor (*par. 5: "heartbeat waveform sensor"*), the method comprising: reconstructing (*par. 5: "remove"*) a representation of the heart-related signal (*par. 5: "from heartbeat waveform signals"*) to produce a reconstructed (*par. 5: "remove...from the output data"*) representation of

the heart-related signal (*par. 5: "from the heartbeat waveform sensor"*), the reconstructing based on (i) a time-varying spectral analysis (*par. 136: "power spectral estimation"; par. 145: "wavelet transforms"*) of the heart-related signal (*par. 136: "PPG signal"*) and a motion signal (*par. 136: "movement signal"*), the motion signal output by a motion sensor (*par. 136: "motion sensor"*) and representative of motion artifacts (*par. 136: "motion artifacts...movement artifact"*) in the heart-related signal (*par. 136: "in the PPG signal"*), the motion artifacts being signal artifacts (par. 136: "components of the PPG signal") produced by movement (*par. 136: "attributable to movement"*) of the biomedical sensor relative to a sensing location (*par. 136: "user's motion"*), and (ii) a classification of the movement (*par. 136: "when the user's motion is periodic"*); and
outputting (*par. 145: "time domain signal"; par. 153: "power spectral density of the signal is calculated"*) the reconstructed representation (*par. 153: "after removing the motion artifact"*) of the heart-related signal (*par. 152: "for the processed heartbeat waveform output data"*).

2.2 For the sake of completeness it is pointed out that also document **D2** discloses the subject-matter of **claim 1**. For the relevant passages it is referred to the search report.

2.3 Documents **D1** (*fig. 1*) and **D2** (*fig. 2*) also disclose the **apparatus** of **independent claim 37** corresponding to claim 1 which is not new. Hence, the same arguments as of the preceding paragraphs apply, mutatis mutandis, to **claim 37** which therefore is not new.

2.4 Document **D1** (*par. 186: "instructions for controlling the heartbeat waveform sensor"*) also discloses the **non-transitory computer-readable medium** of **independent claim 73** corresponding to claims 1 and 37. Hence, the same arguments as of the preceding paragraphs apply, mutatis mutandis, to **claim 73** which therefore is not new.

2.5 The additional subject-matter of **dependent claims 2-4, 6-19, 21-23, 26-36, 38-40, 42-55, 57-60 and 62-72** is also disclosed by documents **D1** and/or **D2**:

claims 2, 38: D1: *par. 177: "adaptive filter subtracts the motion artifact from the heart rate output signal"*; **D2**: *p. 5, l. 13: "equivalent frequency response having zeros at the motion frequency"*
claims 3, 39: D1: *par. 30: "high pass filtered"; par. 136: "heart rate...using a peak counting algorithm"; par. 168: "user has not moved or*

moved only slightly"; **D2**: *p. 9, l. 24: "analog low-pass filter"; p. 4, l. 18: "instantaneous heart rate"; l. 20: "averaging the heart rate"; p. 5, l. 7-8: "motion artifacts being smaller than large-band background noise"*

claims 4, 40: D1: *par. 30: "high pass filtered"*; **D2**: *p. 9, l. 24: "analog low-pass filter"*

claims 6, 42: D1: *par. 148: "fundamental frequency and the higher harmonics of the motion artifact, as measured using, e.g., an accelerometer"; par. 153: "power spectral density of the signal"*; **D2**: *p. 4, l. 12: "principal frequency component"; p. 5, l. 3: "motion frequency"*

claims 7, 43: D1: *par. 398: "wavelet transform"; "Whole...transform coefficients"*

claims 8, 44: D1: *par. 153: "power spectral density"*

claims 9, 13, 45, 49: D1: *par. 136: "gauge a user's motion...when user's motion is periodic"; par. 198: "ignoring certain portions of collected heart-rate data"*; **D2**: *p. 4, l. 24-25: "selecting projected PPG signals having a predetermined amplitude"*

claims 10, 12, 46, 48: D1: *par. 249: "heart rate signal may be determined...in a frequency band of, for instance, 0.5 Hz to 4 Hz"*; **D2**: *p. 14, l. 13: "equal or above 0.7"*

claims 11, 47: D1: *par. 154: "measuring the step rate...set a lower bound on the expected heart rate"*

claims 14, 15, 50, 51: D1: *par. 203: "observing periods where the user's heart rate decreases...by at least a certain threshold but within a pre-determined margin"; par. 247: "user's heart rate may be selected...indicative of changes in activity"; "shift toward higher frequency"*

claims 16, 52: D1: *par. 153: "peak with the highest amplitude"*

claims 17, 53: D1: *par. 136: "user's motion is periodic"; par. 154: "accelerometer...motion artifacts related peaks"*

claims 18, 19, 54, 55: D1: *par. 30: "filtered"; par. 247: "similar set of operations may be performed on the motion signal"*; **D2**: *p. 9, l. 23: "Filtering of the measured analog PPG, motion"*

claims 21, 57: D1: *par. 132: "user motion exceeds a certain threshold"*; **D2**: *p. 15, l. 8-9: "relative importance of the level of large-band background noise and movement artifact"*

claims 22, 58: D1: *par. 45: "accelerometer or a gyroscope"*; **D2**: *p. 8, l. 18-19: "other types of accelerometers", l. 21: "gyro sensor", l. 22: "rotating or vibrating element"; the thresholds are per se different*

because one type of sensor is measuring linear acceleration and the other rotation
claims 23, 59: D1: *par. 136: "when the user's motion is periodic"*
claims 26, 62: D1: *par. 140: "High Band Pass Filter"; "average heart rate...filter"*
claims 27, 63: D1: *par. 163: "processed together"*; **D2**: *p. 8, l. 8-9: "motion signal is better correlated with the measured multichannel sensor 1 signal"*
claims 28, 64: D1: *par. 203: "windowed...processing"*; **D2**: *p. 12, l. 1: "window length"*
claims 29, 65: D1: *par. 52: "5 to 15 seconds"*; **D2**: *p. 17, l. 11: "20 to 120 sec"*
claims 30, 66: D1: *par. 45: "photoplethysmographic sensor..."; "accelerometer"* ; **D2**: *p. 3, l. 26: "PPG signal"; p. 8, l. 16: "accelerometer"*
claims 31, 67: D1: *par. 292: "single device in only one of those locations"*; **D2**: *p. 8, l. 6: "integrated sensor"*
claims 32, 68: D1: *par. 5: "heart rate"*; **D2**: *p. 3, l. 28: "heart rate"*
claims 33, 69: D1: *par. 212: "SpO2"*; **D2**: *p. 7, l. 11: "SpO2"*
claims 34, 70: D1: *par. 212: "heart rate variability"*; **D2**: *p. 3, l. 28-29: "heart rate variability"*
claims 35, 36, 71, 72: D1: *par. 203: "Real-time...or batch processing"*

Inventive Step (Article 33(3) PCT)

3 Furthermore, the below-mentioned lack of clarity notwithstanding, the subject-matter of **dependent claims 5, 20, 24, 25, 41, 56, 60 and 61** does not involve an inventive step in the sense of Article 33(3) PCT, and the criteria of Article 33(1) PCT are therefore not met.

3.1 Pre-processing by down-sampling according to **claims 5, 20, 41 and 56** is straightforward, see, e.g., document **D3** (*p. 5, l. 33-34: "down-sampling"*).

3.2 Detecting fundamental and harmonic peaks by frequency ratios according to **claims 24, 25, 60 and 61** is straightforward, see, e.g., document **D4** (*par. 87: "twice and three times the fundamental frequency"*).

Re Item VII

Certain defects in the international application

4 Contrary to the requirements of Rule 5.1(a)(ii) PCT, the relevant background art disclosed in documents **D1** and **D2** is not mentioned in the description, nor are those documents identified therein.

5 The features of the claims are not provided with reference signs placed in parentheses (Rule 6.2(b) PCT).

Re Item VIII

Certain observations on the international application

6 The application does not meet the requirements of Article 6 PCT, because **claims 1, 33, 34, 37, 69, 70 and 73** are not clear.

6.1 **Independent claims 1, 37 and 73** are not supported by the description as required by Article 6 PCT, as their scope is broader than justified by the description and drawings. Particularly, the expression "classification of the movement" is so broad that it includes, e.g., gait analysis, whereas the application appears to be more specifically directed to the discrimination of "periodic" movement (see also claims 9, 17 and 24).

6.2 **Dependent claims 33 and 69** are unclear, because it is not clear how "arterial oxygen saturation" could be derived from the generic "heart-related signal" defined in claim 1 and 37 to which **claims 33 and 69** refer. For the sake of completeness it is pointed out that, contrarily, it appears in principle possible to derive a "heart rate estimate" from any "heart-related signal" as defined in claims 32 and 68.

6.3 **Dependent claims 34 and 70** are unclear because the expression "heart rate variability (HRV) condition" is unclear, and because it is unclear how "atrial fibrillation", "congestive heart failure" and "tachycardia" could be diagnosed from the generic signal reconstruction of claim 1 and 37 to which **claims 34 and 70** refer.

6.4 For the sake of completeness it is pointed out that **dependent claim 34** does not meet the requirements of Rule 39.1(iv), because the claim comprises a diagnostic method.

Possible steps after receipt of the international search report (ISR) and written opinion of the International Searching Authority (WO/ISA)

General information

For all international applications, the competent International Searching Authority **(ISA)** will establish an international search report **(ISR)** accompanied by a written opinion of the International Searching Authority **(WO/ISA)**. The **WO/ISA** may be responded to by

- filing informal comments with the **International Bureau of WIPO (IB)** (where no demand for international preliminary examination **(demand)** is filed)
- filing amendments under Art. 19 PCT (this can be done whether or not a **demand** is filed)
- filing amendments under Art. 34 PCT and/or formal observations in response to objections raised in the **WO/ISA** (where a **demand** *is* actually filed)

This document explains these possibilities.

Filing informal comments

After receipt of the **ISR and WO/ISA**, the applicant may file informal comments on the **WO/ISA, directly with the IB** (see International Search and Preliminary Examination Guidelines 2.15). These will be communicated to the designated/elected Offices, together with the International Preliminary Report on Patentability **(IPRP)** at 30 months from the priority date.

Amending claims under Art. 19 PCT

The applicant may file **amended claims** under Art. 19 PCT, **directly with the IB** by the later of the following dates:

- 2 months from the date of mailing of the **ISR** and the **WO/ISA**
- 16 months from the priority date

However, any such amendment received by the **IB** after the expiration of the applicable time limit shall be **considered to have been received on time** by the **IB**, if it reaches it **before** the technical preparations for international publication have been completed (the 15th day prior to the date of publication, see PCT Applicant's Guide, International Phase, 9.013).

For further information, please see Rule 46 PCT as well as form PCT/ISA/220.

Please also note that, when filing amended claims under Art. 19 PCT, such amendments shall be **accompanied by a letter** identifying the amendments made and also the basis for the amendments in the application as originally filed (Rule 46.5(b) PCT). Where a **demand** is filed, failure to comply with this requirement may result in the amendments being ignored in the International Preliminary Examination Report **(IPER)**, see Rule 70.2(c-*bis*) PCT.

BNSDOCID: <XS_____200704010CK_I_>

Filing a demand for international preliminary examination

In principle, the **WO/ISA** will be considered to be the written opinion of the International Preliminary Examining Authority (**IPEA**). Where the **WO/ISA** issued by the **EPO** as **ISA** gives a positive opinion on the international application and the invention to which it relates, filing a **demand** with the **EPO** as **IPEA** would normally be unnecessary, since a positive IPRP would anyway be established by the IB based on the WO/ISA (see also further below).

If the applicant wishes to file a **demand** (for example, to allow him to argue his case in international preliminary examination with regard to objections raised in a negative **WO/ISA** before the **IPEA** issues an **IPER**), this must be done before expiration of **3 months after the date of mailing of the ISR and WO/ISA** or **22 months after priority date,** whichever expires later (Rule 54*bis* PCT). Amendments under Art. 34 PCT can be filed with the IPEA, normally at the same time as filing the demand (Rule 66.1(b) PCT) or within the time limit set for reply to any written opinion issued during international preliminary examination by the **IPEA**.

If a **demand** is filed at the **EPO** as **IPEA** and no comments/amendments have been received by the time the **EPO** starts drawing up the **IPER** (Rule 66.4*bis* PCT), the **WO/ISA** will be transformed by the **IPEA** into an **IPER** (also called the **IPRP (Chapter II)** which would merely reflect the content of the **WO/ISA** (OJ 10/2011, 532). The **demand** can still be withdrawn (Art. 37 PCT).

Please also note that, when filing amendments under Art. 34 PCT, such amendments shall be accompanied by a letter which identifies the amendments made and also the basis for the amendments in the application as originally filed (Rule 66.8(a) PCT). Failure to comply with this requirement may result in the amendments being ignored in the **IPER (IPRP (Chapter II))**, see Rule 70.2(c-*bis*) PCT.

Filing a request for supplementary international search

The applicant may, with the **IB**, file a request for **supplementary international search** under Rule 45*bis*.1 PCT. The present **ISR** and **WO/ISA** may also be taken into account in the execution of that supplementary international search, provided that these are available to the Authority charged with this task before it starts the supplementary search (Rule 45*bis*.5 PCT).

This kind of request **cannot be filed specifying the ISA** who did the **international search**.

More information on this topic can be found in the **PCT Applicant's Guide**, Chapter 8 (http://www.wipo.int/pct/en/guide/ip08.html).

End of the international phase

Where no **demand** is filed, at the end of the international phase, the **IB** will transform the **WO/ISA** into the IPRP (PCT Chapter I) (Rule 44*bis* PCT), which will then be transmitted together with possible informal comments to the designated Offices. Where a demand is filed, the **WO/ISA** is not transformed into an **IPRP (Chapter I)** by the **IB**, but rather the **IPEA** will establish an **IPER**, (the IPER is the same as the IPRP (PCT Chapter II), see Rule 70.15 PCT).

BNSDOCID: <XS_____200704010CK_I_>

Electronic Acknowledgement Receipt

EFS ID:	29124210
Application Number:	15178089
International Application Number:	
Confirmation Number:	7605
Title of Invention:	METHOD AND APPARATUS FOR REMOVING MOTION ARTIFACTS FROM BIOMEDICAL SIGNALS
First Named Inventor/Applicant Name:	Seyed M. A. Salehizadeh
Customer Number:	21005
Filer:	Mark B Solomon/Katie Norris
Filer Authorized By:	Mark B Solomon
Attorney Docket Number:	4147.1020-002 (15-089)
Receipt Date:	05-MAY-2017
Filing Date:	09-JUN-2016
Time Stamp:	11:31:21
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	no

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Transmittal Letter	41471020002SIDSTrans.pdf	90292 3ba181f037988265a16b9d6d8ab8d65c3612880b	no	3

Warnings:

Information:					
2	Information Disclosure Statement (IDS) Form (SB08)	41471020002LOR.pdf	107852 8ab02a7cc0fa1669990545b1a6c00c934cc71aeb	no	1
Warnings:					
Information:					
This is not an USPTO supplied IDS fillable form					
3	Foreign Reference	EP1297784A1.PDF	289587 17943a458bd23bead159b8dd6f5e6fce477ae34d	no	18
Warnings:					
The page size in the PDF is too large. The pages should be 8.5 x 11 or A4. If this PDF is submitted, the pages will be resized upon entry into the Image File Wrapper and may affect subsequent processing					
Information:					
4	Foreign Reference	EP1757224A2.PDF	302478 01cbea574711ecebed63991d114cf9dbb75acb1d	no	25
Warnings:					
The page size in the PDF is too large. The pages should be 8.5 x 11 or A4. If this PDF is submitted, the pages will be resized upon entry into the Image File Wrapper and may affect subsequent processing					
Information:					
5	Foreign Reference	WO2011_026669A1.PDF	354157 16de46e354526c8794a2e8f58510941243f3e5a9	no	34
Warnings:					
The page size in the PDF is too large. The pages should be 8.5 x 11 or A4. If this PDF is submitted, the pages will be resized upon entry into the Image File Wrapper and may affect subsequent processing					
Information:					
6	Foreign Reference	WO2012_123828A1.PDF	341935 9e3036b25930096bca33e9c60cbf65f04cc7efed	no	31
Warnings:					
Information:					
7	Foreign Reference	WO2017019184.pdf	10418296 5b8c8e94ebcd169bbcef2d524149edf40e221b90	no	102
Warnings:					
Information:					

8	Non Patent Literature	ISRWOPCTUS2016036734.pdf	2132503 fca0f5bab1df2f448d88b87bdf0422783fe3f7d1	no	17

Warnings:	
Information:	
Total Files Size (in bytes):	14037100

This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

New Applications Under 35 U.S.C. 111

If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371

If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office

If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Inventors:	Seyed M. A. Salehizadeh, Ki H. Chon and Yeonsik Noh		
Application No.:	15/178,089	Group:	3766
Filed:	June 9, 2016	Examiner:	Unknown
Confirmation No.:	7605		
For:	Method And Apparatus For Removing Motion Artifacts From Biomedical Signals		

TRANSMITTAL LETTER FOR SUPPLEMENTAL INFORMATION DISCLOSURE STATEMENT

Mail Stop Amendment
Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Commissioner:

This Information Disclosure Statement is submitted:

☒ under 37 CFR 1.97(b), or
(Within any one of the following time periods: three months of filing national application (other than a CPA) or date of entry of the national stage in an international application; or before the mailing date of a first office action on the merits; or before the mailing of a first office action after the filing of a Request for Continued Examination)

☐ under 37 CFR 1.97(c) together with either:
- ☐ a Statement under 37 CFR 1.97(e), as checked below, or
- ☐ a $[180/90/45] fee under 37 CFR 1.17(p), or

(After the 37 CFR 1.97(b) time period, but before any of a final action, notice of allowance, or an action that closes prosecution, whichever occurs first)

☐ under 37 CFR 1.97(d) together with:
- ☐ a Statement under 37 CFR 1.97(e), as checked below, and
- ☐ a $[180/90/45] fee under 37 CFR 1.17(p), or

(Filed after final action, notice of allowance, or an action that otherwise closes prosecution, but on or before payment of the issue fee)

☐ under 37 CFR 1.97(i):
Applicant requests that the IDS and cited reference(s) be placed in the application file.
(Filed after payment of issue fee) [Consider QPIDS Pilot]

No aspect of this submission constitutes a disclaimer of claim scope.

Statement Under 37 CFR 1.97(e)

☐ Each item of information contained in this Information Disclosure Statement was first cited in any communication from a foreign patent office in a counterpart foreign application not more than three months prior to the filing of this Information Disclosure Statement; or

☐ No item of information contained in this Information Disclosure Statement was cited in a communication from a foreign patent office in a counterpart foreign application, and, to the knowledge of the undersigned, after making reasonable inquiry, no item of information contained in the information disclosure statement was known to any individual designated in 37 CFR 1.56(c) more than three months prior to the filing of this Information Disclosure Statement.

Statement Under 37 CFR 1.704(d) (Patent Term Adjustment)
Applies to original applications (other than design) filed on or after May 29, 2000

☐ (1) A paper containing only an information disclosure statement in compliance with §§ 1.97 and 1.98 will not be considered a failure to engage in reasonable efforts to conclude prosecution (processing or examination) of the application under paragraphs (c)(6), (c)(8), (c)(9), or (c)(10) of this section if it is accompanied by a statement that each item of information contained in the information disclosure statement:

☐ (i) Was first cited in any communication from a patent office in a counterpart foreign or international application or from the Office, and this communication was not received by any individual designated in §1.56(c) more than thirty days prior to the filing of the information disclosure statement; or

☐ (ii) Is a communication that was issued by a patent office in a counterpart foreign or international application or by the Office, and this communication was not received by any individual designated in §1.56(c) more than thirty days prior to the filing of the information disclosure statement.

☒ Enclosed herewith is a Listing of References. Copies of the cited references are enclosed except as indicated below or in the attached Listing of References.

☐ Copies of the cited references submitted with an Information Disclosure Statement in prior application, U.S. Application No. [ ], to which priority under 35 U.S.C. 120 is claimed, are not required under 37 CFR 1.98(d)(1) and (2) and are thus not provided.

☒ The listed references were cited in the enclosed Search Report in counterpart foreign application PCT/US2016/036734, which is listed in the attached Listing of References.

☐ The "concise explanation" requirement (non-English references) for reference(s) [ ] under 37 CFR 1.98(a)(3) is satisfied by:

- ☐ the explanation provided on the attached sheet.
- ☐ the explanation provided in the Specification.
- ☐ submission of the enclosed International Search Report.
- ☐ submission of the enclosed English-language version of a foreign Search Report and/or foreign Office Action.
- ☐ the enclosed English language abstract.

Method of payment:

☐ Authorization is NOT granted to charge any fees which may be due in this matter to our Deposit Account.

☐ Please charge Deposit Account 08-0380 in the amount of $[ ].

☒ Please charge any deficiency in fees and credit any overpayment to Deposit Account 08-0380.

Respectfully submitted,

HAMILTON, BROOK, SMITH & REYNOLDS, P.C.

By /Mark B. Solomon, Reg. No. 44348/

Mark B. Solomon
Registration No. 44,348
Telephone: (978) 341-0036
Facsimile: (978) 341-0136

Concord, MA 01742-9133
Dated: 5/5/2017

Substitute for form 1449B/PTO	ATTORNEY DOCKET NO.	APPLICATION NO.	
SUPPLEMENTAL INFORMATION DISCLOSURE STATEMENT IN AN APPLICATION	4147.1020-002 (15-089)	15/178,089	
	FIRST NAMED INVENTOR	FILING DATE	
LISTING OF REFERENCES	Seyed M. A. Salehizadeh	June 9, 2016	
May 25, 2017 (Use several sheets if necessary)	EXAMINER	CONFIRMATION NO.	GROUP
	Thomson, William D.	7605	3769

U.S. PATENT DOCUMENTS

Examiner's Initials	Cite No.	DOCUMENT NUMBER Number-Kind Code (if known)	ISSUE DATE / PUBLICATION DATE MM-DD-YYYY	NAME OF PATENTEE OR APPLICANT OF CITED DOCUMENT
	1.	2014/0005988 A1	01-02-2014	Brockway
	2.	2014/0222350 A1	08-07-2014	Zheng, et al.
	3.	5,609,158	03-11-1997	Chan
	4.			
	5.			
	6.			
	7.			
	8.			
	9.			
	10.			
	11.			
	12.			
	13.			
	14.			
	15.			
	16.			
	17.			
	18.			

Copies of issued U.S. Patents and Published U.S. Applications are not required and are not being provided. We are not listing separately prior U.S. Patent Office communications regarding the cited documents because the Examiner has access to any such actions through PAIR.

EXAMINER	DATE CONSIDERED

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Inventors:	Seyed M. A. Salehizadeh, Ki H. Chon and Yeonsik Noh		
Application No.:	15/178,089	Group:	3769
Filed:	June 9, 2016	Examiner:	Thomson, William D.
Confirmation No.:	7605		
For:	Method And Apparatus For Removing Motion Artifacts From Biomedical Signals		

TRANSMITTAL LETTER FOR SUPPLEMENTAL INFORMATION DISCLOSURE STATEMENT

Mail Stop Amendment
Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Commissioner:

This Supplemental Information Disclosure Statement is submitted:

☒ under 37 CFR 1.97(b), or
(Within any one of the following time periods: three months of filing national application (other than a CPA) or date of entry of the national stage in an international application; or before the mailing date of a first office action on the merits; or before the mailing of a first office action after the filing of a Request for Continued Examination)

☐ under 37 CFR 1.97(c) together with either:
- ☐ a Statement under 37 CFR 1.97(e), as checked below, or
- ☐ a $[180/90/45] fee under 37 CFR 1.17(p), or

(After the 37 CFR 1.97(b) time period, but before any of a final action, notice of allowance, or an action that closes prosecution, whichever occurs first)

☐ under 37 CFR 1.97(d) together with:
- ☐ a Statement under 37 CFR 1.97(e), as checked below, and
- ☐ a $[180/90/45] fee under 37 CFR 1.17(p), or

(Filed after final action, notice of allowance, or an action that otherwise closes prosecution, but on or before payment of the issue fee)

☐ under 37 CFR 1.97(i):
Applicant requests that the IDS and cited reference(s) be placed in the application file.
(Filed after payment of issue fee) [Consider QPIDS Pilot]

No aspect of this submission constitutes a disclaimer of claim scope.

Statement Under 37 CFR 1.97(e)

☐ Each item of information contained in this Information Disclosure Statement was first cited in any communication from a foreign patent office in a counterpart foreign application not more than three months prior to the filing of this Information Disclosure Statement; or

☐ No item of information contained in this Information Disclosure Statement was cited in a communication from a foreign patent office in a counterpart foreign application, and, to the knowledge of the undersigned, after making reasonable inquiry, no item of information contained in the information disclosure statement was known to any individual designated in 37 CFR 1.56(c) more than three months prior to the filing of this Information Disclosure Statement.

Statement Under 37 CFR 1.704(d) (Patent Term Adjustment)
Applies to original applications (other than design) filed on or after May 29, 2000

☐ (1) A paper containing only an information disclosure statement in compliance with §§ 1.97 and 1.98 will not be considered a failure to engage in reasonable efforts to conclude prosecution (processing or examination) of the application under paragraphs (c)(6), (c)(8), (c)(9), or (c)(10) of this section if it is accompanied by a statement that each item of information contained in the information disclosure statement:

☐ (i) Was first cited in any communication from a patent office in a counterpart foreign or international application or from the Office, and this communication was not received by any individual designated in §1.56(c) more than thirty days prior to the filing of the information disclosure statement; or

☐ (ii) Is a communication that was issued by a patent office in a counterpart foreign or international application or by the Office, and this communication was not received by any individual designated in §1.56(c) more than thirty days prior to the filing of the information disclosure statement.

☒ Enclosed herewith is a Listing of References. Copies of the cited references are enclosed except as indicated below or in the attached Listing of References.

☐ Copies of the cited references submitted with an Information Disclosure Statement in prior application, U.S. Application No. [ ], to which priority under 35 U.S.C. 120 is claimed, are not required under 37 CFR 1.98(d)(1) and (2) and are thus not provided.

☐ The listed references were cited in the enclosed Search Report in counterpart foreign application [add application number], which is listed in the attached Listing of References.

☐ The "concise explanation" requirement (non-English references) for reference(s) [ ] under 37 CFR 1.98(a)(3) is satisfied by:

- ☐ the explanation provided on the attached sheet.
- ☐ the explanation provided in the Specification.
- ☐ submission of the enclosed International Search Report.
- ☐ submission of the enclosed English-language version of a foreign Search Report and/or foreign Office Action.
- ☐ the enclosed English language abstract.

Method of payment:

☐ Authorization is NOT granted to charge any fees which may be due in this matter to our Deposit Account.

☐ Please charge Deposit Account 08-0380 in the amount of $[ ].

☒ Please charge any deficiency in fees and credit any overpayment to Deposit Account 08-0380.

Respectfully submitted,

HAMILTON, BROOK, SMITH & REYNOLDS, P.C.

By /Mark B. Solomon, Reg. No. 44348/

Mark B. Solomon
Registration No. 44,348
Telephone: (978) 341-0036
Facsimile: (978) 341-0136

Concord, MA 01742-9133
Dated: 5/25/17

Electronic Acknowledgement Receipt

EFS ID:	29315029
Application Number:	15178089
International Application Number:	
Confirmation Number:	7605
Title of Invention:	METHOD AND APPARATUS FOR REMOVING MOTION ARTIFACTS FROM BIOMEDICAL SIGNALS
First Named Inventor/Applicant Name:	Seyed M. A. Salehizadeh
Customer Number:	21005
Filer:	Mark B Solomon/Katie Norris
Filer Authorized By:	Mark B Solomon
Attorney Docket Number:	4147.1020-002 (15-089)
Receipt Date:	25-MAY-2017
Filing Date:	09-JUN-2016
Time Stamp:	16:18:29
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	no

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Information Disclosure Statement (IDS) Form (SB08)	41471020002LOR.pdf	86807 d4a6eed688254820e53dabfec30b5e94064c0018	no	1

Warnings:

Information:					
This is not an USPTO supplied IDS fillable form					
2	Transmittal Letter	41471020002SIDSTrans.pdf	90289 f5c07f20ba03940700213b1a20c1b877dc13a090	no	3
Warnings:					
Information:					
		Total Files Size (in bytes):	177096		

This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

New Applications Under 35 U.S.C. 111

If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371

If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office

If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

PTO/SB/08a (03-15)
Approved for use through 07/31/2016. OMB 0651-0031
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it contains a valid OMB control number.

INFORMATION DISCLOSURE STATEMENT BY APPLICANT

(Not for submission under 37 CFR 1.99)

Application Number	15178089
Filing Date	2016-06-09
First Named Inventor	Seyed M. A. Salehizadeh
Art Unit	3769
Examiner Name	Thomson William D.
Attorney Docket Number	4147.1020-002 (15-089)

U.S.PATENTS Remove

Examiner Initial*	Cite No	Patent Number	Kind Code[1]	Issue Date	Name of Patentee or Applicant of cited Document	Pages,Columns,Lines where Relevant Passages or Relevant Figures Appear
	1	9872652	B2	2018-01-23	Salehizadeh et al	

If you wish to add additional U.S. Patent citation information please click the Add button. Add

U.S.PATENT APPLICATION PUBLICATIONS Remove

Examiner Initial*	Cite No	Publication Number	Kind Code[1]	Publication Date	Name of Patentee or Applicant of cited Document	Pages,Columns,Lines where Relevant Passages or Relevant Figures Appear
	1					

If you wish to add additional U.S. Published Application citation information please click the Add button. Add

FOREIGN PATENT DOCUMENTS Remove

Examiner Initial*	Cite No	Foreign Document Number[3]	Country Code[2] i	Kind Code[4]	Publication Date	Name of Patentee or Applicant of cited Document	Pages,Columns,Lines where Relevant Passages or Relevant Figures Appear	T[5]
	1							

If you wish to add additional Foreign Patent Document citation information please click the Add button Add

NON-PATENT LITERATURE DOCUMENTS Remove

Examiner Initials*	Cite No	Include name of the author (in CAPITAL LETTERS), title of the article (when appropriate), title of the item (book, magazine, journal, serial, symposium, catalog, etc), date, pages(s), volume-issue number(s), publisher, city and/or country where published.	T[5]

INFORMATION DISCLOSURE STATEMENT BY APPLICANT (Not for submission under 37 CFR 1.99)		
	Application Number	15178089
	Filing Date	2016-06-09
	First Named Inventor	Seyed M. A. Salehizadeh
	Art Unit	3769
	Examiner Name	Thomson William D.
	Attorney Docket Number	4147.1020-002 (15-089)

	1	

If you wish to add additional non-patent literature document citation information please click the Add button Add

EXAMINER SIGNATURE

Examiner Signature		Date Considered	

*EXAMINER: Initial if reference considered, whether or not citation is in conformance with MPEP 609. Draw line through a citation if not in conformance and not considered. Include copy of this form with next communication to applicant.

[1] See Kind Codes of USPTO Patent Documents at www.USPTO.GOV or MPEP 901.04. [2] Enter office that issued the document, by the two-letter code (WIPO Standard ST.3). [3] For Japanese patent documents, the indication of the year of the reign of the Emperor must precede the serial number of the patent document. [4] Kind of document by the appropriate symbols as indicated on the document under WIPO Standard ST.16 if possible. [5] Applicant is to place a check mark here if English language translation is attached.

INFORMATION DISCLOSURE STATEMENT BY APPLICANT

(Not for submission under 37 CFR 1.99)

Application Number	15178089
Filing Date	2016-06-09
First Named Inventor	Seyed M. A. Salehizadeh
Art Unit	3769
Examiner Name	Thomson William D.
Attorney Docket Number	4147.1020-002 (15-089)

CERTIFICATION STATEMENT

Please see 37 CFR 1.97 and 1.98 to make the appropriate selection(s):

That each item of information contained in the information disclosure statement was first cited in any communication from a foreign patent office in a counterpart foreign application not more than three months prior to the filing of the information disclosure statement. See 37 CFR 1.97(e)(1).

OR

☐ That no item of information contained in the information disclosure statement was cited in a communication from a foreign patent office in a counterpart foreign application, and, to the knowledge of the person signing the certification after making reasonable inquiry, no item of information contained in the information disclosure statement was known to any individual designated in 37 CFR 1.56(c) more than three months prior to the filing of the information disclosure statement. See 37 CFR 1.97(e)(2).

See attached certification statement.

The fee set forth in 37 CFR 1.17 (p) has been submitted herewith.

✓ A certification statement is not submitted herewith.

SIGNATURE

A signature of the applicant or representative is required in accordance with CFR 1.33, 10.18. Please see CFR 1.4(d) for the form of the signature.

Signature	/Mark B. Solomon, Reg. No. 44348/	Date (YYYY-MM-DD)	2018-01-23
Name/Print	Mark B. Solomon	Registration Number	44348

This collection of information is required by 37 CFR 1.97 and 1.98. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 1 hour to complete, including gathering, preparing and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

Privacy Act Statement

The Privacy Act of 1974 (P.L. 93-579) requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C. 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether the Freedom of Information Act requires disclosure of these record s.

2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.

3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.

4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).

5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.

6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).

7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (i.e., GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.

8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspections or an issued patent.

9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

Electronic Acknowledgement Receipt

EFS ID:	31582154
Application Number:	15178089
International Application Number:	
Confirmation Number:	7605
Title of Invention:	METHOD AND APPARATUS FOR REMOVING MOTION ARTIFACTS FROM BIOMEDICAL SIGNALS
First Named Inventor/Applicant Name:	Seyed M. A. Salehizadeh
Customer Number:	21005
Filer:	Mark B Solomon/Julie Chandler
Filer Authorized By:	Mark B Solomon
Attorney Docket Number:	4147.1020-002 (15-089)
Receipt Date:	23-JAN-2018
Filing Date:	09-JUN-2016
Time Stamp:	18:13:42
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	no

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Transmittal Letter	41471020002SIDSTrans.pdf	111366 f54e7313d78affbf71261c50602e8d96f36cc86b	no	3

Warnings:

Information:					
2	Information Disclosure Statement (IDS) Form (SB08)	41471020002LOR.PDF	1030758 f5f96b3d69fb9d683eabf4e0173a448940078234	no	4
Warnings:					
Information:					
			Total Files Size (in bytes):	1142124	

This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

New Applications Under 35 U.S.C. 111

If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371

If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office

If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Inventors:	Seyed M. A. Salehizadeh, Ki Chon, Yeonsik Noh		
Application No.:	15/178,089	Group:	3769
Filed:	June 9, 2016	Examiner:	Thomson William D.
Confirmation No.:	7605		
For:	Method And Apparatus For Removing Motion Artifacts From Biomedical Signals		

TRANSMITTAL LETTER FOR SUPPLEMENTAL INFORMATION DISCLOSURE STATEMENT

Mail Stop Amendment
Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Commissioner:

This Supplemental Information Disclosure Statement is submitted:

☒ under 37 CFR 1.97(b), or
(Within any one of the following time periods: three months of filing national application (other than a CPA) or date of entry of the national stage in an international application; or before the mailing date of a first office action on the merits; or before the mailing of a first office action after the filing of a Request for Continued Examination)

☐ under 37 CFR 1.97(c) together with either:
- ☐ a Statement under 37 CFR 1.97(e), as checked below, or
- ☐ a $[240/120/60] fee under 37 CFR 1.17(p), or
(After the 37 CFR 1.97(b) time period, but before any of a final action, notice of allowance, or an action that closes prosecution, whichever occurs first)

☐ under 37 CFR 1.97(d) together with:
- ☐ a Statement under 37 CFR 1.97(e), as checked below, and
- ☐ a $[240/120/60] fee under 37 CFR 1.17(p), or
(Filed after final action, notice of allowance, or an action that otherwise closes prosecution, but on or before payment of the issue fee)

☐ under 37 CFR 1.97(i):
Applicant requests that the IDS and cited reference(s) be placed in the application file.
(Filed after payment of issue fee) [Consider QPIDS Pilot]

No aspect of this submission constitutes a disclaimer of claim scope.

Statement Under 37 CFR 1.97(e)

☐ Each item of information contained in this Information Disclosure Statement was first cited in any communication from a foreign patent office in a counterpart foreign application not more than three months prior to the filing of this Information Disclosure Statement; or

☐ No item of information contained in this Information Disclosure Statement was cited in a communication from a foreign patent office in a counterpart foreign application, and, to the knowledge of the undersigned, after making reasonable inquiry, no item of information contained in the information disclosure statement was known to any individual designated in 37 CFR 1.56(c) more than three months prior to the filing of this Information Disclosure Statement.

Statement Under 37 CFR 1.704(d) (Patent Term Adjustment)
Applies to original applications (other than design) filed on or after May 29, 2000

☐ (1) A paper containing only an information disclosure statement in compliance with §§ 1.97 and 1.98 will not be considered a failure to engage in reasonable efforts to conclude prosecution (processing or examination) of the application under paragraphs (c)(6), (c)(8), (c)(9), or (c)(10) of this section if it is accompanied by a statement that each item of information contained in the information disclosure statement:

☐ (i) Was first cited in any communication from a patent office in a counterpart foreign or international application or from the Office, and this communication was not received by any individual designated in §1.56(c) more than thirty days prior to the filing of the information disclosure statement; or

☐ (ii) Is a communication that was issued by a patent office in a counterpart foreign or international application or by the Office, and this communication was not received by any individual designated in §1.56(c) more than thirty days prior to the filing of the information disclosure statement.

☒ Enclosed herewith is a Listing of References. Copies of the cited references are enclosed except as indicated below or in the attached Listing of References.

☐ Copies of the cited references submitted with an Information Disclosure Statement in prior application, U.S. Application No. [ ], to which priority under 35 U.S.C. 120 is claimed, are not required under 37 CFR 1.98(d)(1) and (2) and are thus not provided.

☐ The listed references were cited in the enclosed Search Report in counterpart foreign application [add application number], which is listed in the attached Listing of References.

☐ The "concise explanation" requirement (non-English references) for reference(s) [ ] under 37 CFR 1.98(a)(3) is satisfied by:

- ☐ the explanation provided on the attached sheet.
- ☐ the explanation provided in the Specification.
- ☐ submission of the enclosed International Search Report.
- ☐ submission of the enclosed English-language version of a foreign Search Report and/or foreign Office Action.
- ☐ the enclosed English language abstract.

Method of payment:

☐ Authorization is NOT granted to charge any fees which may be due in this matter to our Deposit Account.

☐ Please charge Deposit Account 08-0380 in the amount of $[ ].

☒ Please charge any deficiency in fees and credit any overpayment to Deposit Account 08-0380.

Respectfully submitted,

HAMILTON, BROOK, SMITH & REYNOLDS, P.C.

By /Mark B. Solomon, Reg. No. 44348/
Mark B. Solomon
Registration No. 44,348
Telephone: (978) 341-0036
Facsimile: (978) 341-0136

Concord, MA 01742-9133
Dated: 1/23/2018

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
15/178,089	06/09/2016	Seyed M. A. Salehizadeh	4147.1020-002 (15-089)	7605

21005 7590 04/18/2018

HAMILTON, BROOK, SMITH & REYNOLDS, P.C.
530 VIRGINIA ROAD
P.O. BOX 9133
CONCORD, MA 01742-9133

EXAMINER
GEDEON, BRIAN T

ART UNIT	PAPER NUMBER
3766	

NOTIFICATION DATE	DELIVERY MODE
04/18/2018	ELECTRONIC

Please find below and/or attached an Office communication concerning this application or proceeding.

The time period for reply, if any, is set in the attached communication.

Notice of the Office communication was sent electronically on above-indicated "Notification Date" to the following e-mail address(es):

docketing.department@hbsr.com
helpdesk@hbsr.com

Office Action Summary	Application No. 15/178,089	Applicant(s) SALEHIZADEH ET AL.	
	Examiner BRIAN T. GEDEON	Art Unit 3766	AIA (First Inventor to File) Status Yes

-- The MAILING DATE of this communication appears on the cover sheet with the correspondence address --

Period for Reply

A SHORTENED STATUTORY PERIOD FOR REPLY IS SET TO EXPIRE *3* MONTHS FROM THE MAILING DATE OF THIS COMMUNICATION.

- Extensions of time may be available under the provisions of 37 CFR 1.136(a). In no event, however, may a reply be timely filed after SIX (6) MONTHS from the mailing date of this communication.
- If NO period for reply is specified above, the maximum statutory period will apply and will expire SIX (6) MONTHS from the mailing date of this communication.
- Failure to reply within the set or extended period for reply will, by statute, cause the application to become ABANDONED (35 U.S.C. § 133). Any reply received by the Office later than three months after the mailing date of this communication, even if timely filed, may reduce any earned patent term adjustment. See 37 CFR 1.704(b).

Status

1)☒ Responsive to communication(s) filed on *9 June 2016*.

☐ A declaration(s)/affidavit(s) under **37 CFR 1.130(b)** was/were filed on _____.

2a)☐ This action is **FINAL**. 2b)☒ This action is non-final.

3)☐ An election was made by the applicant in response to a restriction requirement set forth during the interview on _____; the restriction requirement and election have been incorporated into this action.

4)☐ Since this application is in condition for allowance except for formal matters, prosecution as to the merits is closed in accordance with the practice under *Ex parte Quayle*, 1935 C.D. 11, 453 O.G. 213.

Disposition of Claims*

5)☒ Claim(s) *1-73* is/are pending in the application.

5a) Of the above claim(s) _____ is/are withdrawn from consideration.

6)☐ Claim(s) _____ is/are allowed.

7)☒ Claim(s) *1-8,27-44 and 63-73* is/are rejected.

8)☒ Claim(s) *9-26 and 45-62* is/are objected to.

9)☐ Claim(s) _____ are subject to restriction and/or election requirement.

* If any claims have been determined allowable, you may be eligible to benefit from the **Patent Prosecution Highway** program at a participating intellectual property office for the corresponding application. For more information, please see http://www.uspto.gov/patents/init_events/pph/index.jsp or send an inquiry to PPHfeedback@uspto.gov.

Application Papers

10)☐ The specification is objected to by the Examiner.

11)☒ The drawing(s) filed on *30 August 2016* is/are: a)☒ accepted or b)☐ objected to by the Examiner.

Applicant may not request that any objection to the drawing(s) be held in abeyance. See 37 CFR 1.85(a).

Replacement drawing sheet(s) including the correction is required if the drawing(s) is objected to. See 37 CFR 1.121(d).

Priority under 35 U.S.C. § 119

12)☐ Acknowledgment is made of a claim for foreign priority under 35 U.S.C. § 119(a)-(d) or (f).

Certified copies:

a)☐ All b)☐ Some** c)☐ None of the:

1.☐ Certified copies of the priority documents have been received.

2.☐ Certified copies of the priority documents have been received in Application No. _____.

3.☐ Copies of the certified copies of the priority documents have been received in this National Stage application from the International Bureau (PCT Rule 17.2(a)).

** See the attached detailed Office action for a list of the certified copies not received.

Attachment(s)

1) ☒ Notice of References Cited (PTO-892)

2) ☒ Information Disclosure Statement(s) (PTO/SB/08a and/or PTO/SB/08b) Paper No(s)/Mail Date *10/21/2016, 12/13/2016, 1/18/2017, 2/14/2017, 5/5/2017, 5/25/2017, 1/23/2018*.

3) ☐ Interview Summary (PTO-413) Paper No(s)/Mail Date. _____ .

4) ☐ Other: _____.

DETAILED ACTION

Notice of Pre-AIA or AIA Status

1. The present application, filed on or after March 16, 2013, is being examined under the first inventor to file provisions of the AIA.

Information Disclosure Statement

2. The information disclosure statements filed 23 January 2018, 25 May 2017, 5 May 2017, 14 February 2017, 18 January 2018, 13 December 2016, and 21 October 2016 have been considered.

Applicant should note that the large number of references in the attached IDS have been considered by the examiner in the same manner as other documents in Office search files are considered by the examiner while conducting a search of the prior art in a proper field of search. See MPEP 609.05(b). Applicant is requested to point out any particular references in the IDS which may be of particular relevance to the presently claimed invention in response to this Office Action.

Claim Rejections - 35 USC § 102

3. In the event the determination of the status of the application as subject to AIA 35 U.S.C. 102 and 103 (or as subject to pre-AIA 35 U.S.C. 102 and 103) is incorrect, any correction of the statutory basis for the rejection will not be considered a new ground of rejection if the prior art relied upon, and the rationale supporting the rejection, would be the same under either status.

4. The following is a quotation of the appropriate paragraphs of 35 U.S.C. 102 that form the basis for the rejections under this section made in this Office action:

> A person shall be entitled to a patent unless –
>
> (a)(1) the claimed invention was patented, described in a printed publication, or in public use, on sale or otherwise available to the public before the effective filing date of the claimed invention.
>
> -and-
>
> (a)(2) the claimed invention was described in a patent issued under section 151, or in an application for patent published or deemed published under section 122(b), in which the patent or application, as the case may be, names another inventor and was effectively filed before the effective filing date of the claimed invention.

5. Claim(s) 1-4, 27, 35-40, 63, 71, and 72 is/are rejected under 35 U.S.C. 102(a1/a2) as being anticipated by Grundlehner et al. (US Publication no. 2014/0309943).

In regard to claims 1, 37, and 73, Grundlehner et al. describes a system and method for reconstructing a heart related signal by removing motion artifacts. The features of Grundlehner et al. include: reconstructing a representation of a heart-related signal for output using spectral analysis of an acquired biopotential signal (i.e., and ECG or even an EEG or EMG) and a secondary signal pertaining to a motion signal. The secondary signal pertaining to motion is obtained from a motion sensor such as an accelerometer which senses the motion artifacts resulting from the movement of recording electrodes, cables, or acquisition system with respect to the user's skin and environment (see paragraphs 5, 9, 14, 19, 21, 25, 26, 56-58, 64, and 70). The system and method of Grundlehner et al. also includes a motion classification module 110 configured to extract motion artifact and determine the type of motion causing the artifact and communication setting for artifact removal from the biopotential signal (para

63). Ultimately, Grundlehner et al. provides as output the cleaned, reconstructed biopotential signal which is free from motion artifact (para 64).

In regard to claims 2 and 38, the signal ultimately output by Grundlehner et al. is cleaned from motion artifact such that the motion artifact is suppressed from the reconstructed signal (para 64).

In regard to claims 3 and 39, before conducting the spectral analysis, the signals are pre-processed by removing powerline noise and resampling. Additionally, the pre-processing determines the type of motion artifact and communicates optimal settings for artifact removal (para 66).

In regard to claims 4 and 40, part of the pre-processing includes filtering the signal for noise (para 65-66).

In regard to claims 27 and 63, the motion signal and biopotential signal are considered to be acquired and produced concurrently in time as the motion signal is acquired to indicate motion artifacts resulting from the movement of recording electrodes, cables, or acquisition system with respect to the user's skin and environment (para 5, 14, 15, 63 and 64).

In regard to claims 35, 36, 71, and 72, one of ordinary skill in the art is considered to find that Grundlehner et al. may employed in real-time or non-real time.

Claim Rejections - 35 USC § 103

6. In the event the determination of the status of the application as subject to AIA 35 U.S.C. 102 and 103 (or as subject to pre-AIA 35 U.S.C. 102 and 103) is incorrect, any

correction of the statutory basis for the rejection will not be considered a new ground of rejection if the prior art relied upon, and the rationale supporting the rejection, would be the same under either status.

7. The following is a quotation of 35 U.S.C. 103 which forms the basis for all obviousness rejections set forth in this Office action:

> A patent for a claimed invention may not be obtained, notwithstanding that the claimed invention is not identically disclosed as set forth in section 102, if the differences between the claimed invention and the prior art are such that the claimed invention as a whole would have been obvious before the effective filing date of the claimed invention to a person having ordinary skill in the art to which the claimed invention pertains. Patentability shall not be negated by the manner in which the invention was made.

8. Claims 5, 28-34, 41, and 64-70 is/are rejected under 35 U.S.C. 103 as being unpatentable over Grundlehner et al. (US Publication no. 2014/0309943) in view of Venkatraman et al. (US Patent no. 8,945,017).

In regard to claims 5 and 41, Grundlehner et al. is considered to substantially disclose the invention as claimed, however does not teach that the filtering during pre-processing of biopotential signals includes downsampling the filtered heart-related signal wherein the downsampling is at a rate less than the original sampling rate. Venkatraman et al. describes a wearable heart rate sensor that combines sensors for heart-related signals with motion sensors for removing motion artifacts from the heart-related signal (col 1 line 61 - col 2 line 16). Venkatraman et al. during processing of the biopotential signals determines to modify or reduce the sampling rate when the device determines that a user's motion is below a threshold (col 20 lines 13-32). Reducing the sampling rate, or downsampling as claimed, during periods of low activity reduces the consumption demands of the power source. In view of this, modification of Grundlehner et al. in view of the teaching in Venkatraman et al. to downsample the sampling rate is

considered obvious to one of ordinary skill in the art since Venkatraman et al. demonstrates that the technique was known in the art to reduce power consumption demands. Modification is considered to include application of a known technique to a known device to yield a predictable result.

In regard to claims 28, 29, 64, and 65, Grundlehner et al. is considered to substantially disclose the invention as claimed, however does not teach segmenting the acquired signals into windowed segments for signal reconstruction. Venkatraman et al. is directed to reconstructing a heart-related signal with suppressed motion artifacts similar to that in Grundlehner et al. Vankatraman et al. teaches that signal processing for reconstruction includes real-time windowed segments wherein the heart rate information is measured with in a time window segment (col 42 lines 41-45). Use of windows is considered routine in spectral analysis as windowing is a known technique for breaking down large datasets into smaller, more easily handled subsets. Therefore modification of Grundlehner et al. to include a windowing technique is considered obvious as the modification would include the application of a known technique to a known process to yield a predictable result. Determination of the time window duration is considered to only require routine skill.

In regard to claims 30, 31, 66, and 67, Grundlehner et al. is considered to disclose equivalent sensors for biopotential signal recording and an accelerometer for motion signal detection (para 56-58). Alternatively, the biopotential sensor of Venkatraman et al. includes a PPG sensor utilizing LED sources (col 17 line 62 – col 18 line 67). Modification of the sensor type in Grundlehner et al. is considered to be

obvious to one of ordinary skill in the art since the sensors of Grundlehner et al. and Venkatramam et al. are suitable alternative equivalents for biopotential sensing and may be selected by choice.

In regard to claims 32 and 68, one of the sensors that may be employed by Grundlehner et al. is a heart rate sensor (para 56). One of ordinary skill in the art is considered to possess the knowledge to determine a representation of heart rate estimate from the heart rate sensor and/or ECG. Alternatively, the objective of Venkatraman et al. is to provide a reliable measure of heart rate and thus provides enabling disclosure for determining a heart rate estimate (col 17 lines 54-61).

In regard to claims 33 and 69, Grundlehner et al. does not disclose an oxygen saturation measure from the biopotential signal. Venkatraman et al. includes an oxygen saturation sensor (col 33 lines 1-18). Measurement of oxygen saturation from the sensors employed by Venkatraman et al. is a well-known function, and modification of Grundlehner et al. with one of these sensors to obtain oxygen saturation as a biopotential signal is considered obvious to one of ordinary skill in the art since the sensors are well known and would constitute the substation of one known biopotential sensor for another to yield a predictable result.

In regard to claims 34 and 70, Grundlehner et al. utilize EEG as the exemplary biopotential signal description of reconstruction processes, however the biopotential may also be an ECG, wherein it is considered that one of ordinary skill in the art is considered to possess the knowledge to determine a representation to predict heart rate ailments from the ECG.

9. Claims 6-8 and 42-44 is/are rejected under 35 U.S.C. 103 as being unpatentable over Grundlehner et al. (US Publication no. 2014/0309943) in view of Chon et al. (US Patent no. 9,713,428).

In regard to claims 6, 7, 42, and 43, Grundlehner et al. is considered to substantially disclose the invention as claimed except does not teach computing a time-frequency spectra of the measured signals as part of the spectral analysis of the signals. Chon et al. describes a system and method for removing insignificant artifacts from a heart related signal. To do this, Chon et al. employ computation of time-frequency spectrum analysis of the signals (col 8 line 49 – col 9 line 17). Modification of Grundlehner et al. to compute a time-frequency spectra of the measured signals as part of the spectral analysis of the signals is considered obvious to one of ordinary skill in the art at the time of the invention since Chon et al. demonstrates that this is a suitable technique for removing artifacts from a heart related signal. Modification is considered to comprise application of a known technique to a known process to yield a predictable result. Three-dimensional spectra is also considered to be within routine skill in the art.

In regard to claims 8 and 44, the time-frequency spectra in Chon et al. is a power spectral density (col 10 lines 35-42).

Allowable Subject Matter

10. Claims 9-26 and 45-62 are objected to as being dependent upon a rejected base claim, but would be allowable if rewritten in independent form including all of the limitations of the base claim and any intervening claims.

The following is a statement of reasons for the indication of allowable subject matter: the prior art fails to teach or suggest the additional limitations for reconstruction of the heart related signal representation.

Statement on Communication via Internet

11. Communications via Internet e-mail are at the discretion of the applicant. Without a written authorization by applicant in place, the USPTO will not respond via Internet e-mail to any Internet correspondence which contains information subject to the confidentiality requirement as set forth in 35 U.S.C. 122. Where a written authorization is given by the applicant, communications via Internet e-mail, other than those under 35 U.S.C. 132 or which otherwise require a signature, may be used. USPTO employees are NOT permitted to initiate communications with applicants via Internet e-mail unless there is a written authorization of record in the patent application by the applicant. The following is a sample authorization form which may be used by applicant:

> "Recognizing that Internet communications are not secure, I hereby authorize the USPTO to communicate with me concerning any subject matter of this application by electronic mail. I understand that a copy of these communications will be made of record in the application file."

Please refer to MPEP 502.03 for guidance on Communications via Internet.

Conclusion

12. Any inquiry concerning this communication or earlier communications from the examiner should be directed to BRIAN T. GEDEON whose telephone number is (571)272-3447. The examiner can normally be reached on M-F 8:30-5:00.

Examiner interviews are available via telephone, in-person, and video conferencing using a USPTO supplied web-based collaboration tool. To schedule an interview, applicant is encouraged to use the USPTO Automated Interview Request (AIR) at http://www.uspto.gov/interviewpractice.

If attempts to reach the examiner by telephone are unsuccessful, the examiner's supervisor, Carl H. Layno can be reached on (571) 272-4949. The fax phone number for the organization where this application or proceeding is assigned is 571-273-8300.

Information regarding the status of an application may be obtained from the Patent Application Information Retrieval (PAIR) system. Status information for published applications may be obtained from either Private PAIR or Public PAIR. Status information for unpublished applications is available through Private PAIR only. For more information about the PAIR system, see http://pair-direct.uspto.gov. Should you have questions on access to the Private PAIR system, contact the Electronic Business Center (EBC) at 866-217-9197 (toll-free). If you would like assistance from a USPTO Customer Service Representative or access to the automated information system, call 800-786-9199 (IN USA OR CANADA) or 571-272-1000.

/BRIAN T GEDEON/
Primary Examiner, Art Unit 3766
13 April 2018

Notice of References Cited	Application/Control No. 15/178,089	Applicant(s)/Patent Under Reexamination SALEHIZADEH ET AL.	
	Examiner BRIAN T. GEDEON	Art Unit 3766	Page 1 of 1

U.S. PATENT DOCUMENTS

*		Document Number Country Code-Number-Kind Code	Date MM-YYYY	Name	CPC Classification	US Classification
*	A	US-2014/0309943 A1	10-2014	Grundlehner; Bernard	G06F19/321	702/19
*	B	US-9,713,428 B2	07-2017	Chon; Ki H.	A61B5/02405	1/1
*	C	US-8,945,017 B2	02-2015	Venkatraman; Subramaniam	A61B5/721	600/500
	D	US-				
	E	US-				
	F	US-				
	G	US-				
	H	US-				
	I	US-				
	J	US-				
	K	US-				
	L	US-				
	M	US-				

FOREIGN PATENT DOCUMENTS

*		Document Number Country Code-Number-Kind Code	Date MM-YYYY	Country	Name	CPC Classification
	N					
	O					
	P					
	Q					
	R					
	S					
	T					

NON-PATENT DOCUMENTS

*		Include as applicable: Author, Title Date, Publisher, Edition or Volume, Pertinent Pages)
	U	
	V	
	W	
	X	

*A copy of this reference is not being furnished with this Office action. (See MPEP § 707.05(a).)
Dates in MM-YYYY format are publication dates. Classifications may be US or foreign.

Substitute for form 1449B/PTO **SUPPLEMENTAL INFORMATION DISCLOSURE STATEMENT IN AN APPLICATION** **LISTING OF REFERENCES** January 18, 2017 (Use several sheets if necessary)	ATTORNEY DOCKET NO. 4147.1020-002 (15-089)	APPLICATION NO. 15/178,089	
	FIRST NAMED INVENTOR Seyed M. A. Salehizadeh	FILING DATE June 9, 2016	
	EXAMINER	CONFIRMATION NO. 7605	GROUP 3766

U.S. PATENT DOCUMENTS

Examiner's Initials	Cite No.	DOCUMENT NUMBER Number-Kind Code (if known)	ISSUE DATE / PUBLICATION DATE MM-DD-YYYY	NAME OF PATENTEE OR APPLICANT OF CITED DOCUMENT
	1.	2016/0360977 A1	12-15-2016	Salehizadeh et al.

Copies of issued U.S. Patents and Published U.S. Applications are not required and are not being provided. We are not listing separately prior U.S. Patent Office communications regarding the cited documents because the Examiner has access to any such actions through PAIR.

FOREIGN PATENT DOCUMENTS

Examiner's Initials	Cite No.	DOCUMENT NUMBER Country Code-Number-Kind Code (if known)	DATE MM-DD-YYYY	NAME OF PATENTEE OR APPLICANT OF CITED DOCUMENT
	1.	WO 2016/201130	12-15-2016	University of Connecticut

EXAMINER /BRIAN T GEDEON/	DATE CONSIDERED 04/13/2018

Petitioner Ex. 1004, 0942

ALL REFERENCES CONSIDERED EXCEPT WHERE LINED THROUGH. /B.T.G/

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

BIB DATA SHEET

CONFIRMATION NO. 7605

SERIAL NUMBER	FILING or 371(c) DATE RULE	CLASS	GROUP ART UNIT	ATTORNEY DOCKET NO.
15/178,089	06/09/2016	600	3766	4147.1020-002 (15-089)

APPLICANTS

University of Connecticut, Farmington, CT;

INVENTORS

Seyed M. A. Salehizadeh, Coventry, CT;
Ki H. Chon, Mansfield Center, CT;
Yeonsik Noh, Willington, CT;

**** CONTINUING DATA ***************************

This appln claims benefit of 62/299,944 02/25/2016
and claims benefit of 62/172,862 06/09/2015

**** FOREIGN APPLICATIONS ***************************

**** IF REQUIRED, FOREIGN FILING LICENSE GRANTED **** ** SMALL ENTITY **
06/28/2016

Foreign Priority claimed ☐ Yes ☑ No 35 USC 119(a-d) conditions met ☐ Yes ☐ No Verified and Acknowledged /BRIAN T GEDEON/ Examiner's Signature	☐ Met after Allowance Initials	STATE OR COUNTRY	SHEETS DRAWINGS	TOTAL CLAIMS	INDEPENDENT CLAIMS
		CT	25	73	3

ADDRESS

HAMILTON, BROOK, SMITH & REYNOLDS, P.C.
530 VIRGINIA ROAD
P.O. BOX 9133
CONCORD, MA 01742-9133
UNITED STATES

TITLE

METHOD AND APPARATUS FOR REMOVING MOTION ARTIFACTS FROM BIOMEDICAL SIGNALS

FILING FEE RECEIVED		
2920	FEES: Authority has been given in Paper No._____ to charge/credit DEPOSIT ACCOUNT No._____ for following:	☐ All Fees ☐ 1.16 Fees (Filing) ☐ 1.17 Fees (Processing Ext. of time) ☐ 1.18 Fees (Issue) ☐ Other _____ ☐ Credit

Substitute for form 1449B/PTO **SUPPLEMENTAL INFORMATION DISCLOSURE STATEMENT IN AN APPLICATION** **LISTING OF REFERENCES** May 5, 2017 (Use several sheets if necessary)	ATTORNEY DOCKET NO. 4147.1020-002 (15-089)	APPLICATION NO. 15/178,089	
	FIRST NAMED INVENTOR Seyed M. A. Salehizadeh	FILING DATE June 9, 2016	
	EXAMINER	CONFIRMATION NO. 7605	GROUP 3766

U.S. PATENT DOCUMENTS

Examiner's Initials	Cite No.	DOCUMENT NUMBER Number-Kind Code (if known)	ISSUE DATE / PUBLICATION DATE MM-DD-YYYY	NAME OF PATENTEE OR APPLICANT OF CITED DOCUMENT
	1.	2008/167564 A1	07-10-2008	Hete, *et al.*
	2.	2014/275854 A1	09-18-2014	Venkatraman, *et al.*
	3.	2014/275852 A1	09-18-2014	Hong, *et al.*

Copies of issued U.S. Patents and Published U.S. Applications are not required and are not being provided. We are not listing separately prior U.S. Patent Office communications regarding the cited documents because the Examiner has access to any such actions through PAIR.

FOREIGN PATENT DOCUMENTS

Examiner's Initials	Cite No.	DOCUMENT NUMBER Country Code-Number-Kind Code (if known)	DATE MM-DD-YYYY	NAME OF PATENTEE OR APPLICANT OF CITED DOCUMENT
	1.	EP 1 297 784 A1	04-02-2003	Csem Ct Suisse Electronique
	2.	EP 1 757 224 A2	02-28-2007	Nihon Kohden Corp
	3.	WO 2011/026669 A1	03-10-2011	Suisse Electronique Microtech
	4.	WO 2012/123828 A1	09-20-2012	Koninkl Philips Electronics
	5.	WO 2017/019184 A2	02-02-2017	University of Connecticut

Examiner's Initials	Cite No.	**OTHER DOCUMENTS** *(Including Author, Title, Date, Pertinent Pages, Etc.)*
	1.	Notification and Transmittal of International Search Report and Written Opinion dated March 16, 2017, for International Appl. No. PCT/US2016/036734, entitled "Method And Apparatus For Removing Motion Artifacts From Biomedical Signals", consisting of 17 pages. (Attorney Docket No: 4147.1020-004).

***Copies of any non-published U.S. Patent Applications are not being provided because the examiner has access to such documents through PAIR. We are not listing separately prior U.S. Patent Office communications regarding the cited documents because the Examiner has access to any such actions through PAIR.**

EXAMINER /BRIAN T GEDEON/	DATE CONSIDERED 04/13/2018

Petitioner Ex. 1004, 0944

ALL REFERENCES CONSIDERED EXCEPT WHERE LINED THROUGH. /B.T.G/

Substitute for form 1449B/PTO **SUPPLEMENTAL INFORMATION DISCLOSURE STATEMENT IN AN APPLICATION** **LISTING OF REFERENCES** May 25, 2017 (Use several sheets if necessary)	ATTORNEY DOCKET NO. 4147.1020-002 (15-089)	APPLICATION NO. 15/178,089	
	FIRST NAMED INVENTOR Seyed M. A. Salehizadeh	FILING DATE June 9, 2016	
	EXAMINER Thomson, William D.	CONFIRMATION NO. 7605	GROUP 3769

U.S. PATENT DOCUMENTS

Examiner's Initials	Cite No.	DOCUMENT NUMBER Number-Kind Code (if known)	ISSUE DATE / PUBLICATION DATE MM-DD-YYYY	NAME OF PATENTEE OR APPLICANT OF CITED DOCUMENT
	1.	2014/0005988 A1	01-02-2014	Brockway
	2.	2014/0222350 A1	08-07-2014	Zheng, et al.
	3.	5,609,158	03-11-1997	Chan
	4.			
	5.			
	6.			
	7.			
	8.			
	9.			
	10.			
	11.			
	12.			
	13.			
	14.			
	15.			
	16.			
	17.			
	18.			

Copies of issued U.S. Patents and Published U.S. Applications are not required and are not being provided. We are not listing separately prior U.S. Patent Office communications regarding the cited documents because the Examiner has access to any such actions through PAIR.

ALL REFERENCES CONSIDERED EXCEPT WHERE LINED THROUGH. /B.T.G/

EXAMINER /BRIAN T GEDEON/	DATE CONSIDERED 04/13/2018

Doc code: IDS
Doc description: Information Disclosure Statement (IDS) Filed

PTO/SB/08a (03-15)
Approved for use through 07/31/2016. OMB 0651-0031
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it contains a valid OMB control number.

INFORMATION DISCLOSURE STATEMENT BY APPLICANT

(Not for submission under 37 CFR 1.99)

Application Number	15178089
Filing Date	2016-06-09
First Named Inventor	Seyed M. A. Salehizadeh
Art Unit	3769
Examiner Name	Thomson William D.
Attorney Docket Number	4147.1020-002 (15-089)

U.S.PATENTS Remove

Examiner Initial*	Cite No	Patent Number	Kind Code[1]	Issue Date	Name of Patentee or Applicant of cited Document	Pages,Columns,Lines where Relevant Passages or Relevant Figures Appear
	1	9872652	B2	2018-01-23	Salehizadeh et al	

If you wish to add additional U.S. Patent citation information please click the Add button. Add

U.S.PATENT APPLICATION PUBLICATIONS Remove

Examiner Initial*	Cite No	Publication Number	Kind Code[1]	Publication Date	Name of Patentee or Applicant of cited Document	Pages,Columns,Lines where Relevant Passages or Relevant Figures Appear
	1					

If you wish to add additional U.S. Published Application citation information please click the Add button. Add

FOREIGN PATENT DOCUMENTS Remove

Examiner Initial*	Cite No	Foreign Document Number[3]	Country Code[2] i	Kind Code[4]	Publication Date	Name of Patentee or Applicant of cited Document	Pages,Columns,Lines where Relevant Passages or Relevant Figures Appear	T[5]
	1							

If you wish to add additional Foreign Patent Document citation information please click the Add button Add

NON-PATENT LITERATURE DOCUMENTS Remove

Examiner Initials*	Cite No	Include name of the author (in CAPITAL LETTERS), title of the article (when appropriate), title of the item (book, magazine, journal, serial, symposium, catalog, etc), date, pages(s), volume-issue number(s), publisher, city and/or country where published.	T[5]

ALL REFERENCES CONSIDERED EXCEPT WHERE LINED THROUGH. /B.T.G/

INFORMATION DISCLOSURE STATEMENT BY APPLICANT

(Not for submission under 37 CFR 1.99)

Application Number	15178089
Filing Date	2016-06-09
First Named Inventor	Seyed M. A. Salehizadeh
Art Unit	3769
Examiner Name	Thomson William D.
Attorney Docket Number	4147.1020-002 (15-089)

	1	

If you wish to add additional non-patent literature document citation information please click the Add button [Add]

EXAMINER SIGNATURE

Examiner Signature	/BRIAN T GEDEON/	Date Considered	04/13/2018

*EXAMINER: Initial if reference considered, whether or not citation is in conformance with MPEP 609. Draw line through a citation if not in conformance and not considered. Include copy of this form with next communication to applicant.

[1] See Kind Codes of USPTO Patent Documents at www.USPTO.GOV or MPEP 901.04. [2] Enter office that issued the document, by the two-letter code (WIPO Standard ST.3). [3] For Japanese patent documents, the indication of the year of the reign of the Emperor must precede the serial number of the patent document. [4] Kind of document by the appropriate symbols as indicated on the document under WIPO Standard ST.16 if possible. [5] Applicant is to place a check mark here if English language translation is attached.

ALL REFERENCES CONSIDERED EXCEPT WHERE LINED THROUGH. /B.T.G/

INFORMATION DISCLOSURE STATEMENT BY APPLICANT

(Not for submission under 37 CFR 1.99)

Application Number	15178089
Filing Date	2016-06-09
First Named Inventor	Seyed M. A. Salehizadeh
Art Unit	3769
Examiner Name	Thomson William D.
Attorney Docket Number	4147.1020-002 (15-089)

CERTIFICATION STATEMENT

Please see 37 CFR 1.97 and 1.98 to make the appropriate selection(s):

That each item of information contained in the information disclosure statement was first cited in any communication from a foreign patent office in a counterpart foreign application not more than three months prior to the filing of the information disclosure statement. See 37 CFR 1.97(e)(1).

OR

☐ That no item of information contained in the information disclosure statement was cited in a communication from a foreign patent office in a counterpart foreign application, and, to the knowledge of the person signing the certification after making reasonable inquiry, no item of information contained in the information disclosure statement was known to any individual designated in 37 CFR 1.56(c) more than three months prior to the filing of the information disclosure statement. See 37 CFR 1.97(e)(2).

See attached certification statement.

The fee set forth in 37 CFR 1.17 (p) has been submitted herewith.

✓ A certification statement is not submitted herewith.

SIGNATURE

A signature of the applicant or representative is required in accordance with CFR 1.33, 10.18. Please see CFR 1.4(d) for the form of the signature.

Signature	/Mark B. Solomon, Reg. No. 44348/	Date (YYYY-MM-DD)	2018-01-23
Name/Print	Mark B. Solomon	Registration Number	44348

This collection of information is required by 37 CFR 1.97 and 1.98. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 1 hour to complete, including gathering, preparing and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

ALL REFERENCES CONSIDERED EXCEPT WHERE LINED THROUGH. /B.T.G/

Privacy Act Statement

The Privacy Act of 1974 (P.L. 93-579) requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C. 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether the Freedom of Information Act requires disclosure of these record s.

2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.

3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.

4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).

5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.

6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).

7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (i.e., GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.

8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspections or an issued patent.

9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

ALL REFERENCES CONSIDERED EXCEPT WHERE LINED THROUGH. /B.T.G/

Substitute for form 1449B/PTO **SUPPLEMENTAL INFORMATION DISCLOSURE STATEMENT IN AN APPLICATION** **LISTING OF REFERENCES** December 13, 2016 (Use several sheets if necessary)	ATTORNEY DOCKET NO. 4147.1020-002 (15-089)	APPLICATION NO. 15/178,089	
	FIRST NAMED INVENTOR Seyed M. A. Salehizadeh	FILING DATE June 9, 2016	
	EXAMINER Not Yet Assigned	CONFIRMATION NO. 7605	GROUP 3766

U.S. PATENT DOCUMENTS

Examiner's Initials	Cite No.	DOCUMENT NUMBER Number-Kind Code (if known)	ISSUE DATE / PUBLICATION DATE MM-DD-YYYY	NAME OF PATENTEE OR APPLICANT OF CITED DOCUMENT
	1.	4,938,228	07-03-1990	Righter *et al.*
	2.	8,388,543 B2	03-05-2013	Chon, *et al.*
	3.	8,417,326	04-09-2013	Chon, *et al.*
	4.	8,998,815 B2	04-07-2015	Venkatraman *et al.*
	5.			
	6.			
	7.			
	8.			
	9.			
	10.			
	11.			
	12.			
	13.			
	14.			
	15.			
	16.			
	17.			
	18.			

Copies of issued U.S. Patents and Published U.S. Applications are not required and are not being provided. We are not listing separately any prior U.S. Patent Office communications regarding the cited documents because the Examiner has access to any such actions through PAIR.

EXAMINER /BRIAN T GEDEON/	DATE CONSIDERED 04/13/2018

2418282.v1 ALL REFERENCES CONSIDERED EXCEPT WHERE LINED THROUGH. /B.T.G/

Substitute for form 1449B/PTO	ATTORNEY DOCKET NO.	APPLICATION NO.	
SUPPLEMENTAL INFORMATION DISCLOSURE STATEMENT IN AN APPLICATION	4147.1020-002 (15-089)	15/178,089	
	FIRST NAMED INVENTOR	FILING DATE	
	Seyed M. A. Salehizadeh	June 9, 2016	
LISTING OF REFERENCES	EXAMINER	CONFIRMATION NO.	GROUP
December 13, 2016	Not Yet Assigned	7605	3766
(Use several sheets if necessary)			

Examiner's Initials	Cite No.	**OTHER DOCUMENTS** *(Including Author, Title, Date, Pertinent Pages, Etc.)*
	1.	2015 IEEE Signal Processing Cup. Available online: / http://www.zhilinzhang.com/spcup2015/
	2.	Boreom Lee, *et al.*, "Improved Elimination Of Motion Artifacts From A Photoplethysmographic Signal Using A Kalman Smoother With Simultaneous Accelerometry," *Physiological Measurement*, 31(12):1585 (2010).
	3.	Salehizadeh, S., *et al.*, "Photoplethysmograph Signal Reconstruction Based On A Novel Motion Artifact Detection-Reduction Approach. Part II: Motion And Noise Artifact Removal," *Ann. Biomed. Eng.*, 42:2251-2263 (2014).
	4.	Dash S., Chon, K.H. Raeder E."Automatic real time detection of atrial fibrillation", Ann Biomed Eng, 2009 Sep;37(9):1701-9
	5.	Dash, S., *et al.*, "Estimation Of Respiratory Rate From ECG, Photoplethysmogram, And Piezoelectric Pulse Transducer Signals: A Comparative Study Of Time– Frequency Methods," *Biomedical Engineering, IEEE Transactions on*, 57(5):1099-1107 (2010).
	6.	Deepak Vala , D.T.P., "A Survey On Ambulatory ECG And Identification Of Motion Artifact," *International Journal of Engineering Research and Development*, 1(7):38-41 (2012).
	7.	Devlin PH, M.R., and Ketchum, J.W., "Detection Electrode Motion Noise In ECG Signals By Monitoring Electrode Impedance," *Computers in Cardiology*, p. 51-56 (1984).
	8.	Hamilton, P.S., *et al.*, "Comparison Of Methods For Adaptive Removal Of Motion Artifact," *Computers in Cardiology*, 2000 (2000).
	9.	Hamilton, P.S., *et al.*, "Effect Of Adaptive Motion-Artifact Reduction On QRS Detection," *Biomed Instrum. Technol.*, 34(3):197-202 (2000).
	10.	Hashim, F.R., *et al.*, "Wavelet Based Motion Artifact Removal For ECG Signals," In: IEEE EMBS International on Biomedical Engineering and Sciences (IECBES). Langkawi: IEEE: 2012, 339-342
	11.	Hyvärinen, A. and Oja, E., "Independent Component Analysis: Algorithms And Applications," *Neural Networks*, 13(4–5):411-430 (2000).
	12.	Jinseok, L., *et al.*, "Automatic Motion And Noise Artifact Detection In Holter ECG Data Using Empirical Mode Decomposition And Statistical Approaches,"*Biomedical Engineering, IEEE Transactions on*, 59(6):1499-1506 (2012).
	13.	Kalman, R.E., "A New Approach To Linear Filtering And Prediction Problems," *Trans. ASME J. Basic Eng.*, 82:35-45 (1960).
	14.	Kearney, K., *et al.*, "Quantification Of Motion Artifact In ECG Electrode Design," *Engineering in Medicine and Biology Society, EMBS 2007. 29th Annual International Conference of the IEEE*, (2007).
	15.	Kim, B.S. and Yoo, S.K., "Motion Artifact Reduction In Photoplethysmography Using Independent Component Analysis," *IEEE Trans. Biomed. Eng.*,53:566-568 (2006).
	16.	Krishnan, R., B., *et al.*, "Two-Stage Approach For Detection And Reduction Of Motion Artifacts In Photoplethysmographic Data," *Biomedical Engineering, IEEE Transactions on*, 57(8):1867-1876 (2010).
	17.	Maeda, Y., *et al.*, "Relationship Between Measurement Site And Motion Artifacts In Wearable Reflected Photoplethysmography," *J Med Syst*, 35(5):969-76 (2011).
	18.	Rahman, M.Z.U., *et al.*, "An Efficient Noise Cancellation Technique To Remove Noise From The ECG Signal Using Normalized Signed Regressor LMS Algorithm," *Bioinformatics and Biomedicine, BIBM '09, IEEE International Conference on (*2009). 257-260

EXAMINER	/BRIAN T GEDEON/	DATE CONSIDERED	04/13/2018

Petitioner Ex. 1004, 0951

ALL REFERENCES CONSIDERED EXCEPT WHERE LINED THROUGH. /B.T.G/

Substitute for form 1449B/PTO	ATTORNEY DOCKET NO.	APPLICATION NO.	
SUPPLEMENTAL INFORMATION DISCLOSURE STATEMENT IN AN APPLICATION	4147.1020-002 (15-089)	15/178,089	
	FIRST NAMED INVENTOR	FILING DATE	
	Seyed M. A. Salehizadeh	June 9, 2016	
LISTING OF REFERENCES	EXAMINER	CONFIRMATION NO.	GROUP
December 13, 2016	Not Yet Assigned	7605	3766
(Use several sheets if necessary)			

Examiner's Initials	Cite No.	**OTHER DOCUMENTS** *(Including Author, Title, Date, Pertinent Pages, Etc.)*
	19.	Raya, M.A.D. and Sison, L.G., "Adaptive Noise Cancelling Of Motion Artifact In Stress ECG Signals Using Accelerometer," *Engineering in Medicine and Biology, 24th Annual Conference and the Annual Fall Meeting of the Biomedical Engineering Society EMBS/BMES Conference, Proceedings of the Second Joint* (2002). 1756-1757
	20.	Reyes, B.A., *et al.*, "Novel Electrodes For Underwater ECG Monitoring," *IEEE Trans Biomed Eng.*, 61(6):1863-76 (2014).
	21.	Salehizadeh, S., *et al.*, "A Novel Time-Varying Spectral Filtering Algorithm For Reconstruction Of Motion Artifact Corrupted Heart Rate Signals During Intense Physical Activities Using A Wearable Photoplethysmogram Sensor," *Sensors*, 16(1):10 (2016)
	22.	Sarmiento, S., *et al.*, "Heart Rate Variability During High-Intensity Exercise", *Journal of Systems Science and Complexity*, 26(1):104-116 (2013).
	23.	Seyedtabaii, S.S.A.L., "Kalman Filter Based Adaptive Reduction Of Motion Artifact From Photoplethysmographic Signal," *World Acad. Sci. Eng. Technol.*, 37:136-137 (2008).
	24.	Temko, A., "Estimation Of Heart Rate From Photoplethysmography During Physical Exercise Using Wiener Filtering And The Phase Bocoder," *37th Annual International Conference of the IEEE Engineering In Medicine And Biology Society* (2015).
	25.	Thakor, N.V. and Yi-Sheng, Z., "Applications Of Adaptive Filtering To ECG Analysis: Noise Cancellation And Arrhythmia Detection," *Biomedical Engineering, IEEE Transactions on*, 38(8):785-794 (1991).
	26.	Wang, H., *et al.*, "A High Resolution Approach To Estimating Time-Frequency Spectra And Their Amplitudes," *Annals of Biomedical Engineering*, 34(2):326-338 (2006).
	27.	Yao, J. and Warren, S. "A Short Study To Assess The Potential Of Independent Component Analysis For Motion Artifact Separation In Wearable Pulse Oximeter Signals," *IEEE Eng. Med. Biol. Soc. Conf Proc.*, 4:3585-3588 (2005).
	28.	Yilmaz, T., *et al.*, "Detecting Vital Signs With Wearable Wireless Sensors," *Sensors*, 10(12):10837 (2010).
	29.	Yoon, H. *et al.*, "An Automated Motion Artifact Removal Algorithm In Electrocardiogram Based on Independent Component Analysis", in *The Fifth International Conference on eHealth, Telemedicine, and Social Medicine*, Nice, France. p. 15-20 (2013).
	30.	Zhang, Z., "Photoplethysmography-Based Heart Rate Monitoring In Physical Activities Via Joint Sparse Spectrum Reconstruction," *Biomedical Engineering, IEEE Transactions* PP(99):1,1 (2015).
	31.	Zhang, Z., *et al.*, "TROIKA: A General Framework For Heart Rate Monitoring Using Wrist-Type Photoplethysmographic Signals During Intensive Physical Exercise," *IEEE Trans. on Biomedical Engineering, 62*(2):522-531 (2015).

***Copies of any non-published U.S. Patent Applications are not being provided because the examiner has access to such documents through PAIR. We are not listing separately prior U.S. Patent Office communications regarding the cited documents because the Examiner has access to any such actions through PAIR.**

EXAMINER	/BRIAN T GEDEON/	DATE CONSIDERED	04/13/2018

Petitioner Ex. 1004, 0952

ALL REFERENCES CONSIDERED EXCEPT WHERE LINED THROUGH. /B.T.G/

Substitute for form 1449B/PTO **INFORMATION DISCLOSURE STATEMENT IN AN APPLICATION** **LISTING OF REFERENCES** October 21, 2016 (Use several sheets if necessary)	ATTORNEY DOCKET NO. 4147.1020-002 (15-089)	APPLICATION NO. 15/178,089	
	FIRST NAMED INVENTOR Seyed M. A. Salehizadeh	FILING DATE June 9, 2016	
	EXAMINER	CONFIRMATION NO. 7605	GROUP 3766

U.S. PATENT DOCUMENTS

Examiner's Initials	Cite No.	DOCUMENT NUMBER Number-Kind Code (if known)	ISSUE DATE / PUBLICATION DATE MM-DD-YYYY	NAME OF PATENTEE OR APPLICANT OF CITED DOCUMENT
	1.	2008/0109041 A1	05-08-2008	de Voir
	2.	2009/0069703 A1	03-12-2009	Takla, *et al.*
	3.	2011/0066041 A1	03-17-2011	Pandia, *et al.*
	4.	2012/0123232 A1	05-17-2012	Najarian, *et al.*
	5.			
	6.			
	7.			
	8.			
	9.			
	10.			
	11.			
	12.			
	13.			
	14.			
	15.			
	16.			
	17.			
	18.			

Copies of issued U.S. Patents and Published U.S. Applications are not required and are not being provided. We are not listing separately any prior U.S. Patent Office communications regarding the cited documents because the Examiner has access to any such actions through PAIR.

EXAMINER /BRIAN T GEDEON/	DATE CONSIDERED

2444176.v1 ALL REFERENCES CONSIDERED EXCEPT WHERE LINED THROUGH. /B.T.G/

Substitute for form 1449B/PTO **INFORMATION DISCLOSURE STATEMENT IN AN APPLICATION** **LISTING OF REFERENCES** October 21, 2016 (Use several sheets if necessary)	ATTORNEY DOCKET NO. 4147.1020-002 (15-089)	APPLICATION NO. 15/178,089	
	FIRST NAMED INVENTOR Seyed M. A. Salehizadeh	FILING DATE June 9, 2016	
	EXAMINER	CONFIRMATION NO. 7605	GROUP 3766

FOREIGN PATENT DOCUMENTS

Examiner's Initials	Cite No.	DOCUMENT NUMBER Country Code-Number-Kind Code (if known)	DATE MM-DD-YYYY	NAME OF PATENTEE OR APPLICANT OF CITED DOCUMENT
	1.	WO 03/000125	01-03-2003	Cardiodigital Limited
	2.	EP 1 724 684	11-22-2006	BUSI Incubateur d'entreprises
	3.	WO 2012/100175	07-26-2012	Worcester Polytechnic Institute
	4.	EP 2 792 297	10-22-2014	Stichting IMEC Nederland
	5.			
	6.			
	7.			
	8.			
	9.			
	10.			
	11.			
	12.			
	13.			
	14.			
	15.			
	16.			
	17.			
	18.			
	19.			
	20.			

EXAMINER	DATE CONSIDERED
/BRIAN T GEDEON/	04/13/2018

Petitioner Ex. 1004, 0954

ALL REFERENCES CONSIDERED EXCEPT WHERE LINED THROUGH. /B.T.G/

Substitute for form 1449B/PTO **INFORMATION DISCLOSURE STATEMENT IN AN APPLICATION** **LISTING OF REFERENCES** October 21, 2016 (Use several sheets if necessary)	ATTORNEY DOCKET NO. 4147.1020-002 (15-089)	APPLICATION NO. 15/178,089	
	FIRST NAMED INVENTOR Seyed M. A. Salehizadeh	FILING DATE June 9, 2016	
	EXAMINER	CONFIRMATION NO. 7605	GROUP 3766

Examiner's Initials	Cite No.	**OTHER DOCUMENTS** *(Including Author, Title, Date, Pertinent Pages, Etc.)*
	1.	Zhang, *et al*., "Novel QRS Detection by CWT for ECG Sensor," *Biomedical Circuits and Systems Conference* pages 211-214 (2007).
	2.	
	3.	
	4.	
	5.	
	6.	
	7.	
	8.	
	9.	
	10.	
	11.	
	12.	
	13.	
	14.	
	15.	
	16.	
	17.	

***Copies of any U.S. Office Communications or non-published U.S. Patent Applications are not being provided because the examiner has access to such documents through PAIR. We are not listing separately any prior U.S. Patent Office communications regarding the cited documents because the Examiner has access to any such actions through PAIR.**

EXAMINER /BRIAN T GEDEON/	DATE CONSIDERED 04/13/2018

Petitioner Ex. 1004, 0955

ALL REFERENCES CONSIDERED EXCEPT WHERE LINED THROUGH. /B.T.G/

Search Notes	Application/Control No.	Applicant(s)/Patent Under Reexamination
	15178089	SALEHIZADEH ET AL.
	Examiner	Art Unit
	BRIAN T GEDEON	3766

CPC- SEARCHED		
Symbol	Date	Examiner
A61B 5/02427,0002,02050,02416,02433,02439,11,1118,1123,4812,681,6843,6844,7235 (limited by keyword text search)	4/13/2018	BTG

CPC COMBINATION SETS - SEARCHED		
Symbol	Date	Examiner

US CLASSIFICATION SEARCHED			
Class	Subclass	Date	Examiner

* See search history printout included with this form or the SEARCH NOTES box below to determine the scope of the search.

SEARCH NOTES		
Search Notes	Date	Examiner
Detailed EAST search history attached.	4/13/2018	BTG
Inventor name search.	4/13/2018	BTG

INTERFERENCE SEARCH			
US Class/ CPC Symbol	US Subclass / CPC Group	Date	Examiner

EAST Search History

EAST Search History (Prior Art)

Ref #	Hits	Search Query	DBs	Default Operator	Plurals	Time Stamp
L5	2	"20140005988".pn.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 13:21
L6	984043	sampling	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 13:33
L7	19	(US-20140275854-$ or US-20140309943-$ or US-20160081651-$).did. or (US-9872652-$ or US-7738935-$ or US-7803119-$ or US-8137270-$ or US-8172764-$ or US-8747330-$ or US-8834364-$ or US-8888700-$ or US-8920332-$ or US-8945017-$ or US-8948832-$ or US-9173593-$ or US-9237855-$ or US-9770176-$ or US-9713428-$ or US-8718753-$).did.	US-PGPUB; USPAT	OR	ON	2018/04/13 13:33
L8	11	L6 AND L7	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 13:33
L9	506	("time-frequency" NEAR spectr$4)	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 15:08
L10	3	L9 AND L7	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 15:08
S1	3	"15178089"	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 09:50
S2	14	("time-varying" NEAR spectral NEAR analysis)	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 09:56
S3	1	"20140275854".pn.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 10:01
S4	1578	(motion NEAR (corrupt$4 OR artefact))	US-PGPUB; USPAT; USOCR; FPRS; EPO;	OR	ON	2018/04/09 10:03

			JPO			
S5	15009	(motion NEAR (corrupt$4 OR artifact))	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 10:03
S6	52215	(spectral NEAR analysis)	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 10:03
S7	744	S5 AND S6	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 10:03
S8	683293	heart	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 10:03
S9	4646381	sensor	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 10:03
S10	521	S7 AND S8 AND S9	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 10:04
S11	137313	(sensor NEAR (motion OR movement))	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 10:57
S12	212	S10 AND S11	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 10:57
S13	1	("9872652").PN.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 12:36
S14	456165	reconstruct$4	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 12:37
S15	15009	(motion NEAR (corrupt$4 OR artifact))	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 12:37

S16	52215	(spectral NEAR analysis)	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 12:37
S17	744	S15 AND S16	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 12:37
S18	683293	heart	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 12:37
S19	4646381	sensor	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 12:37
S20	521	S17 AND S18 AND S19	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 12:37
S21	137313	(sensor NEAR (motion OR movement))	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 12:37
S22	212	S20 AND S21	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 12:37
S23	55	S14 AND S22	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 12:37
S24	16	(US-20140275854-$ or US-20140309943-$).did. or (US-9872652-$ or US-7738935-$ or US-7803119-$ or US-8137270-$ or US-8172764-$ or US-8747330-$ or US-8834364-$ or US-8888700-$ or US-8920332-$ or US-8945017-$ or US-8948832-$ or US-9173593-$ or US-9237855-$ or US-9770176-$).did.	US-PGPUB; USPAT	OR	ON	2018/04/09 12:48
S25	20337	A61B5/02427,0002,02050,02416,02433,02439,11,1118,1123,4812,681,6843,6844,7235.cpc.	US-PGPUB; USPAT	OR	ON	2018/04/09 12:54
S26	577	S15 AND S16 AND S18	US-PGPUB; USPAT	OR	ON	2018/04/09 12:54
S27	284	S25 AND S26	US-PGPUB; USPAT	OR	ON	2018/04/09 12:55
S28	1250	(time NEAr frequency NEAr spectrum)	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 13:29
S29	21	S15 AND S18 AND S19 AND S28	US-	OR	ON	2018/04/09

			PGPUB; USPAT; USOCR; FPRS; EPO; JPO			13:30
S30	15	"SpaMA"	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 13:36
S31	1	"8388543".pn.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 14:06
S32	6	salehizadeh-seyed-m-a.in.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 14:21
S33	67	chon-ki-h.in.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 14:21
S34	467301	(spectral OR spectrum) AND peak	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 14:22
S35	26	S33 AND S34	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 14:22
S36	7	noh-yeonsik.in.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 14:35
S37	19	(US-20140275854-$ or US-20140309943-$ or US-20160081651-$).did. or (US-9872652-$ or US-7738935-$ or US-7803119-$ or US-8137270-$ or US-8172764-$ or US-8747330-$ or US-8834364-$ or US-8888700-$ or US-8920332-$ or US-8945017-$ or US-8948832-$ or US-9173593-$ or US-9237855-$ or US-9770176-$ or US-9713428-$ or US-8718753-$).did.	US-PGPUB; USPAT	OR	ON	2018/04/09 15:17
S38	19	(US-20140275854-$ or US-20140309943-$ or US-20160081651-$).did. or (US-9872652-$ or US-7738935-$ or US-7803119-$ or US-8137270-$ or US-8172764-$ or US-8747330-$ or US-8834364-$ or US-8888700-$ or US-8920332-$ or US-8945017-$ or US-8948832-$ or US-9173593-$ or US-9237855-$ or US-9770176-$ or US-9713428-$ or US-8718753-$).did.	US-PGPUB; USPAT	OR	ON	2018/04/13 08:41
S39	4	(spectral NEAR analysis) AND Peaks AND candidate AND frequency AND (discard$4 OR reject$4) AND ("time-frequency" NEAR spectr$4) AND motion	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 09:23
S40	1	"20140275854".pn.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 09:24

S41	14288	(reconstruct$4 SAME (cardiac OR heart))	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 11:09
S42	14	("time-varying" NEAR spectral NEAR analysis)	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 11:10
S43	6	S41 AND S42	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 11:10
S44	506	("time-frequency" NEAR spectr$4)	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 11:17
S45	4	S41 AND S44	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 11:17
S46	56514	(reconstruct$4 AND (cardiac OR heart))	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 11:17
S47	19	S44 AND S46	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 11:17
S48	20375	A61B5/02427,0002,02050,02416,02433,02439,11,1118,1123,4812,681,6843,6844,7235.cpc.	US-PGPUB; USPAT	OR	ON	2018/04/13 11:26
S49	1321	S46 AND S48	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 11:26
S50	456633	reconstruct$4	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 11:26
S51	1321	S49 AND S50	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 11:26
S52	36	S44 AND S48	US-PGPUB; USPAT; USOCR; FPRS;	OR	ON	2018/04/13 11:26

			EPO; JPO				

EAST Search History (Interference)

< This search history is empty>

4/ 13/ 2018 3:22:41 PM
C:\ Users\ bgedeon\ Documents\ EAST\ Workspaces\ 15178089.wsp

Substitute for form 1449B/PTO **SUPPLEMENTAL INFORMATION DISCLOSURE STATEMENT IN AN APPLICATION** **LISTING OF REFERENCES** February 14, 2017 (Use several sheets if necessary)	ATTORNEY DOCKET NO. 4147.1020-002 (15-089)	APPLICATION NO. 15/178,089	
	FIRST NAMED INVENTOR Seyed M. A. Salehizadeh	FILING DATE June 9, 2016	
	EXAMINER	CONFIRMATION NO. 7605	GROUP 3766

FOREIGN PATENT DOCUMENTS

Examiner's Initials	Cite No.	DOCUMENT NUMBER Country Code-Number-Kind Code (if known)	DATE MM-DD-YYYY	NAME OF PATENTEE OR APPLICANT OF CITED DOCUMENT
	1.	WO 2017019184 A2	02-02-2017	University of Connecticut
	2.			
	3.			
	4.			
	5.			
	6.			
	7.			
	8.			
	9.			
	10.			
	11.			
	12.			
	13.			
	14.			
	15.			
	16.			
	17.			
	18.			

EXAMINER	DATE CONSIDERED
/BRIAN T GEDEON/	04/13/2018

Petitioner Ex. 1004, 0963

ALL REFERENCES CONSIDERED EXCEPT WHERE LINED THROUGH. /B.T.G/

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Inventors:	Seyed M.A. Salehizadeh, Ki H. Chon, Yeonsik Noh		
Application No.:	15/178,089	Group:	3766
Filed:	June 9, 2016	Examiner:	Brian T. Gedeon
Confirmation No:	7605		
For:	Method And Apparatus For Removing Motion Artifacts From Biomedical Signals		

AMENDMENT

Mail Stop Amendment
Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Sir:

This Amendment is being filed in response to the Office Action mailed from the U.S. Patent and Trademark Office on April 18, 2018 in the above-identified Application. Reconsideration and further examination are requested.

Please amend the Application as follows:

Amendments to the Claims

Please cancel Claims 6, 18, 42, and 54. Please amend Claims 1, 3, 4, 7–9, 11, 19, 21, 26, 37, 39, 40, 43–45, 47, 55, 57, 62, and 73. Please add new Claims 74–79.

The Claim Listing below will replace all prior versions of the claims in the application:

Claim Listing

1. (Currently Amended) A method for reconstructing a heart-related signal output by a biomedical sensor, the method comprising:

reconstructing a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal, the reconstructing based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of the movement, wherein the time-varying spectral analysis includes pre-processing the heart-related signal to produce a pre-processed heart-related signal, pre-processing the motion signal to produce a pre-processed motion signal, and computing a first time-frequency spectrum (TFS) of the heart-related signal using the pre-processed heart-related signal and a second TFS of the motion signal using the pre-processed motion signal; and

outputting the reconstructed representation of the heart-related signal.

2. (Original) The method of Claim 1, wherein the motion artifacts are suppressed in the reconstructed representation of the heart-related signal.

3. (Currently Amended) The method of Claim 1, wherein:

~~the time-varying spectral analysis includes pre-processing the heart-related signal to produce a pre-processed heart-related signal; and~~

in an event the classification indicates that the movement does not rise to a level causing the motion artifacts, the reconstructed representation is based on an average value of peak-to-peak intervals in the pre-processed heart-related signal.

4. (Currently Amended) The method of Claim [[3]] 1, wherein the pre-processing includes filtering the heart-related signal to produce a filtered heart-related signal, the filtered heart-related signal being the pre-processed heart-related signal.

5. (Original) The method of Claim 4, wherein the pre-processing further includes down-sampling the filtered heart-related signal, the down-sampling being at a sampling rate less than an original sampling rate.

6. (Cancelled)

7. (Currently Amended) The method of Claim [[6]] 1, wherein the first TFS computed and the second TFS computed are 3-dimensional spectra, the first TFS computed and the second TFS computed each including a respective time-varying amplitude or power distribution with respect to time and frequency.

8. (Currently Amended) The method of Claim [[6]] 1, wherein the first TFS computed is a first time-varying power spectral density (PSD) and the second TFS computed is a second time-varying PSD.

9. (Currently Amended) The method of Claim [[6]] 1, wherein the reconstructed representation is a current reconstructed representation and wherein, based on the classification indicating that the movement does rise to a level causing the motion artifacts and is a pseudo-periodic movement or a periodic movement, the reconstructing includes:

determining whether at least one spectral peak is present having a corresponding frequency within a given frequency range at a point in time in the first TFS computed, the current reconstructed representation being reconstructed for the point in time; and

wherein, based on a determination that the at least one spectral peak is not present, the current reconstructed representation is based on a prior reconstructed representation, the prior reconstructed representation associated with a previous point in time in the first TFS computed.

10. (Original) The method of Claim 9, wherein the given frequency range is 0.5 Hz to 3 Hz.

11. (Currently Amended) The method of Claim [[6]] 1, wherein the reconstructing includes:

retaining up to a pre-determined number of candidate spectral peaks located at a first point in time in the first TFS computed, the candidate spectral peaks retained based on having corresponding frequencies within a given frequency range and highest amplitude or power values relative to other spectral peaks located at the first point in time, the other spectral peaks having respective frequencies within the given frequency range; and

discarding each of the candidate spectral peaks retained that is associated with a same frequency as a dominant spectral peak located at a second point in time in the second TFS computed, the first point in time and the second point in time having same time values.

12. (Original) The method of Claim 11, wherein the given frequency range is 0.5 Hz to 3 Hz.

13. (Original) The method of Claim 11, wherein the representation is a current representation, wherein the reconstructed representation is a current reconstructed representation, and wherein, in an event the discarding discards each of the candidate spectral peaks retained, reconstructing the current representation is based on a prior reconstructed representation, the prior reconstructed representation associated with a previous point in time in the first TFS computed, the previous point in time being an earlier point in time with respect to the first point in time.

14. (Original) The method of Claim 11, wherein the discarding is a first discarding and wherein the representation is a current representation and, wherein, in an event the first

discarding results in at least one remaining candidate spectral peak retained, reconstructing the current representation further includes:

second discarding, wherein the second discarding discards remaining candidate spectral peaks, of the at least one remaining candidate spectral peak retained, based on whether a corresponding frequency of the at least one remaining candidate spectral peak retained is distanced by at least a frequency difference threshold from a prior reconstructed representation's frequency, the prior reconstructed representation associated with a previous point in time in the first TFS computed, the previous point in time being an earlier point in time with respect to the first point in time.

15. (Original) The method of Claim 14, wherein:

based on each of the at least one remaining candidate spectral peak retained having been discarded by the second discarding, reconstructing the current representation is based on the prior reconstructed representation; and

based on at least one last candidate spectral peak remaining, the at least one last candidate spectral peak remaining not discarded by the second discarding, reconstructing the current representation is based on a selected candidate spectral peak selected from amongst the at least one last candidate spectral peak remaining having a closest corresponding frequency to the prior reconstructed representation's frequency relative to respective frequencies of each of the at least one last candidate spectral peak remaining.

16. (Original) The method of Claim 11, wherein the dominant spectral peak has a largest power or amplitude value relative to other peaks located at the second point in time in the second TFS.

17. (Original) The method of Claim 11, wherein the retaining and the discarding are based on:

the classification indicating that the movement is a pseudo-periodic movement or a periodic movement; and

determining that at least one spectral peak with a corresponding frequency in the given frequency range is present at the first point in time.

18. (Cancelled)

19. (Currently Amended) The method of Claim [[6]] 1, wherein the pre-processing includes filtering the heart-related signal and the motion signal to produce a filtered heart-related signal and a filtered motion signal, respectively, the filtered heart-related signal being the pre-processed heart-related signal and the filtered motion signal being the pre-processed motion signal.

20. (Original) The method of Claim 19, wherein the pre-processing further includes down-sampling both the filtered heart-related signal and the filtered motion signal, the down-sampling being at a sampling rate less than an original sampling rate.

21. (Currently Amended) The method of Claim [[6]] 1, further including:

classifying the classification of the movement by comparing an amount of amplitude modulation in the second TFS computed to an amplitude modulation threshold, wherein the classification indicates whether the movement rises to a level of causing the motion artifacts based on a result of the comparing.

22. (Original) The method of Claim 21, wherein the amplitude modulation threshold is dependent on a type of the motion detector sensor.

23. (Original) The method of Claim 21, wherein, in an event the result indicates that the movement does rise to the level causing the motion artifacts, classifying the classification of the movement further includes determining whether the movement is either a pseudo-periodic movement or a periodic movement, versus a random movement.

24. (Original) The method of Claim 23, wherein, in determining whether the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement includes, the method further includes:

identifying a first, second, and third frequency associated, respectively, with a first, second, and third spectral peak in the second TFS at a point in time in the second TFS, the first, second, and third peaks having largest power or amplitude values relative to other peaks in the second TFS at the point in time, the first spectral peak being a largest spectral peak amongst the first, second, and third spectral peaks;

computing a first ratio of the second frequency identified to the first frequency identified and determining a first comparison result by comparing the first ratio computed to a first ratio value; and

computing a second ratio of the third frequency identified to the first frequency identified and determining a second comparison result by comparing the second ratio computed to a second ratio value, wherein the classification further indicates that the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement, based on the first comparison result and the second comparison result.

25. (Original) The method of Claim 24, wherein the first ratio value is 2 and the second ratio value is 3.

26. (Currently Amended) The method of Claim 1, wherein ~~the time-varying signal analysis includes pre-processing the heart-related signal to produce a pre-processed heart-related signal and~~, in an event the classification of the movement indicates random movement, the reconstructing includes:

computing an average value of a number of prior reconstructed representations outputted prior to the reconstructing, the number based on a duration of consecutive motion artifacts, detected prior to the reconstructing;

computing a bandpass filter cutoff frequency based on the average value computed;

filtering the pre-processed heart-related signal by applying the band pass filter computed to produce a filtered, pre-processed heart-related signal; and

wherein the reconstructed representation is based on an average peak-to-peak interval value of the filtered, pre-processed heart-related signal.

27. (Original) The method of Claim 1, wherein the heart-related signal and the motion signal are produced, concurrently.

28. (Original) The method of Claim 1, further comprising:

segmenting the heart-related signal into a plurality of windowed heart-related signal data segments and the motion signal into a corresponding plurality of windowed motion signal data segments; and

repeating the reconstructing and the outputting for each windowed heart-related signal data segment and each corresponding motion signal data segment.

29. (Original) The method of Claim 28, wherein the time window is a value in a range from 2 to 32 seconds.

30. (Original) The method of Claim 1, wherein the biomedical sensor is at least one of: a photoplethysmogram (PPG) sensor, piezoelectric sensor, Light Emitting Diode (LED) based sensor, camera sensor, and pulse oximeter sensor, and wherein the motion sensor is an accelerometer.

31. (Original) The method of Claim 1, wherein the biomedical sensor and the motion sensor are co-located.

32. (Original) The method of Claim 1, further comprising employing the reconstructed representation to determine a heart rate estimate.

33. (Original) The method of Claim 1, further comprising employing the reconstructed representation to determine an arterial oxygen saturation (SpO2) estimate.

34. (Original) The method of Claim 1, further comprising employing the reconstructed representation to detect or predict a heart-related ailment, the heart-related ailment

including at least one of a heart rate variability (HRV) condition, atrial fibrillation condition, congestive heart failure condition, and tachycardia condition.

35. (Original) The method of Claim 1, wherein the reconstructing and the outputting are performed in real-time with respect to production of the heart-related signal and the motion signal.

36. (Original) The method of Claim 1, wherein the reconstructing and the outputting are performed in non-real-time with respect to production of the heart-related signal and the motion signal.

37. (Currently Amended) An apparatus for reconstructing a heart-related signal output by a biomedical sensor, the apparatus comprising:

a reconstruction unit configured to reconstruct a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal, the reconstructing based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of the movement, wherein the time-varying spectral analysis includes pre-processing the heart-related signal to produce a pre-processed heart-related signal, pre-processing the motion signal to produce a pre-processed motion signal, and computing a first time-frequency spectrum (TFS) of the heart-related signal using the pre-processed heart-related signal and a second TFS of the motion signal using the pre-processed motion signal; and

an output unit configured to output the reconstructed representation of the heart-related signal.

38. (Original) The apparatus of Claim 37, wherein the motion artifacts are suppressed in the reconstructed representation of the heart-related signal.

39. (Currently Amended) The apparatus of Claim 37, wherein:

~~the time-varying spectral analysis includes pre-processing the heart-related signal to produce a pre-processed heart-related signal; and~~

in an event the classification indicates that the movement does not rise to level causing the motion artifacts, the reconstructed representation is based on an average value of peak-to-peak intervals in the pre-processed heart-related signal**.**

40. (Currently Amended) The apparatus of Claim [[39]] 37, wherein the pre-processing includes filtering the heart-related signal to produce a filtered heart-related signal, the filtered heart-related signal being the pre-processed heart-related signal.

41. (Original) The apparatus of Claim 40, wherein the pre-processing further includes down-sampling the filtered heart-related signal, the down-sampling being at a sampling rate less than an original sampling rate.

42. (Cancelled)

43. (Currently Amended) The apparatus of Claim [[42]] 37, wherein the first TFS computed and the second TFS computed are 3-dimensional spectra, the first TFS computed and the second TFS computed each including a respective time-varying amplitude or power distribution with respect to time and frequency.

44. (Currently Amended) The apparatus of Claim [[42]] 37, wherein the first TFS computed is a first time-varying power spectral density (PSD) and the second TFS computed is a second time-varying PSD.

45. (Currently Amended) The apparatus of Claim [[42]] 37, wherein the reconstructed representation is a current reconstructed representation and wherein, based on the classification indicating that the movement does rise to a level causing the motion artifacts and is a pseudo-periodic movement or a periodic movement, to reconstruct the representation includes:

determining whether at least one spectral peak is present having a corresponding frequency within a given frequency range at a point in time in the first TFS computed, the current reconstructed representation being reconstructed for the point in time; and

wherein, based on a determination that the at least one spectral peak is not present, the reconstructed current representation is based on a prior reconstructed representation, the prior reconstructed representation associated with a previous point in time in the first TFS computed.

46. (Original) The apparatus of Claim 45, wherein the given frequency range is 0.5 Hz to 3 Hz.

47. (Currently Amended) The apparatus of Claim [[42]] 37, wherein to reconstruct the representation includes:

retaining up to a pre-determined number of candidate spectral peaks located at a first point in time in the first TFS computed, the candidate spectral peaks retained based on having corresponding frequencies within a given frequency range and highest amplitude or power values relative to other spectral peaks located at the first point in time, the other spectral peaks having respective frequencies within the given frequency range; and

discarding each of the candidate spectral peaks retained that is associated with a same frequency as a dominant spectral peak located at a second point in time in the second TFS computed, the first point in time and the second point in time having same time values.

48. (Original) The apparatus of Claim 47, wherein the given frequency range is 0.5 Hz to 3 Hz.

49. (Original) The apparatus of Claim 47, wherein the representation is a current representation, wherein the reconstructed representation is a current reconstructed representation, and wherein, in an event the discarding discards each of the candidate spectral peaks retained, reconstructing the current representation is based on a prior

reconstructed representation, the prior reconstructed representation associated with a previous point in time in the first TFS computed, the previous point in time being an earlier point in time with respect to the first point in time.

50. (Original) The apparatus of Claim 47, wherein the discarding is a first discarding and wherein the representation is a current representation and, wherein, in an event the first discarding results in at least one remaining candidate spectral peak retained, reconstructing the current representation further includes:

second discarding, wherein the second discarding discards remaining candidate spectral peaks, of the at least one remaining candidate spectral peak retained, based on whether a corresponding frequency of the at least one remaining candidate spectral peak retained is distanced by at least a frequency difference threshold from a prior reconstructed representation's frequency, the prior reconstructed representation associated with a previous point in time in the first TFS computed, the previous point in time being an earlier point in time with respect to the first point in time.

51. (Original) The apparatus of Claim 50, wherein:

based on each of the at least one remaining candidate spectral peak retained having been discarded by the second discarding, reconstructing the current representation is based on the prior reconstructed representation; and

based on at least one last candidate spectral peak remaining, the at least one last candidate spectral peak remaining not discarded by the second discarding, reconstructing the current representation is based on a selected candidate spectral peak selected from amongst the at least one last candidate spectral peak remaining having a closest corresponding frequency to the prior reconstructed representation's frequency relative to respective frequencies of each of the at least one last candidate spectral peak remaining.

52. (Original) The apparatus of Claim 47, wherein the dominant spectral peak has a largest power or amplitude value relative to other peaks located at the second point in time in the second TFS.

53. (Original) The apparatus of Claim 47, wherein the retaining and the discarding are based on:

the classification of the movement indicating that the movement is a pseudo-periodic movement or a periodic movement; and

determining that at least one spectral peak with a corresponding frequency in the given frequency range is present at the first point in time.

54. (Cancelled)

55. (Currently Amended) The apparatus of Claim [[42]] 37, wherein the pre-processing includes filtering the heart-related signal and the motion signal to produce a filtered heart-related signal and a filtered motion signal, respectively, the filtered heart-related signal being the pre-processed heart-related signal and the filtered motion signal being the pre-processed motion signal.

56. (Original) The apparatus of Claim 55, wherein the pre-processing further includes down-sampling, at a sampling rate less than an original sampling rate, both the filtered heart-related signal and the filtered motion signal.

57. (Currently Amended) The apparatus of Claim [[42]] 37, further including a classification unit, the classification unit configured to:

classify the classification of the movement by comparing an amount of amplitude modulation in the second TFS computed to an amplitude modulation threshold, wherein the classification indicates whether the movement rises to a level causing the motion artifacts based on a result of the comparing.

58. (Original) The apparatus of Claim 57, wherein the amplitude modulation threshold is dependent on a type of the motion detector sensor.

59. (Original) The apparatus of Claim 57, wherein, in an event the result indicates that the movement does rise to the level causing the motion artifacts, the classification unit is

further configured to classify the classification of the movement by determining whether the movement is either a pseudo-periodic movement or a periodic movement, versus a random movement.

60. (Original) The apparatus of Claim 59, wherein to determine whether the movement is either the pseudo-periodic movement or the periodic movement versus a random movement includes:

identifying a first, second, and third frequency associated, respectively, with a first, second, and third spectral peak in the second TFS at a point in time in the second TFS, the first, second, and third peaks having largest power or amplitude values relative to other peaks in the second TFS at the point in time, the first spectral peak being a largest spectral peak amongst the first, second, and third spectral peaks;

computing a first ratio of the second frequency identified to the first frequency identified and determining a first comparison result by comparing the first ratio computed to a first ratio value; and

computing a second ratio of the third frequency identified to the first frequency identified and determining a second comparison result by comparing the second ratio computed to a second ratio value, wherein the classification further indicates that the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement, based on the first comparison result and the second comparison result.

61. (Original) The apparatus of Claim 60, wherein the first ratio value is 2 and the second ratio value is 3.

62. (Currently Amended) The apparatus of Claim 59, wherein ~~the time-varying signal analysis includes pre-processing the heart-related signal to produce a pre-processed heart-related signal and~~, in an event the classification of the movement indicates random movement, the reconstructing includes:

computing an average value of a number of prior reconstructed representations outputted prior to the reconstructing, the number based on a duration of consecutive motion artifacts, detected prior to the reconstructing;

computing a bandpass filter cutoff frequency based on the average value computed;

filtering the pre-processed heart-related signal by applying the band pass filter computed to produce a filtered, pre-processed heart-related signal; and

wherein the reconstructed representation is based on an average peak-to-peak interval value of the filtered, pre-processed heart-related signal.

63. (Original) The apparatus of Claim 37, wherein the heart-related signal and the motion signal are produced, concurrently.

64. (Original) The apparatus of Claim 37, further comprising segmentation unit configured to:

segment the heart-related signal into a plurality of windowed heart-related signal data segments and the motion signal into corresponding plurality of windowed motion signal data segments, wherein the reconstruction unit and the output unit reconstruct the representation and output the reconstructed representation, respectively, based on each windowed heart-related signal data segment and each corresponding motion signal data segment.

65. (Original) The apparatus of Claim 64, wherein the time window is a value in a range from 2 to 32 seconds.

66. (Original) The apparatus of Claim 37, wherein the biomedical sensor is at least one of: a photoplethysmogram (PPG) sensor, piezoelectric sensor, Light Emitting Diode (LED) based sensor, camera sensor, and pulse oximeter sensor, and wherein the motion sensor is an accelerometer.

67. (Original) The apparatus of Claim 37, wherein the apparatus includes the biomedical sensor and the motion sensor.

68. (Original) The apparatus of Claim 37, further comprising a heart rate unit configured to employ the reconstructed representation to determine a heart rate estimate.

69. (Original) The apparatus of Claim 37, further comprising an arterial oxygen saturation (SpO2) unit configured to employ the reconstructed representation to determine a SpO2 estimate.

70. (Original) The apparatus of Claim 37, further comprising an ailment unit configured to employ the reconstructed representation to detect or predict a heart-related ailment, the heart-related ailment including at least one of a heart rate variability (HRV) condition, an atrial fibrillation condition, a congestive heart failure condition, and a tachycardia condition.

71. (Original) The apparatus of Claim 37, wherein the reconstruction unit and the output unit are configured to reconstruct and to output, respectively, in real-time with respect to production of the heart-related signal and the motion signal.

72. (Original) The apparatus of Claim 37, wherein the reconstruction unit and the output unit are configured to reconstruct and to output, respectively, in non-real-time with respect to production of the heart-related signal and the motion signal.

73. (Currently Amended) A non-transitory computer-readable medium having encoded thereon a sequence of instructions which, when loaded and executed by a processor, causes the processor to reconstruct a heart-related signal output by a biomedical sensor, the processor reconstructing the heart-related signal by:

reconstructing a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal, the reconstructing based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion

signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of the movement, wherein the time-varying spectral analysis includes pre-processing the heart-related signal to produce a pre-processed heart-related signal, pre-processing the motion signal to produce a pre-processed motion signal, and computing a first time-frequency spectrum (TFS) of the heart-related signal using the pre-processed heart-related signal and a second TFS of the motion signal using the pre-processed motion signal; and

outputting the reconstructed representation of the heart-related signal.

74. (New) A method for reconstructing a heart-related signal output by a biomedical sensor, the method comprising:

reconstructing a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal, the reconstructing based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of the movement, wherein the time-varying spectral analysis includes computing a first time-frequency spectrum (TFS) of the heart-related signal and computing a second TFS of the motion signal; and

outputting the reconstructed representation of the heart-related signal, wherein the reconstructed representation is a current reconstructed representation and wherein, based on the classification indicating that the movement does rise to a level causing the motion artifacts and is a pseudo-periodic movement or a periodic movement, the reconstructing includes:

determining whether at least one spectral peak is present having a corresponding frequency within a given frequency range at a point in time in the first TFS computed, the current reconstructed representation being reconstructed for the point in time; and

wherein, based on a determination that the at least one spectral peak is not present, the current reconstructed representation is based on a prior reconstructed representation, the prior reconstructed representation associated with a previous point in time in the first TFS computed.

75. (New) A method for reconstructing a heart-related signal output by a biomedical sensor, the method comprising:

reconstructing a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal, the reconstructing based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of the movement, wherein the time-varying spectral analysis includes computing a first time-frequency spectrum (TFS) of the heart-related signal and computing a second TFS of the motion signal; and

outputting the reconstructed representation of the heart-related signal, wherein the reconstructing includes:

retaining up to a pre-determined number of candidate spectral peaks located at a first point in time in the first TFS computed, the candidate spectral peaks retained based on having corresponding frequencies within a given frequency range and highest amplitude or power values relative to other spectral peaks located at the first point in time, the other spectral peaks having respective frequencies within the given frequency range; and

discarding each of the candidate spectral peaks retained that is associated with a same frequency as a dominant spectral peak located at a second point in time in the second TFS computed, the first point in time and the second point in time having same time values.

76. (New) A method for reconstructing a heart-related signal output by a biomedical sensor, the method comprising:

reconstructing a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal, the reconstructing based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of the movement, wherein the time-varying spectral analysis includes computing a first time-frequency spectrum (TFS) of the heart-related signal and computing a second TFS of the motion signal;

classifying the classification of the movement by comparing an amount of amplitude modulation in the second TFS computed to an amplitude modulation threshold, wherein the classification indicates whether the movement rises to a level of causing the motion artifacts based on a result of the comparing; and

outputting the reconstructed representation of the heart-related signal.

77. (New) An apparatus for reconstructing a heart-related signal output by a biomedical sensor, the apparatus comprising:

a reconstruction unit configured to reconstruct a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal, the reconstructing based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of the movement, wherein the time-varying spectral analysis includes computing a first time-frequency spectrum (TFS) of the heart-related signal and computing a second TFS of the motion signal; and

an output unit configured to output the reconstructed representation of the heart-related signal, wherein the reconstructed representation is a current reconstructed representation and wherein, based on the classification indicating that the movement does rise to a level causing the motion artifacts and is a pseudo-periodic movement or a periodic movement, to reconstruct the representation includes:

determining whether at least one spectral peak is present having a corresponding frequency within a given frequency range at a point in time in the first TFS computed, the current reconstructed representation being reconstructed for the point in time; and

wherein, based on a determination that the at least one spectral peak is not present, the reconstructed current representation is based on a prior reconstructed representation, the prior reconstructed representation associated with a previous point in time in the first TFS computed.

78. (New) An apparatus for reconstructing a heart-related signal output by a biomedical sensor, the apparatus comprising:

a reconstruction unit configured to reconstruct a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal, the reconstructing based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of the movement, wherein the time-varying spectral analysis includes computing a first time-frequency spectrum (TFS) of the heart-related signal and computing a second TFS of the motion signal; and

an output unit configured to output the reconstructed representation of the heart-related signal, wherein to reconstruct the representation includes:

retaining up to a pre-determined number of candidate spectral peaks located at a first point in time in the first TFS computed, the candidate spectral peaks retained based on having corresponding frequencies within a given frequency range and highest amplitude or power values relative to other spectral peaks located at the first point in time, the other spectral peaks having respective frequencies within the given frequency range; and

discarding each of the candidate spectral peaks retained that is associated with a same frequency as a dominant spectral peak located at a second point in

time in the second TFS computed, the first point in time and the second point in time having same time values.

79. (New) An apparatus for reconstructing a heart-related signal output by a biomedical sensor, the apparatus comprising:

a reconstruction unit configured to reconstruct a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal, the reconstructing based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of the movement, wherein the time-varying spectral analysis includes computing a first time-frequency spectrum (TFS) of the heart-related signal and computing a second TFS of the motion signal;

a classification unit configured to classify the classification of the movement by comparing an amount of amplitude modulation in the second TFS computed to an amplitude modulation threshold, wherein the classification indicates whether the movement rises to a level causing the motion artifacts based on a result of the comparing; and

an output unit configured to output the reconstructed representation of the heart-related signal.

REMARKS

Claims 1−73 are pending in the Application, of which Claims 1, 37, and 73 are independent. Claims 1, 3, 4, 7−9, 11, 19, 21, 26, 37, 39, 40, 43−45, 47, 55, 57, 62, and 73 are being amended. Claims 6, 18, 42, and 54 are being cancelled. Claims 74−79 are being added. Support for the amendments and new claims may be found throughout Applicant's Specification, as originally filed, including at least at page 4, paragraph [0020]; pages 19 through 20, paragraphs [0078] and [0079]; and Claims 6, 9, 11, 18, 42, 45, 47, and 54 as originally filed. No new matter is being added by way of this Amendment.

The amendments are made to expedite prosecution of this application. Applicant is not conceding that the claims prior to amendment are not patentable. No inference should be made that Applicant is disclaiming any subject matter of the present application, and Applicant reserves the right to pursue the unamended claims or any other broader or narrower claims supported by the disclosure at a later date, including in one or more continuing applications. Cancellation of any claim herein is without prejudice to reinstatement in this or continuing application.

Claims 1−4, 27, 35−40, 63, and 71−73 stand rejected under 35 U.S.C. §102(a1/a2) as being said to be anticipated by cited art. Claims 5−8, 27−34, 41−44, and 64−70 stand rejected under 35 U.S.C. §103 as being said to be obvious in view of cited art. Claims 9−26 and 45−62 have been indicated to be allowable. Applicant respectfully addresses the indication of allowable subject matter, as well as each rejection, in turn, below.

Allowable Subject Matter

Applicant thanks Examiner Gedeon for the indication of allowable subject matter, namely, that Claims 9−26 and 45−62 "would be allowable if rewritten in independent form including all of the limitations of the base claim and any intervening claims." *See* Office Action, page 8.

Claims 6, 18, 42, and 54 are being cancelled. Independent Claim 1 is being rewritten to include all of the allowable subject matter of cancelled dependent Claim 18 and intervening Claim 6. Independent Claim 37 is being rewritten to include all of the allowable subject matter of cancelled dependent Claim 54 and intervening Claim 42. Independent Claim 73 is being amended to include similar allowable subject matter as Claim 1, as currently amended.

Applicant Note

Since Claim 73 is identified in the second paragraph of Section 5 (*see* Office Action, page 3), Applicant is proceeding with the understanding that omission of Claim 73 from the first paragraph of Section 5 is a typographical error. As such, Applicant is proceeding with the understanding that the recitation "Claim(s) 1−4, 27, 35−40, 63, 71, and 72" is to be replaced with "Claim(s) 1−4, 27, 35−40, 63, and 71−73" and respectfully requests confirmation regarding same.

Claim Rejections under 35 U.S.C. §102(a1/a2)

Claims 1−4, 27, 35−40, 63, 71−73 stand rejected under 35 U.S.C. § 102(a1/a2) as being said to be anticipated by U.S. Patent Publication 2014/0309943 to Grundlehner *et al.* (hereinafter, "Grundlehner"). Applicant respectfully disagrees.

Claims 6, 18, 42, and 54 are being cancelled. Independent Claim 1 is being rewritten to include all of the allowable subject matter of cancelled dependent Claim 18 and intervening Claim 6. Independent Claim 37 is being rewritten to include all of the allowable subject matter of cancelled dependent Claim 54 and intervening Claim 42. Independent Claim 73 is being amended to include similar allowable subject matter as Claim 1, as currently amended. As such, Claims 1, 37, and 73, as currently amended are novel over Grundlehner and are allowable.

Claims 2−4, 27, 35, and 36, and Claims 38−40, 63, 71, and 72, depend from Claims 1 and 37, respectively, include the same elements as the claim(s) from which they depend, and are novel over Grundlehner and allowable for similar reasons set forth above in regard to amended Claims 1 and 37.

In light of the above, Applicant respectfully requests withdrawal of the rejections of Claims 1−4, 27, 35−40, 63, 71−73 under 35 U.S.C. § 102(a1/a2) and requests the claims be accepted for allowance.

Petitioner Ex-1004, 0986

Rejections Under 35 U.S.C. §103

Claims 5, 28–34, 41, and 64–70

Claims 5, 28–34, 41, and 64–70 stand rejected under 35 U.S.C. §103 as being said to be obvious over Grundlehner in view of U.S. Patent No. 8,945,017 by Venkatraman *et al.* (hereinafter, "Venkatraman"). Applicant respectfully disagrees.

Claims 6, 18, 42, and 54 are being cancelled. Independent Claim 1 is being rewritten to include all of the allowable subject matter of cancelled dependent Claim 18 and intervening Claim 6. Independent Claim 37 is being rewritten to include all of the allowable subject matter of cancelled dependent Claim 54 and intervening Claim 42. As such, even if the references could be combined, which Applicant does not concede, Claims 1 and 37, as currently amended, are novel and non-obvious over the cited hypothetical combination and are allowable.

Claims 5 and 28–34, and Claims 41 and 64–70, depend from Claims 1 and 37, respectively, include the same elements as the claim(s) from which they depend, and are novel over Grundlehner and allowable for similar reasons set forth above in regard to amended Claims 1 and 37.

In light of the above, Applicant respectfully requests withdrawal of the rejections of Claims 5, 28–34, 41, and 64–70 under 35 U.S.C. §103 and requests the claims be accepted for allowance.

Claims 6–8 and 42–44

Claims 6–8 and 42–44 stand rejected under 35 U.S.C. §103 as being said to be obvious over Grundlehner in view of U.S. Patent No. 9,713,428 by Chon *et al.* (hereinafter, "Chon"). Applicant respectfully disagrees.

Claims 6, 18, 42, and 54 are being cancelled. Independent Claim 1 is being rewritten to include all of the allowable subject matter of cancelled dependent Claim 18 and intervening Claim 6. Independent Claim 37 is being rewritten to include all of the allowable subject matter of cancelled dependent Claim 54 and intervening Claim 42. As such, even if the references could be combined, which Applicant does not concede, Claims 1 and 37, as currently amended, are novel and non-obvious over the cited hypothetical combination and are allowable.

Claims 7 and 8, and Claims 43 and 44, depend from Claims 1 and 37, respectively, include the same elements as the claim(s) from which they depend, and are novel over

Grundlehner and allowable for similar reasons set forth above in regard to amended Claims 1 and 37.

In light of the above, Applicant respectfully requests withdrawal of the rejections of Claims 7, 8, 43, and 44 under 35 U.S.C. §103 and requests the claims be accepted for allowance.

New Claims 74–79

New Claim 74 is allowed Claim 9 rewritten in independent form to include all of the subject matter of base Claim 1 and intervening Claim 6. New Claim 75 is allowed Claim 11 rewritten in independent form to include all of the subject matter of base Claim 1 and intervening Claim 6. New Claim 76 is allowed Claim 21 rewritten in independent form to include all of the subject matter of base Claim 1 and intervening Claim 6.

New Claim 77 is allowed Claim 45 rewritten in independent form to include all of the subject matter of base Claim 1 and intervening Claim 42. New Claim 78 is allowed Claim 47 rewritten in independent form to include all of the subject matter of base Claim 1 and intervening Claim 42. New Claim 79 is allowed Claim 57 rewritten in independent form to include all of the subject matter of base Claim 1 and intervening Claim 42.

In light of the above, Applicant respectfully requests new Claims 74–79 be accepted for allowance.

Payment of Fees

Authorization is hereby granted to charge the fees due with this submission, including any extension of time fee, to Deposit Account No. 08-0380.

CONCLUSION

In view of the above amendments and remarks, it is believed that all claims that will be pending upon entry of this Amendment, namely Claims 1–5, 7–17, 19–41, 43–53, and 55–79, are in condition for allowance, and it is respectfully requested that the application be passed to issue. If the Examiner feels that a telephone conference would expedite prosecution of this case, the Examiner is invited to call the undersigned.

Respectfully submitted,

HAMILTON, BROOK, SMITH & REYNOLDS, P.C.

By /Mark B. Solomon, Reg. No. 44348/
Mark B. Solomon
Registration No. 44,348
Telephone: (978) 341-0036
Facsimile: (978) 341-0136

Concord, MA 01742-9133
Date: 7/16/2018

Petitioner Ex-1004, 0989

Electronic Patent Application Fee Transmittal

Application Number:	15178089
Filing Date:	09-Jun-2016
Title of Invention:	METHOD AND APPARATUS FOR REMOVING MOTION ARTIFACTS FROM BIOMEDICAL SIGNALS
First Named Inventor/Applicant Name:	Seyed M. A. Salehizadeh
Filer:	Mark B Solomon/ann giso
Attorney Docket Number:	4147.1020-002 (15-089)

Filed as Small Entity

Filing Fees for Utility under 35 USC 111(a)

Description	Fee Code	Quantity	Amount	Sub-Total in USD($)
Basic Filing:				
Pages:				
Claims:				
CLAIMS IN EXCESS OF 20	2202	2	50	100
INDEPENDENT CLAIMS IN EXCESS OF 3	2201	6	230	1380
Miscellaneous-Filing:				
Petition:				
Patent-Appeals-and-Interference:				

Description	Fee Code	Quantity	Amount	Sub-Total in USD($)
Post-Allowance-and-Post-Issuance:				
Extension-of-Time:				
Miscellaneous:				
		Total in USD ($)		**1480**

Electronic Acknowledgement Receipt

EFS ID:	33181353
Application Number:	15178089
International Application Number:	
Confirmation Number:	7605
Title of Invention:	METHOD AND APPARATUS FOR REMOVING MOTION ARTIFACTS FROM BIOMEDICAL SIGNALS
First Named Inventor/Applicant Name:	Seyed M. A. Salehizadeh
Customer Number:	21005
Filer:	Mark B Solomon/ann giso
Filer Authorized By:	Mark B Solomon
Attorney Docket Number:	4147.1020-002 (15-089)
Receipt Date:	16-JUL-2018
Filing Date:	09-JUN-2016
Time Stamp:	11:06:19
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	yes
Payment Type	DA
Payment was successfully received in RAM	$1480
RAM confirmation Number	071618INTEFSW00008958080380
Deposit Account	
Authorized User	

The Director of the USPTO is hereby authorized to charge indicated fees and credit any overpayment as follows:

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1		41471020002_15089Amendment_final.pdf	172100 9b1de6f36d03994f6e2c295e15717a74b877dd65	yes	26

	Multipart Description/PDF files in .zip description		
	Document Description	**Start**	**End**
	Amendment/Req. Reconsideration-After Non-Final Reject	1	1
	Claims	2	21
	Applicant Arguments/Remarks Made in an Amendment	22	26

Warnings:					
Information:					
2	Fee Worksheet (SB06)	fee-info.pdf	32387 0a78f05e9d8c4cc36488fd9e2d90b320dd064cfb	no	2
Warnings:					
Information:					
			Total Files Size (in bytes):	204487	

This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

New Applications Under 35 U.S.C. 111

If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371

If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office

If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
15/178,089	06/09/2016	Seyed M. A. Salehizadeh	4147.1020-002 (15-089)	7605

21005 7590 10/22/2018

HAMILTON, BROOK, SMITH & REYNOLDS, P.C.
530 VIRGINIA ROAD
P.O. BOX 9133
CONCORD, MA 01742-9133

EXAMINER	
GEDEON, BRIAN T	

ART UNIT	PAPER NUMBER
3792	

NOTIFICATION DATE	DELIVERY MODE
10/22/2018	ELECTRONIC

Please find below and/or attached an Office communication concerning this application or proceeding.

The time period for reply, if any, is set in the attached communication.

Notice of the Office communication was sent electronically on above-indicated "Notification Date" to the following e-mail address(es):

docketing.department@hbsr.com
helpdesk@hbsr.com

Office Action Summary	Application No. 15/178,089	Applicant(s) SALEHIZADEH ET AL.	
	Examiner BRIAN T. GEDEON	Art Unit 3792	AIA (First Inventor to File) Status Yes

-- The MAILING DATE of this communication appears on the cover sheet with the correspondence address --

Period for Reply

A SHORTENED STATUTORY PERIOD FOR REPLY IS SET TO EXPIRE *3* MONTHS FROM THE MAILING DATE OF THIS COMMUNICATION.

- Extensions of time may be available under the provisions of 37 CFR 1.136(a). In no event, however, may a reply be timely filed after SIX (6) MONTHS from the mailing date of this communication.
- If NO period for reply is specified above, the maximum statutory period will apply and will expire SIX (6) MONTHS from the mailing date of this communication.
- Failure to reply within the set or extended period for reply will, by statute, cause the application to become ABANDONED (35 U.S.C. § 133). Any reply received by the Office later than three months after the mailing date of this communication, even if timely filed, may reduce any earned patent term adjustment. See 37 CFR 1.704(b).

Status

1)☒ Responsive to communication(s) filed on *16 July 2018*.

☐ A declaration(s)/affidavit(s) under **37 CFR 1.130(b)** was/were filed on _____.

2a)☒ This action is **FINAL**. 2b)☐ This action is non-final.

3)☐ An election was made by the applicant in response to a restriction requirement set forth during the interview on _____; the restriction requirement and election have been incorporated into this action.

4)☐ Since this application is in condition for allowance except for formal matters, prosecution as to the merits is closed in accordance with the practice under *Ex parte Quayle*, 1935 C.D. 11, 453 O.G. 213.

Disposition of Claims*

5)☒ Claim(s) *1-5,7-17,19-41,43-53 and 55-79* is/are pending in the application.

5a) Of the above claim(s) _____ is/are withdrawn from consideration.

6)☒ Claim(s) *74-79* is/are allowed.

7)☒ Claim(s) *1-5,7-17,19-41,43-53 and 55-73* is/are rejected.

8)☐ Claim(s) _____ is/are objected to.

9)☐ Claim(s) _____ are subject to restriction and/or election requirement.

* If any claims have been determined allowable, you may be eligible to benefit from the **Patent Prosecution Highway** program at a participating intellectual property office for the corresponding application. For more information, please see http://www.uspto.gov/patents/init_events/pph/index.jsp or send an inquiry to PPHfeedback@uspto.gov.

Application Papers

10)☐ The specification is objected to by the Examiner.

11)☐ The drawing(s) filed on _____ is/are: a)☐ accepted or b)☐ objected to by the Examiner.

Applicant may not request that any objection to the drawing(s) be held in abeyance. See 37 CFR 1.85(a).

Replacement drawing sheet(s) including the correction is required if the drawing(s) is objected to. See 37 CFR 1.121(d).

Priority under 35 U.S.C. § 119

12)☐ Acknowledgment is made of a claim for foreign priority under 35 U.S.C. § 119(a)-(d) or (f).

Certified copies:

a)☐ All b)☐ Some** c)☐ None of the:

1.☐ Certified copies of the priority documents have been received.

2.☐ Certified copies of the priority documents have been received in Application No. _____.

3.☐ Copies of the certified copies of the priority documents have been received in this National Stage application from the International Bureau (PCT Rule 17.2(a)).

** See the attached detailed Office action for a list of the certified copies not received.

Attachment(s)

1) ☐ Notice of References Cited (PTO-892)

2) ☐ Information Disclosure Statement(s) (PTO/SB/08a and/or PTO/SB/08b) Paper No(s)/Mail Date _____.

3) ☐ Interview Summary (PTO-413) Paper No(s)/Mail Date. _____ .

4) ☐ Other: _____.

DETAILED ACTION

Response to Amendment

1. This action is in response to the amendment after non-final filed 16 July 2018. Claims 1-5, 7-17, 19-41, 43-53, and 55-79 are pending, wherein claims 74-79 are new.

2. As a formal note, Applicant points out that claim 73 was omitted from the header listing claims rejected under 35 USC 102(a1/a2) as being anticipated by Grundlehner et al. Applicant correctly assumed that the omission was the result of a typographical error and should have been included with the listing of rejected claims. The Examiner confirms that omission of claim 72 under the 35 USC 102(a1/a2) rejection was inadvertent, and claim 73 was included with the rejection articulated with respect to claims 1, 37 and 73.

Response to Arguments

3. Applicant's arguments filed with respect to rejections under 35 USC 102(a1/a2) as being anticipated by Grundlehner et al. (US Publication no. 2014/0309943) and under 35 USC 103 as obvious over Grundlehner et al. (US Publication no. 2014/0309943) in view of Venkatraman et al. (US Patent no. 8,945,017) have been fully considered and are persuasive in light of Applicant's claim amendments. The rejections formulated under these references have been withdrawn.

Double Patenting

4. The nonstatutory double patenting rejection is based on a judicially created doctrine grounded in public policy (a policy reflected in the statute) so as to prevent the unjustified or improper timewise extension of the "right to exclude" granted by a patent and to prevent possible harassment by multiple assignees. A nonstatutory double patenting rejection is appropriate where the conflicting claims are not identical, but at least one examined application claim is not patentably distinct from the reference claim(s) because the examined application claim is either anticipated by, or would have been obvious over, the reference claim(s). See, e.g., *In re Berg*, 140 F.3d 1428, 46 USPQ2d 1226 (Fed. Cir. 1998); *In re Goodman*, 11 F.3d 1046, 29 USPQ2d 2010 (Fed. Cir. 1993); *In re Longi*, 759 F.2d 887, 225 USPQ 645 (Fed. Cir. 1985); *In re Van Ornum*, 686 F.2d 937, 214 USPQ 761 (CCPA 1982); *In re Vogel*, 422 F.2d 438, 164 USPQ 619 (CCPA 1970); *In re Thorington*, 418 F.2d 528, 163 USPQ 644 (CCPA 1969).

A timely filed terminal disclaimer in compliance with 37 CFR 1.321(c) or 1.321(d) may be used to overcome an actual or provisional rejection based on nonstatutory double patenting provided the reference application or patent either is shown to be commonly owned with the examined application, or claims an invention made as a result of activities undertaken within the scope of a joint research agreement. See MPEP § 717.02 for applications subject to examination under the first inventor to file provisions of the AIA as explained in MPEP § 2159. See MPEP §§ 706.02(l)(1) - 706.02(l)(3) for applications not subject to examination under the first inventor to file

provisions of the AIA. A terminal disclaimer must be signed in compliance with 37 CFR 1.321(b).

The USPTO Internet website contains terminal disclaimer forms which may be used. Please visit www.uspto.gov/patent/patents-forms. The filing date of the application in which the form is filed determines what form (e.g., PTO/SB/25, PTO/SB/26, PTO/AIA/25, or PTO/AIA/26) should be used. A web-based eTerminal Disclaimer may be filled out completely online using web-screens. An eTerminal Disclaimer that meets all requirements is auto-processed and approved immediately upon submission. For more information about eTerminal Disclaimers, refer to www.uspto.gov/patents/process/file/efs/guidance/eTD-info-I.jsp.

5. Claims 1-5, 7-17, 19-41, 43-53, and 55-73 are rejected on the ground of nonstatutory double patenting as being unpatentable over claims 1-49 of U.S. Patent No. 9,872,652. Although the claims at issue are not identical, they are not patentably distinct from each other because it has been found that the ‘652 patent recites subject matter similar in scope to the subject matter presented by the present invention. For instance, claims 1, 3, 8, 15, and 16 of the '652, in combination, recite elements of claim 1 of the present invention. Claims 1 and 3 of the ‘652 sets for the limitations pertaining to the method of reconstructing a heart-related signal output by a biomedical sensor utilizing steps for reconstructing a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal based on a time-varying spectral analysis of a heart-related signal that includes a motion artifact indicative of signal-artifacts produced by movement of the biomedical sensor relative to a sensing

location. Claims 1 and 3 of the ‘652 also indicates that the reconstruction is based on a time-varying spectral analysis of a pre-processed heart-related signal to reduce motion artifacts by pre-processing as required by claim 1 of the present invention. Claim 8 of the '652 recites the newly incorporated subject matter of present claim 1 that the time-varying spectral analysis includes producing a time-frequency spectrum. Claim 15 of the '652 recites that the analysis includes computing a first time-varying spectral analysis of the heart-related signal, and a second time-varying spectral analysis of the motion signal. Claim 16 of the '652 recites the newly incorporated subject matter of present claim 1 that provides for classification of the movement. For these reasons, the '652 is considered to overlap in scope with the present invention as the listed claims of the ‘652 provide support for each limitation recited by the present invention.

Additionally, claims 25, 27, 32, 39, and 40 of the '652 patent are considered to present limitations relating to the apparatus of the present invention such that the '652 is considered to overlap in scope with the present invention as the listed claims of the ‘652 provide support for each limitation recited by the present invention.

Allowable Subject Matter

6. Claims 74-79 are allowed for incorporating limitations of the base claim with subject matter previously indicated as allowable.

7. Claims 1-5, 7-17, 19-41, 43-53, and 55-73 would be allowable should applicant's reply comply with all formal requirements or specifically traverse each requirement of the double patenting rejection set forth above.

Statement on Communication via Internet

8. Communications via Internet e-mail are at the discretion of the applicant. Without a written authorization by applicant in place, the USPTO will not respond via Internet e-mail to any Internet correspondence which contains information subject to the confidentiality requirement as set forth in 35 U.S.C. 122. Where a written authorization is given by the applicant, communications via Internet e-mail, other than those under 35 U.S.C. 132 or which otherwise require a signature, may be used. USPTO employees are NOT permitted to initiate communications with applicants via Internet e-mail unless there is a written authorization of record in the patent application by the applicant. The following is a sample authorization form which may be used by applicant:

> "Recognizing that Internet communications are not secure, I hereby authorize the USPTO to communicate with me concerning any subject matter of this application by electronic mail. I understand that a copy of these communications will be made of record in the application file."

Please refer to MPEP 502.03 for guidance on Communications via Internet.

Conclusion

9. **THIS ACTION IS MADE FINAL.** Applicant is reminded of the extension of time policy as set forth in 37 CFR 1.136(a).

A shortened statutory period for reply to this final action is set to expire THREE MONTHS from the mailing date of this action. In the event a first reply is filed within TWO MONTHS of the mailing date of this final action and the advisory action is not mailed until after the end of the THREE-MONTH shortened statutory period, then the

shortened statutory period will expire on the date the advisory action is mailed, and any extension fee pursuant to 37 CFR 1.136(a) will be calculated from the mailing date of the advisory action. In no event, however, will the statutory period for reply expire later than SIX MONTHS from the mailing date of this final action.

10. Any inquiry concerning this communication or earlier communications from the examiner should be directed to BRIAN T. GEDEON whose telephone number is (571)272-3447. The examiner can normally be reached on M-F 8:30-5:00.

Examiner interviews are available via telephone, in-person, and video conferencing using a USPTO supplied web-based collaboration tool. To schedule an interview, applicant is encouraged to use the USPTO Automated Interview Request (AIR) at http://www.uspto.gov/interviewpractice.

If attempts to reach the examiner by telephone are unsuccessful, the examiner's supervisor, Carl H. Layno can be reached on (571) 272-4949. The fax phone number for the organization where this application or proceeding is assigned is 571-273-8300.

Information regarding the status of an application may be obtained from the Patent Application Information Retrieval (PAIR) system. Status information for published applications may be obtained from either Private PAIR or Public PAIR. Status information for unpublished applications is available through Private PAIR only. For more information about the PAIR system, see http://pair-direct.uspto.gov. Should you have questions on access to the Private PAIR system, contact the Electronic Business Center (EBC) at 866-217-9197 (toll-free). If you would like assistance from a USPTO Customer Service Representative or access to the automated information system, call 800-786-9199 (IN USA OR CANADA) or 571-272-1000.

/BRIAN T. GEDEON/
Primary Examiner, Art Unit 3792
17 October 2018

EAST Search History

EAST Search History (Prior Art)

Ref #	Hits	Search Query	DBs	Default Operator	Plurals	Time Stamp
L1	19	(("time-varying" OR "time-variant") NEAR spectral NEAR analysis)	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/10/17 09:38
S1	3	"15178089"	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 09:50
S2	14	("time-varying" NEAR spectral NEAR analysis)	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 09:56
S3	1	"20140275854".pn.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 10:01
S4	1578	(motion NEAR (corrupt$4 OR artefact))	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 10:03
S5	15009	(motion NEAR (corrupt$4 OR artifact))	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 10:03
S6	52215	(spectral NEAR analysis)	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 10:03
S7	744	S5 AND S6	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 10:03
S8	683293	heart	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 10:03
S9	4646381	sensor	US-PGPUB; USPAT;	OR	ON	2018/04/09 10:03

			USOCR; FPRS; EPO; JPO			
S10	521	S7 AND S8 AND S9	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 10:04
S11	137313	(sensor NEAR (motion OR movement))	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 10:57
S12	212	S10 AND S11	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 10:57
S13	1	("9872652").PN.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 12:36
S14	456165	reconstruct$4	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 12:37
S15	15009	(motion NEAR (corrupt$4 OR artifact))	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 12:37
S16	52215	(spectral NEAR analysis)	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 12:37
S17	744	S15 AND S16	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 12:37
S18	683293	heart	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 12:37
S19	4646381	sensor	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 12:37
S20	521	S17 AND S18 AND S19	US-PGPUB; USPAT; USOCR;	OR	ON	2018/04/09 12:37

			FPRS; EPO; JPO			
S21	137313	(sensor NEAR (motion OR movement))	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 12:37
S22	212	S20 AND S21	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 12:37
S23	55	S14 AND S22	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 12:37
S24	16	(US-20140275854-$ or US-20140309943-$).did. or (US-9872652-$ or US-7738935-$ or US-7803119-$ or US-8137270-$ or US-8172764-$ or US-8747330-$ or US-8834364-$ or US-8888700-$ or US-8920332-$ or US-8945017-$ or US-8948832-$ or US-9173593-$ or US-9237855-$ or US-9770176-$).did.	US-PGPUB; USPAT	OR	ON	2018/04/09 12:48
S25	20337	A61B5/02427,0002,02050,02416,02433,02439,11,1118,1123,4812,681,6843,6844,7235.cpc.	US-PGPUB; USPAT	OR	ON	2018/04/09 12:54
S26	577	S15 AND S16 AND S18	US-PGPUB; USPAT	OR	ON	2018/04/09 12:54
S27	284	S25 AND S26	US-PGPUB; USPAT	OR	ON	2018/04/09 12:55
S28	1250	(time NEAr frequency NEAr spectrum)	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 13:29
S29	21	S15 AND S18 AND S19 AND S28	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 13:30
S30	15	"SpaMA"	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 13:36
S31	1	"8388543".pn.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 14:06
S32	6	salehizadeh-seyed-m-a.in.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 14:21
S33	67	chon-ki-h.in.	US-PGPUB; USPAT; USOCR; FPRS;	OR	ON	2018/04/09 14:21

			EPO; JPO			
S34	467301	(spectral OR spectrum) AND peak	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 14:22
S35	26	S33 AND S34	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 14:22
S36	7	noh-yeonsik.in.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/09 14:35
S37	19	(US-20140275854-$ or US-20140309943-$ or US-20160081651-$).did. or (US-9872652-$ or US-7738935-$ or US-7803119-$ or US-8137270-$ or US-8172764-$ or US-8747330-$ or US-8834364-$ or US-8888700-$ or US-8920332-$ or US-8945017-$ or US-8948832-$ or US-9173593-$ or US-9237855-$ or US-9770176-$ or US-9713428-$ or US-8718753-$).did.	US-PGPUB; USPAT	OR	ON	2018/04/09 15:17
S38	19	(US-20140275854-$ or US-20140309943-$ or US-20160081651-$).did. or (US-9872652-$ or US-7738935-$ or US-7803119-$ or US-8137270-$ or US-8172764-$ or US-8747330-$ or US-8834364-$ or US-8888700-$ or US-8920332-$ or US-8945017-$ or US-8948832-$ or US-9173593-$ or US-9237855-$ or US-9770176-$ or US-9713428-$ or US-8718753-$).did.	US-PGPUB; USPAT	OR	ON	2018/04/13 08:41
S39	4	(spectral NEAR analysis) AND Peaks AND candidate AND frequency AND (discard$4 OR reject$4) AND ("time-frequency" NEAR spectr$4) AND motion	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 09:23
S40	1	"20140275854".pn.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 09:24
S41	14288	(reconstruct$4 SAME (cardiac OR heart))	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 11:09
S42	14	("time-varying" NEAR spectral NEAR analysis)	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 11:10
S43	6	S41 AND S42	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 11:10
S44	506	("time-frequency" NEAR spectr$4)	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 11:17
S45	4	S41 AND S44	US-PGPUB; USPAT; USOCR;	OR	ON	2018/04/13 11:17

			FPRS; EPO; JPO			
S46	56514	(reconstruct$4 AND (cardiac OR heart))	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 11:17
S47	19	S44 AND S46	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 11:17
S48	20375	A61B5/02427,0002,02050,02416,02433,02439,11,1118,1123,4812,681,6843,6844,7235.cpc.	US-PGPUB; USPAT	OR	ON	2018/04/13 11:26
S49	1321	S46 AND S48	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 11:26
S50	456633	reconstruct$4	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 11:26
S51	1321	S49 AND S50	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 11:26
S52	36	S44 AND S48	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 11:26
S53	2	"20140005988".pn.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 13:21
S54	984043	sampling	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 13:33
S55	19	(US-20140275854-$ or US-20140309943-$ or US-20160081651-$).did. or (US-9872652-$ or US-7738935-$ or US-7803119-$ or US-8137270-$ or US-8172764-$ or US-8747330-$ or US-8834364-$ or US-8888700-$ or US-8920332-$ or US-8945017-$ or US-8948832-$ or US-9173593-$ or US-9237855-$ or US-9770176-$ or US-9713428-$ or US-8718753-$).did.	US-PGPUB; USPAT	OR	ON	2018/04/13 13:33
S56	11	S54 AND S55	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 13:33
S57	506	("time-frequency" NEAR spectr$4)	US-PGPUB; USPAT; USOCR;	OR	ON	2018/04/13 15:08

			FPRS; EPO; JPO			
S58	3	S57 AND S55	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 15:08
S59	7	(20140309943|9713428|8945017).pn.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO	OR	ON	2018/04/13 15:35

EAST Search History (Interference)

Ref #	Hits	Search Query	DBs	Default Operator	Plurals	Time Stamp
L2	3	(("time-varying" OR "time-variant") NEAR spectral NEAR analysis).clm.	US-PGPUB; USPAT	OR	ON	2018/10/17 09:43

10/17/2018 11:16:01 AM
C:\Users\bgedeon\Documents\EAST\Workspaces\15178089.wsp

Search Notes	Application/Control No.	Applicant(s)/Patent Under Reexamination
	15178089	SALEHIZADEH ET AL.
	Examiner	Art Unit
	BRIAN T GEDEON	3766

CPC- SEARCHED		
Symbol	Date	Examiner
A61B 5/02427,0002,02050,02416,02433,02439,11,1118,1123,4812,681,6843,6844,7235 (limited by keyword text search)	4/13/2018	BTG

CPC COMBINATION SETS - SEARCHED		
Symbol	Date	Examiner

US CLASSIFICATION SEARCHED			
Class	Subclass	Date	Examiner

* See search history printout included with this form or the SEARCH NOTES box below to determine the scope of the search.

SEARCH NOTES		
Search Notes	Date	Examiner
Detailed EAST search history attached.	4/13/2018	BTG
Inventor name search.	4/13/2018	BTG
Search updated.	10/17/2018	BTG

INTERFERENCE SEARCH			
US Class/ CPC Symbol	US Subclass / CPC Group	Date	Examiner
	US PG-Pub, USPAT claim text search.	10/17/2018	BTG

Doc Code: DIST.E.FILE **Document Description: Electronic Terminal Disclaimer - Filed**	PTO/SB/26 U.S. Patent and Trademark Office Department of Commerce

Electronic Petition Request	**TERMINAL DISCLAIMER TO OBVIATE A DOUBLE PATENTING REJECTION OVER A "PRIOR" PATENT**
Application Number	15178089
Filing Date	09-Jun-2016
First Named Inventor	Seyed Salehizadeh
Attorney Docket Number	4147.1020-002 (15-089)
Title of Invention	METHOD AND APPARATUS FOR REMOVING MOTION ARTIFACTS FROM BIOMEDICAL SIGNALS

☒ Filing of terminal disclaimer does not obviate requirement for response under 37 CFR 1.111 to outstanding Office Action

☒ This electronic Terminal Disclaimer is not being used for a Joint Research Agreement.

Owner	Percent Interest
University of Connecticut	100%

The owner(s) with percent interest listed above in the instant application hereby disclaims, except as provided below, the terminal part of the statutory term of any patent granted on the instant application which would extend beyond the expiration date of the full statutory term of prior patent number(s)

9872652

as the term of said prior patent is presently shortened by any terminal disclaimer. The owner hereby agrees that any patent so granted on the instant application shall be enforceable only for and during such period that it and the prior patent are commonly owned. This agreement runs with any patent granted on the instant application and is binding upon the grantee, its successors or assigns.

In making the above disclaimer, the owner does not disclaim the terminal part of the term of any patent granted on the instant application that would extend to the expiration date of the full statutory term of the prior patent, "as the term of said prior patent is presently shortened by any terminal disclaimer," in the event that said prior patent later:
- expires for failure to pay a maintenance fee;
- is held unenforceable;
- is found invalid by a court of competent jurisdiction;
- is statutorily disclaimed in whole or terminally disclaimed under 37 CFR 1.321;
- has all claims canceled by a reexamination certificate;
- is reissued; or
- is in any manner terminated prior to the expiration of its full statutory term as presently shortened by any terminal disclaimer.

◉ Terminal disclaimer fee under 37 CFR 1.20(d) is included with Electronic Terminal Disclaimer request.

○ I certify, in accordance with 37 CFR 1.4(d)(4), that the terminal disclaimer fee under 37 CFR 1.20(d) required for this terminal disclaimer has already been paid in the above-identified application.
Applicant claims the following fee status: ◉ Small Entity ○ Micro Entity ○ Regular Undiscounted I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.
THIS PORTION MUST BE COMPLETED BY THE SIGNATORY OR SIGNATORIES I certify, in accordance with 37 CFR 1.4(d)(4) that I am: ◉ An attorney or agent registered to practice before the Patent and Trademark Office who is of record in this application Registration Number 44348 ○ A sole inventor ○ A joint inventor; I certify that I am authorized to sign this submission on behalf of all of the inventors as evidenced by the power of attorney in the application ○ A joint inventor; all of whom are signing this request

Signature	/Mark B. Solomon, Reg. No. 44348/
Name	Mark B. Solomon

*Statement under 37 CFR 3.73(b) is required if terminal disclaimer is signed by the assignee (owner).
Form PTO/SB/96 may be used for making this certification. See MPEP § 324.

Electronic Patent Application Fee Transmittal

Application Number:	15178089
Filing Date:	09-Jun-2016
Title of Invention:	METHOD AND APPARATUS FOR REMOVING MOTION ARTIFACTS FROM BIOMEDICAL SIGNALS
First Named Inventor/Applicant Name:	Seyed M. A. Salehizadeh
Filer:	Mark B Solomon/Kristina Fay
Attorney Docket Number:	4147.1020-002 (15-089)

Filed as Small Entity

Filing Fees for Utility under 35 USC 111(a)

Description	Fee Code	Quantity	Amount	Sub-Total in USD($)
Basic Filing:				
STATUTORY OR TERMINAL DISCLAIMER	2814	1	160	160
Pages:				
Claims:				
Miscellaneous-Filing:				
Petition:				
Patent-Appeals-and-Interference:				
Post-Allowance-and-Post-Issuance:				

Description	Fee Code	Quantity	Amount	Sub-Total in USD($)
Extension-of-Time:				
Miscellaneous:				
			Total in USD ($)	**160**

Doc Code: DISQ.E.FILE
Document Description: Electronic Terminal Disclaimer – Approved

Application No.: 15178089

Filing Date: 09-Jun-2016

Applicant/Patent under Reexamination: Salehizadeh

Electronic Terminal Disclaimer filed on December 6, 2018

☒ APPROVED

This patent is subject to a terminal disclaimer

☐ DISAPPROVED

Approved/Disapproved by: Electronic Terminal Disclaimer automatically approved by EFS-Web

U.S. Patent and Trademark Office

Electronic Acknowledgement Receipt

EFS ID:	34501220
Application Number:	15178089
International Application Number:	
Confirmation Number:	7605
Title of Invention:	METHOD AND APPARATUS FOR REMOVING MOTION ARTIFACTS FROM BIOMEDICAL SIGNALS
First Named Inventor/Applicant Name:	Seyed M. A. Salehizadeh
Customer Number:	21005
Filer:	Mark B Solomon/Kristina Fay
Filer Authorized By:	Mark B Solomon
Attorney Docket Number:	4147.1020-002 (15-089)
Receipt Date:	06-DEC-2018
Filing Date:	09-JUN-2016
Time Stamp:	15:51:03
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	yes
Payment Type	DA
Payment was successfully received in RAM	$160
RAM confirmation Number	120718INTEFSW00002555080380
Deposit Account	
Authorized User	

The Director of the USPTO is hereby authorized to charge indicated fees and credit any overpayment as follows:

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Terminal Disclaimer-Filed (Electronic)	eTerminal-Disclaimer.pdf	33465 8dc5f0dd4c1d218347104bbe486bdb2c3e109f84	no	2
Warnings:					
Information:					
2	Fee Worksheet (SB06)	fee-info.pdf	30622 7cea59f992b0604d07dc53cc4a3f9226d010ef26	no	2
Warnings:					
Information:					
		Total Files Size (in bytes):	64087		

This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

New Applications Under 35 U.S.C. 111

If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371

If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office

If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Inventors:	Seyed M.A. Salehizadeh, Ki H. Chon, Yeonsik Noh		
Application No.:	15/178,089	Group:	3792
Filed:	June 9, 2016	Examiner:	Brian T. Gedeon
Confirmation No.:	7605		
For:	Method And Apparatus For Removing Motion Artifacts From Biomedical Signals		

REPLY AFTER FINAL REJECTION UNDER 37 CFR § 1.116

Mail Stop AF
Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Sir:

This Reply After Final Rejection is being filed in response to the Final Office Action mailed from the U.S. Patent and Trademark Office on October 22, 2018 in the above-identified application. Reconsideration and further examination are requested.

Because this Reply after Final Rejection (37 C.F.R. § 1.116) is being filed within two months of the mailing date of the Final Office Action, Applicant respectfully requests an Advisory Action under MPEP 706.07(f)(I)(C).

Petitioner Ex-1004, 1018

Amendments to the Claims

The Claim Listing below is being provided for the convenience of the Examiner. No claims are being amended, added, or cancelled by way of this Reply.

Claim Listing

1. (Previously Presented) A method for reconstructing a heart-related signal output by a biomedical sensor, the method comprising:

reconstructing a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal, the reconstructing based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of the movement, wherein the time-varying spectral analysis includes pre-processing the heart-related signal to produce a pre-processed heart-related signal, pre-processing the motion signal to produce a pre-processed motion signal, and computing a first time-frequency spectrum (TFS) of the heart-related signal using the pre-processed heart-related signal and a second TFS of the motion signal using the pre-processed motion signal; and

outputting the reconstructed representation of the heart-related signal.

2. (Original) The method of Claim 1, wherein the motion artifacts are suppressed in the reconstructed representation of the heart-related signal.

3. (Previously Presented) The method of Claim 1, wherein:

in an event the classification indicates that the movement does not rise to a level causing the motion artifacts, the reconstructed representation is based on an average value of peak-to-peak intervals in the pre-processed heart-related signal.

4. (Previously Presented) The method of Claim 1, wherein the pre-processing includes filtering the heart-related signal to produce a filtered heart-related signal, the filtered heart-related signal being the pre-processed heart-related signal.

5. (Original) The method of Claim 4, wherein the pre-processing further includes down-sampling the filtered heart-related signal, the down-sampling being at a sampling rate less than an original sampling rate.

6. (Cancelled)

7. (Previously Presented) The method of Claim 1, wherein the first TFS computed and the second TFS computed are 3-dimensional spectra, the first TFS computed and the second TFS computed each including a respective time-varying amplitude or power distribution with respect to time and frequency.

8. (Previously Presented) The method of Claim 1, wherein the first TFS computed is a first time-varying power spectral density (PSD) and the second TFS computed is a second time-varying PSD.

9. (Previously Presented) The method of Claim 1, wherein the reconstructed representation is a current reconstructed representation and wherein, based on the classification indicating that the movement does rise to a level causing the motion artifacts and is a pseudo-periodic movement or a periodic movement, the reconstructing includes:

determining whether at least one spectral peak is present having a corresponding frequency within a given frequency range at a point in time in the first TFS computed, the current reconstructed representation being reconstructed for the point in time; and

wherein, based on a determination that the at least one spectral peak is not present, the current reconstructed representation is based on a prior reconstructed representation, the prior reconstructed representation associated with a previous point in time in the first TFS computed.

10. (Original) The method of Claim 9, wherein the given frequency range is 0.5 Hz to 3 Hz.

11. (Previously Presented) The method of Claim 1, wherein the reconstructing includes:

retaining up to a pre-determined number of candidate spectral peaks located at a first point in time in the first TFS computed, the candidate spectral peaks retained based on having corresponding frequencies within a given frequency range and highest amplitude or power values relative to other spectral peaks located at the first point in time, the other spectral peaks having respective frequencies within the given frequency range; and

discarding each of the candidate spectral peaks retained that is associated with a same frequency as a dominant spectral peak located at a second point in time in the second TFS computed, the first point in time and the second point in time having same time values.

12. (Original) The method of Claim 11, wherein the given frequency range is 0.5 Hz to 3 Hz.

13. (Original) The method of Claim 11, wherein the representation is a current representation, wherein the reconstructed representation is a current reconstructed representation, and wherein, in an event the discarding discards each of the candidate spectral peaks retained, reconstructing the current representation is based on a prior reconstructed representation, the prior reconstructed representation associated with a previous point in time in the first TFS computed, the previous point in time being an earlier point in time with respect to the first point in time.

14. (Original) The method of Claim 11, wherein the discarding is a first discarding and wherein the representation is a current representation and, wherein, in an event the first discarding results in at least one remaining candidate spectral peak retained, reconstructing the current representation further includes:

second discarding, wherein the second discarding discards remaining candidate spectral peaks, of the at least one remaining candidate spectral peak retained, based on whether a corresponding frequency of the at least one remaining candidate spectral peak

retained is distanced by at least a frequency difference threshold from a prior reconstructed representation's frequency, the prior reconstructed representation associated with a previous point in time in the first TFS computed, the previous point in time being an earlier point in time with respect to the first point in time.

15. (Original) The method of Claim 14, wherein:

based on each of the at least one remaining candidate spectral peak retained having been discarded by the second discarding, reconstructing the current representation is based on the prior reconstructed representation; and

based on at least one last candidate spectral peak remaining, the at least one last candidate spectral peak remaining not discarded by the second discarding, reconstructing the current representation is based on a selected candidate spectral peak selected from amongst the at least one last candidate spectral peak remaining having a closest corresponding frequency to the prior reconstructed representation's frequency relative to respective frequencies of each of the at least one last candidate spectral peak remaining.

16. (Original) The method of Claim 11, wherein the dominant spectral peak has a largest power or amplitude value relative to other peaks located at the second point in time in the second TFS.

17. (Original) The method of Claim 11, wherein the retaining and the discarding are based on:

the classification indicating that the movement is a pseudo-periodic movement or a periodic movement; and

determining that at least one spectral peak with a corresponding frequency in the given frequency range is present at the first point in time.

18. (Cancelled)

19. (Previously Presented) The method of Claim 1, wherein the pre-processing includes filtering the heart-related signal and the motion signal to produce a filtered heart-related

signal and a filtered motion signal, respectively, the filtered heart-related signal being the pre-processed heart-related signal and the filtered motion signal being the pre-processed motion signal.

20. (Original) The method of Claim 19, wherein the pre-processing further includes down-sampling both the filtered heart-related signal and the filtered motion signal, the down-sampling being at a sampling rate less than an original sampling rate.

21. (Previously Presented) The method of Claim 1, further including:

classifying the classification of the movement by comparing an amount of amplitude modulation in the second TFS computed to an amplitude modulation threshold, wherein the classification indicates whether the movement rises to a level of causing the motion artifacts based on a result of the comparing.

22. (Original) The method of Claim 21, wherein the amplitude modulation threshold is dependent on a type of the motion detector sensor.

23. (Original) The method of Claim 21, wherein, in an event the result indicates that the movement does rise to the level causing the motion artifacts, classifying the classification of the movement further includes determining whether the movement is either a pseudo-periodic movement or a periodic movement, versus a random movement.

24. (Original) The method of Claim 23, wherein, in determining whether the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement includes, the method further includes:

identifying a first, second, and third frequency associated, respectively, with a first, second, and third spectral peak in the second TFS at a point in time in the second TFS, the first, second, and third peaks having largest power or amplitude values relative to other peaks in the second TFS at the point in time, the first spectral peak being a largest spectral peak amongst the first, second, and third spectral peaks;

computing a first ratio of the second frequency identified to the first frequency identified and determining a first comparison result by comparing the first ratio computed to a first ratio value; and

computing a second ratio of the third frequency identified to the first frequency identified and determining a second comparison result by comparing the second ratio computed to a second ratio value, wherein the classification further indicates that the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement, based on the first comparison result and the second comparison result.

25. (Original) The method of Claim 24, wherein the first ratio value is 2 and the second ratio value is 3.

26. (Previously Presented) The method of Claim 1, wherein, in an event the classification of the movement indicates random movement, the reconstructing includes:

computing an average value of a number of prior reconstructed representations outputted prior to the reconstructing, the number based on a duration of consecutive motion artifacts, detected prior to the reconstructing;

computing a bandpass filter cutoff frequency based on the average value computed;

filtering the pre-processed heart-related signal by applying the band pass filter computed to produce a filtered, pre-processed heart-related signal; and

wherein the reconstructed representation is based on an average peak-to-peak interval value of the filtered, pre-processed heart-related signal.

27. (Original) The method of Claim 1, wherein the heart-related signal and the motion signal are produced, concurrently.

28. (Original) The method of Claim 1, further comprising:

segmenting the heart-related signal into a plurality of windowed heart-related signal data segments and the motion signal into a corresponding plurality of windowed motion signal data segments; and

repeating the reconstructing and the outputting for each windowed heart-related signal data segment and each corresponding motion signal data segment.

29. (Original) The method of Claim 28, wherein the time window is a value in a range from 2 to 32 seconds.

30. (Original) The method of Claim 1, wherein the biomedical sensor is at least one of: a photoplethysmogram (PPG) sensor, piezoelectric sensor, Light Emitting Diode (LED) based sensor, camera sensor, and pulse oximeter sensor, and wherein the motion sensor is an accelerometer.

31. (Original) The method of Claim 1, wherein the biomedical sensor and the motion sensor are co-located.

32. (Original) The method of Claim 1, further comprising employing the reconstructed representation to determine a heart rate estimate.

33. (Original) The method of Claim 1, further comprising employing the reconstructed representation to determine an arterial oxygen saturation (SpO2) estimate.

34. (Original) The method of Claim 1, further comprising employing the reconstructed representation to detect or predict a heart-related ailment, the heart-related ailment including at least one of a heart rate variability (HRV) condition, atrial fibrillation condition, congestive heart failure condition, and tachycardia condition.

35. (Original) The method of Claim 1, wherein the reconstructing and the outputting are performed in real-time with respect to production of the heart-related signal and the motion signal.

36. (Original) The method of Claim 1, wherein the reconstructing and the outputting are performed in non-real-time with respect to production of the heart-related signal and the motion signal.

37. (Previously Presented) An apparatus for reconstructing a heart-related signal output by a biomedical sensor, the apparatus comprising:

a reconstruction unit configured to reconstruct a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal, the reconstructing based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of the movement, wherein the time-varying spectral analysis includes pre-processing the heart-related signal to produce a pre-processed heart-related signal, pre-processing the motion signal to produce a pre-processed motion signal, and computing a first time-frequency spectrum (TFS) of the heart-related signal using the pre-processed heart-related signal and a second TFS of the motion signal using the pre-processed motion signal; and

an output unit configured to output the reconstructed representation of the heart-related signal.

38. (Original) The apparatus of Claim 37, wherein the motion artifacts are suppressed in the reconstructed representation of the heart-related signal.

39. (Previously Presented) The apparatus of Claim 37, wherein:

in an event the classification indicates that the movement does not rise to level causing the motion artifacts, the reconstructed representation is based on an average value of peak-to-peak intervals in the pre-processed heart-related signal.

40. (Previously Presented) The apparatus of Claim 37, wherein the pre-processing includes filtering the heart-related signal to produce a filtered heart-related signal, the filtered heart-related signal being the pre-processed heart-related signal.

41. (Original) The apparatus of Claim 40, wherein the pre-processing further includes down-sampling the filtered heart-related signal, the down-sampling being at a sampling rate less than an original sampling rate.

42. (Cancelled)

43. (Previously Presented) The apparatus of Claim 37, wherein the first TFS computed and the second TFS computed are 3-dimensional spectra, the first TFS computed and the second TFS computed each including a respective time-varying amplitude or power distribution with respect to time and frequency.

44. (Previously Presented) The apparatus of Claim 37, wherein the first TFS computed is a first time-varying power spectral density (PSD) and the second TFS computed is a second time-varying PSD.

45. (Previously Presented) The apparatus of Claim 37, wherein the reconstructed representation is a current reconstructed representation and wherein, based on the classification indicating that the movement does rise to a level causing the motion artifacts and is a pseudo-periodic movement or a periodic movement, to reconstruct the representation includes:

determining whether at least one spectral peak is present having a corresponding frequency within a given frequency range at a point in time in the first TFS computed, the current reconstructed representation being reconstructed for the point in time; and

wherein, based on a determination that the at least one spectral peak is not present, the reconstructed current representation is based on a prior reconstructed representation, the prior reconstructed representation associated with a previous point in time in the first TFS computed.

46. (Original) The apparatus of Claim 45, wherein the given frequency range is 0.5 Hz to 3 Hz.

47. (Previously Presented) The apparatus of Claim 37, wherein to reconstruct the representation includes:

retaining up to a pre-determined number of candidate spectral peaks located at a first point in time in the first TFS computed, the candidate spectral peaks retained based on having corresponding frequencies within a given frequency range and highest amplitude or power values relative to other spectral peaks located at the first point in time, the other spectral peaks having respective frequencies within the given frequency range; and

discarding each of the candidate spectral peaks retained that is associated with a same frequency as a dominant spectral peak located at a second point in time in the second TFS computed, the first point in time and the second point in time having same time values.

48. (Original) The apparatus of Claim 47, wherein the given frequency range is 0.5 Hz to 3 Hz.

49. (Original) The apparatus of Claim 47, wherein the representation is a current representation, wherein the reconstructed representation is a current reconstructed representation, and wherein, in an event the discarding discards each of the candidate spectral peaks retained, reconstructing the current representation is based on a prior reconstructed representation, the prior reconstructed representation associated with a previous point in time in the first TFS computed, the previous point in time being an earlier point in time with respect to the first point in time.

50. (Original) The apparatus of Claim 47, wherein the discarding is a first discarding and wherein the representation is a current representation and, wherein, in an event the first

discarding results in at least one remaining candidate spectral peak retained, reconstructing the current representation further includes:

second discarding, wherein the second discarding discards remaining candidate spectral peaks, of the at least one remaining candidate spectral peak retained, based on whether a corresponding frequency of the at least one remaining candidate spectral peak retained is distanced by at least a frequency difference threshold from a prior reconstructed representation's frequency, the prior reconstructed representation associated with a previous point in time in the first TFS computed, the previous point in time being an earlier point in time with respect to the first point in time.

51. (Original) The apparatus of Claim 50, wherein:

based on each of the at least one remaining candidate spectral peak retained having been discarded by the second discarding, reconstructing the current representation is based on the prior reconstructed representation; and

based on at least one last candidate spectral peak remaining, the at least one last candidate spectral peak remaining not discarded by the second discarding, reconstructing the current representation is based on a selected candidate spectral peak selected from amongst the at least one last candidate spectral peak remaining having a closest corresponding frequency to the prior reconstructed representation's frequency relative to respective frequencies of each of the at least one last candidate spectral peak remaining.

52. (Original) The apparatus of Claim 47, wherein the dominant spectral peak has a largest power or amplitude value relative to other peaks located at the second point in time in the second TFS.

53. (Original) The apparatus of Claim 47, wherein the retaining and the discarding are based on:

the classification of the movement indicating that the movement is a pseudo-periodic movement or a periodic movement; and

determining that at least one spectral peak with a corresponding frequency in the given frequency range is present at the first point in time.

54. (Cancelled)

55. (Previously Presented) The apparatus of Claim 37, wherein the pre-processing includes filtering the heart-related signal and the motion signal to produce a filtered heart-related signal and a filtered motion signal, respectively, the filtered heart-related signal being the pre-processed heart-related signal and the filtered motion signal being the pre-processed motion signal.

56. (Original) The apparatus of Claim 55, wherein the pre-processing further includes down-sampling, at a sampling rate less than an original sampling rate, both the filtered heart-related signal and the filtered motion signal.

57. (Previously Presented) The apparatus of Claim 37, further including a classification unit, the classification unit configured to:

classify the classification of the movement by comparing an amount of amplitude modulation in the second TFS computed to an amplitude modulation threshold, wherein the classification indicates whether the movement rises to a level causing the motion artifacts based on a result of the comparing.

58. (Original) The apparatus of Claim 57, wherein the amplitude modulation threshold is dependent on a type of the motion detector sensor.

59. (Original) The apparatus of Claim 57, wherein, in an event the result indicates that the movement does rise to the level causing the motion artifacts, the classification unit is further configured to classify the classification of the movement by determining whether the movement is either a pseudo-periodic movement or a periodic movement, versus a random movement.

60. (Original) The apparatus of Claim 59, wherein to determine whether the movement is either the pseudo-periodic movement or the periodic movement versus a random movement includes:

identifying a first, second, and third frequency associated, respectively, with a first, second, and third spectral peak in the second TFS at a point in time in the second TFS, the first, second, and third peaks having largest power or amplitude values relative to other peaks in the second TFS at the point in time, the first spectral peak being a largest spectral peak amongst the first, second, and third spectral peaks;

computing a first ratio of the second frequency identified to the first frequency identified and determining a first comparison result by comparing the first ratio computed to a first ratio value; and

computing a second ratio of the third frequency identified to the first frequency identified and determining a second comparison result by comparing the second ratio computed to a second ratio value, wherein the classification further indicates that the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement, based on the first comparison result and the second comparison result.

61. (Original) The apparatus of Claim 60, wherein the first ratio value is 2 and the second ratio value is 3.

62. (Previously Presented) The apparatus of Claim 59, wherein, in an event the classification of the movement indicates random movement, the reconstructing includes:

computing an average value of a number of prior reconstructed representations outputted prior to the reconstructing, the number based on a duration of consecutive motion artifacts, detected prior to the reconstructing;

computing a bandpass filter cutoff frequency based on the average value computed;

filtering the pre-processed heart-related signal by applying the band pass filter computed to produce a filtered, pre-processed heart-related signal; and

wherein the reconstructed representation is based on an average peak-to-peak interval value of the filtered, pre-processed heart-related signal.

63. (Original) The apparatus of Claim 37, wherein the heart-related signal and the motion signal are produced, concurrently.

64. (Original) The apparatus of Claim 37, further comprising segmentation unit configured to:

segment the heart-related signal into a plurality of windowed heart-related signal data segments and the motion signal into corresponding plurality of windowed motion signal data segments, wherein the reconstruction unit and the output unit reconstruct the representation and output the reconstructed representation, respectively, based on each windowed heart-related signal data segment and each corresponding motion signal data segment.

65. (Original) The apparatus of Claim 64, wherein the time window is a value in a range from 2 to 32 seconds.

66. (Original) The apparatus of Claim 37, wherein the biomedical sensor is at least one of: a photoplethysmogram (PPG) sensor, piezoelectric sensor, Light Emitting Diode (LED) based sensor, camera sensor, and pulse oximeter sensor, and wherein the motion sensor is an accelerometer.

67. (Original) The apparatus of Claim 37, wherein the apparatus includes the biomedical sensor and the motion sensor.

68. (Original) The apparatus of Claim 37, further comprising a heart rate unit configured to employ the reconstructed representation to determine a heart rate estimate.

69. (Original) The apparatus of Claim 37, further comprising an arterial oxygen saturation (SpO2) unit configured to employ the reconstructed representation to determine a SpO2 estimate.

70. (Original) The apparatus of Claim 37, further comprising an ailment unit configured to employ the reconstructed representation to detect or predict a heart-related ailment, the heart-related ailment including at least one of a heart rate variability (HRV) condition, an atrial fibrillation condition, a congestive heart failure condition, and a tachycardia condition.

71. (Original) The apparatus of Claim 37, wherein the reconstruction unit and the output unit are configured to reconstruct and to output, respectively, in real-time with respect to production of the heart-related signal and the motion signal.

72. (Original) The apparatus of Claim 37, wherein the reconstruction unit and the output unit are configured to reconstruct and to output, respectively, in non-real-time with respect to production of the heart-related signal and the motion signal.

73. (Previously Presented) A non-transitory computer-readable medium having encoded thereon a sequence of instructions which, when loaded and executed by a processor, causes the processor to reconstruct a heart-related signal output by a biomedical sensor, the processor reconstructing the heart-related signal by:

reconstructing a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal, the reconstructing based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of the movement, wherein the time-varying spectral analysis includes pre-processing the heart-related signal to produce a pre-processed heart-related signal, pre-processing the motion signal to produce a pre-processed motion signal, and computing a first time-frequency spectrum

(TFS) of the heart-related signal using the pre-processed heart-related signal and a second TFS of the motion signal using the pre-processed motion signal; and

outputting the reconstructed representation of the heart-related signal.

74. (Previously Presented) A method for reconstructing a heart-related signal output by a biomedical sensor, the method comprising:

reconstructing a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal, the reconstructing based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of the movement, wherein the time-varying spectral analysis includes computing a first time-frequency spectrum (TFS) of the heart-related signal and computing a second TFS of the motion signal; and

outputting the reconstructed representation of the heart-related signal, wherein the reconstructed representation is a current reconstructed representation and wherein, based on the classification indicating that the movement does rise to a level causing the motion artifacts and is a pseudo-periodic movement or a periodic movement, the reconstructing includes:

determining whether at least one spectral peak is present having a corresponding frequency within a given frequency range at a point in time in the first TFS computed, the current reconstructed representation being reconstructed for the point in time; and

wherein, based on a determination that the at least one spectral peak is not present, the current reconstructed representation is based on a prior reconstructed representation, the prior reconstructed representation associated with a previous point in time in the first TFS computed.

75. (Previously Presented) A method for reconstructing a heart-related signal output by a biomedical sensor, the method comprising:

reconstructing a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal, the reconstructing based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of the movement, wherein the time-varying spectral analysis includes computing a first time-frequency spectrum (TFS) of the heart-related signal and computing a second TFS of the motion signal; and

outputting the reconstructed representation of the heart-related signal, wherein the reconstructing includes:

retaining up to a pre-determined number of candidate spectral peaks located at a first point in time in the first TFS computed, the candidate spectral peaks retained based on having corresponding frequencies within a given frequency range and highest amplitude or power values relative to other spectral peaks located at the first point in time, the other spectral peaks having respective frequencies within the given frequency range; and

discarding each of the candidate spectral peaks retained that is associated with a same frequency as a dominant spectral peak located at a second point in time in the second TFS computed, the first point in time and the second point in time having same time values.

76. (Previously Presented) A method for reconstructing a heart-related signal output by a biomedical sensor, the method comprising:

reconstructing a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal, the reconstructing based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of the movement, wherein the time-varying spectral analysis includes computing a first time-frequency

spectrum (TFS) of the heart-related signal and computing a second TFS of the motion signal;

classifying the classification of the movement by comparing an amount of amplitude modulation in the second TFS computed to an amplitude modulation threshold, wherein the classification indicates whether the movement rises to a level of causing the motion artifacts based on a result of the comparing; and

outputting the reconstructed representation of the heart-related signal.

77. (Previously Presented) An apparatus for reconstructing a heart-related signal output by a biomedical sensor, the apparatus comprising:

a reconstruction unit configured to reconstruct a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal, the reconstructing based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of the movement, wherein the time-varying spectral analysis includes computing a first time-frequency spectrum (TFS) of the heart-related signal and computing a second TFS of the motion signal; and

an output unit configured to output the reconstructed representation of the heart-related signal, wherein the reconstructed representation is a current reconstructed representation and wherein, based on the classification indicating that the movement does rise to a level causing the motion artifacts and is a pseudo-periodic movement or a periodic movement, to reconstruct the representation includes:

determining whether at least one spectral peak is present having a corresponding frequency within a given frequency range at a point in time in the first TFS computed, the current reconstructed representation being reconstructed for the point in time; and

wherein, based on a determination that the at least one spectral peak is not present, the reconstructed current representation is based on a prior reconstructed

representation, the prior reconstructed representation associated with a previous point in time in the first TFS computed.

78. (Previously Presented) An apparatus for reconstructing a heart-related signal output by a biomedical sensor, the apparatus comprising:

a reconstruction unit configured to reconstruct a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal, the reconstructing based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of the movement, wherein the time-varying spectral analysis includes computing a first time-frequency spectrum (TFS) of the heart-related signal and computing a second TFS of the motion signal; and

an output unit configured to output the reconstructed representation of the heart-related signal, wherein to reconstruct the representation includes:

retaining up to a pre-determined number of candidate spectral peaks located at a first point in time in the first TFS computed, the candidate spectral peaks retained based on having corresponding frequencies within a given frequency range and highest amplitude or power values relative to other spectral peaks located at the first point in time, the other spectral peaks having respective frequencies within the given frequency range; and

discarding each of the candidate spectral peaks retained that is associated with a same frequency as a dominant spectral peak located at a second point in time in the second TFS computed, the first point in time and the second point in time having same time values.

79. (Previously Presented) An apparatus for reconstructing a heart-related signal output by a biomedical sensor, the apparatus comprising:

a reconstruction unit configured to reconstruct a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal, the

reconstructing based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of the movement, wherein the time-varying spectral analysis includes computing a first time-frequency spectrum (TFS) of the heart-related signal and computing a second TFS of the motion signal;

a classification unit configured to classify the classification of the movement by comparing an amount of amplitude modulation in the second TFS computed to an amplitude modulation threshold, wherein the classification indicates whether the movement rises to a level causing the motion artifacts based on a result of the comparing; and

an output unit configured to output the reconstructed representation of the heart-related signal.

REMARKS

Claims 1–5, 7–17, 19–41, 43–53, and 55–79 are pending in the Application, of which Claims 1, 37, and 73–79 are independent. No claims are being amended, added, or cancelled. No Previously Presented matter is being added by way of this Reply.

Claims 1−5, 7−17, 19−41, 43−53, and 55−73 stand rejected on the ground of nonstatutory double patenting. Claims 74−79 are allowed. Claims 1−5, 7−17, 19−41, 43−53, and 55−73 been indicated to be allowable. Applicant respectfully addresses the indication of allowable subject matter, as well as each rejection, in turn, below.

Allowable Subject Matter

Applicant thanks Examiner Gedeon for the indication of allowable subject matter, namely, that Claims 1−5, 7−17, 19−41, 43−53, and 55−73 "would be allowable should [A]pplicant's reply comply with all the formal requirements or specifically traverse each requirement of the double patenting rejection set forth above" and that Claims 74−79 are allowed. *See* Office Action, page 5.

To expedite prosecution in this Application, a Terminal Disclaimer with respect to U.S. Patent No. 9,872,652 (hereinafter "`652 patent") is being submitted concurrently herewith, together with the requisite fee, to obviate the nonstatutory double patenting rejections and place the Application in condition for allowance, as noted below.

Double Patenting Rejections

Claims 1−5, 7−17, 19−41, 43−53, and 55−73 stand rejected on the ground of nonstatutory double patenting over Claims 1–49 of the `652 patent. Applicant respectfully disagrees; however, to expedite prosecution in this Application, a Terminal Disclaimer with respect to the `652 patent is being submitted concurrently herewith, together with the requisite fee, to obviate these rejections.

Accordingly, Applicant respectfully requests the nonstatutory double patenting rejections of Claims 1−5, 7−17, 19−41, 43−53, and 55−73 over Claims 1–49 of the `652 patent be withdrawn and the claims be accepted for allowance.

Payment of Fees

Authorization is hereby granted to charge the fees due with this submission, including any extension of time fee, to Deposit Account No. 08-0380.

CONCLUSION

In view of the above remarks, it is believed that all claims pending, namely Claims 1–5, 7–17, 19–41, 43–53, and 55–79, are in condition for allowance, and it is respectfully requested that the application be passed to issue. If the Examiner feels that a telephone conference would expedite prosecution of this case, the Examiner is invited to call the undersigned.

Respectfully submitted,

HAMILTON, BROOK, SMITH & REYNOLDS, P.C.

By /Mark B. Solomon, Reg. No. 44348/
Mark B. Solomon
Registration No. 44,348
Telephone: (978) 341-0036
Facsimile: (978) 341-0136

Concord, MA 01742-9133
Date: 12/6/2018

Electronic Acknowledgement Receipt

EFS ID:	34502307
Application Number:	15178089
International Application Number:	
Confirmation Number:	7605
Title of Invention:	METHOD AND APPARATUS FOR REMOVING MOTION ARTIFACTS FROM BIOMEDICAL SIGNALS
First Named Inventor/Applicant Name:	Seyed M. A. Salehizadeh
Customer Number:	21005
Filer:	Mark B Solomon/Kristina Fay
Filer Authorized By:	Mark B Solomon
Attorney Docket Number:	4147.1020-002 (15-089)
Receipt Date:	06-DEC-2018
Filing Date:	09-JUN-2016
Time Stamp:	15:54:24
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	no

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1		41471020002_Reply.pdf	160464 141cfe3893f6ced36d0493f89acb35c055558783	yes	23

	Multipart Description/PDF files in .zip description		
	Document Description	**Start**	**End**
	Response After Final Action	1	1
	Claims	2	21
	Applicant Arguments/Remarks Made in an Amendment	22	23
Warnings:			
Information:			
	Total Files Size (in bytes):	160464	

This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

New Applications Under 35 U.S.C. 111

If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371

If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office

If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

NOTICE OF ALLOWANCE AND FEE(S) DUE

21005 7590 12/20/2018

HAMILTON, BROOK, SMITH & REYNOLDS, P.C.
530 VIRGINIA ROAD
P.O. BOX 9133
CONCORD, MA 01742-9133

EXAMINER
GEDEON, BRIAN T

ART UNIT	PAPER NUMBER
3792	

DATE MAILED: 12/20/2018

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
15/178,089	06/09/2016	Seyed M. A. Salehizadeh	4147.1020-002 (15-089)	7605

TITLE OF INVENTION: METHOD AND APPARATUS FOR REMOVING MOTION ARTIFACTS FROM BIOMEDICAL SIGNALS

APPLN. TYPE	ENTITY STATUS	ISSUE FEE DUE	PUBLICATION FEE DUE	PREV. PAID ISSUE FEE	TOTAL FEE(S) DUE	DATE DUE
nonprovisional	SMALL	$500	$0.00	$0.00	$500	03/20/2019

THE APPLICATION IDENTIFIED ABOVE HAS BEEN EXAMINED AND IS ALLOWED FOR ISSUANCE AS A PATENT. PROSECUTION ON THE MERITS IS CLOSED. THIS NOTICE OF ALLOWANCE IS NOT A GRANT OF PATENT RIGHTS. THIS APPLICATION IS SUBJECT TO WITHDRAWAL FROM ISSUE AT THE INITIATIVE OF THE OFFICE OR UPON PETITION BY THE APPLICANT. SEE 37 CFR 1.313 AND MPEP 1308.

THE ISSUE FEE AND PUBLICATION FEE (IF REQUIRED) MUST BE PAID WITHIN THREE MONTHS FROM THE MAILING DATE OF THIS NOTICE OR THIS APPLICATION SHALL BE REGARDED AS ABANDONED. THIS STATUTORY PERIOD CANNOT BE EXTENDED. SEE 35 U.S.C. 151. THE ISSUE FEE DUE INDICATED ABOVE DOES NOT REFLECT A CREDIT FOR ANY PREVIOUSLY PAID ISSUE FEE IN THIS APPLICATION. IF AN ISSUE FEE HAS PREVIOUSLY BEEN PAID IN THIS APPLICATION (AS SHOWN ABOVE), THE RETURN OF PART B OF THIS FORM WILL BE CONSIDERED A REQUEST TO REAPPLY THE PREVIOUSLY PAID ISSUE FEE TOWARD THE ISSUE FEE NOW DUE.

HOW TO REPLY TO THIS NOTICE:

I. Review the ENTITY STATUS shown above. If the ENTITY STATUS is shown as SMALL or MICRO, verify whether entitlement to that entity status still applies.

If the ENTITY STATUS is the same as shown above, pay the TOTAL FEE(S) DUE shown above.

If the ENTITY STATUS is changed from that shown above, on PART B - FEE(S) TRANSMITTAL, complete section number 5 titled "Change in Entity Status (from status indicated above)".

For purposes of this notice, small entity fees are 1/2 the amount of undiscounted fees, and micro entity fees are 1/2 the amount of small entity fees.

II. PART B - FEE(S) TRANSMITTAL, or its equivalent, must be completed and returned to the United States Patent and Trademark Office (USPTO) with your ISSUE FEE and PUBLICATION FEE (if required). If you are charging the fee(s) to your deposit account, section "4b" of Part B - Fee(s) Transmittal should be completed and an extra copy of the form should be submitted. If an equivalent of Part B is filed, a request to reapply a previously paid issue fee must be clearly made, and delays in processing may occur due to the difficulty in recognizing the paper as an equivalent of Part B.

III. All communications regarding this application must give the application number. Please direct all communications prior to issuance to Mail Stop ISSUE FEE unless advised to the contrary.

IMPORTANT REMINDER: Maintenance fees are due in utility patents issuing on applications filed on or after Dec. 12, 1980. It is patentee's responsibility to ensure timely payment of maintenance fees when due. More information is available at www.uspto.gov/PatentMaintenanceFees.

Petitioner Ex-1004, 1043

PART B - FEE(S) TRANSMITTAL

Complete and send this form, together with applicable fee(s), by mail or fax, or via EFS-Web.

By mail, send to: Mail Stop ISSUE FEE
Commissioner for Patents
P.O. Box 1450
Alexandria, Virginia 22313-1450

By fax, send to: (571)-273-2885

INSTRUCTIONS: This form should be used for transmitting the ISSUE FEE and PUBLICATION FEE (if required). Blocks 1 through 5 should be completed where appropriate. All further correspondence including the Patent, advance orders and notification of maintenance fees will be mailed to the current correspondence address as indicated unless corrected below or directed otherwise in Block 1, by (a) specifying a new correspondence address; and/or (b) indicating a separate "FEE ADDRESS" for maintenance fee notifications.

CURRENT CORRESPONDENCE ADDRESS (Note: Use Block 1 for any change of address)

21005 7590 12/20/2018

HAMILTON, BROOK, SMITH & REYNOLDS, P.C.
530 VIRGINIA ROAD
P.O. BOX 9133
CONCORD, MA 01742-9133

Note: A certificate of mailing can only be used for domestic mailings of the Fee(s) Transmittal. This certificate cannot be used for any other accompanying papers. Each additional paper, such as an assignment or formal drawing, must have its own certificate of mailing or transmission.

Certificate of Mailing or Transmission

I hereby certify that this Fee(s) Transmittal is being deposited with the United States Postal Service with sufficient postage for first class mail in an envelope addressed to the Mail Stop ISSUE FEE address above, or being transmitted to the USPTO via EFS-Web or by facsimile to (571) 273-2885, on the date below.

(Typed or printed name)
(Signature)
(Date)

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
15/178,089	06/09/2016	Seyed M. A. Salehizadeh	4147.1020-002 (15-089)	7605

TITLE OF INVENTION: METHOD AND APPARATUS FOR REMOVING MOTION ARTIFACTS FROM BIOMEDICAL SIGNALS

APPLN. TYPE	ENTITY STATUS	ISSUE FEE DUE	PUBLICATION FEE DUE	PREV. PAID ISSUE FEE	TOTAL FEE(S) DUE	DATE DUE
nonprovisional	SMALL	$500	$0.00	$0.00	$500	03/20/2019

EXAMINER	ART UNIT	CLASS-SUBCLASS
GEDEON, BRIAN T	3792	600-301000

1. Change of correspondence address or indication of "Fee Address" (37 CFR 1.363).

❑ Change of correspondence address (or Change of Correspondence Address form PTO/SB/122) attached.

❑ "Fee Address" indication (or "Fee Address" Indication form PTO/SB/47; Rev 03-09 or more recent) attached. **Use of a Customer Number is required.**

2. For printing on the patent front page, list

(1) The names of up to 3 registered patent attorneys or agents OR, alternatively,

(2) The name of a single firm (having as a member a registered attorney or agent) and the names of up to 2 registered patent attorneys or agents. If no name is listed, no name will be printed.

1 _____

2 _____

3 _____

3. ASSIGNEE NAME AND RESIDENCE DATA TO BE PRINTED ON THE PATENT (print or type)

PLEASE NOTE: Unless an assignee is identified below, no assignee data will appear on the patent. If an assignee is identified below, the document must have been previously recorded, or filed for recordation, as set forth in 37 CFR 3.11 and 37 CFR 3.81(a). Completion of this form is NOT a substitute for filing an assignment.

(A) NAME OF ASSIGNEE

(B) RESIDENCE: (CITY and STATE OR COUNTRY)

Please check the appropriate assignee category or categories (will not be printed on the patent) : ❑ Individual ❑ Corporation or other private group entity ❑ Government

4a. Fees submitted: ❑ Issue Fee ❑ Publication Fee (if required) ❑ Advance Order - # of Copies _____

4b. Method of Payment: *(Please first reapply any previously paid fee shown above)*

❑ Electronic Payment via EFS-Web ❑ Enclosed check ❑ Non-electronic payment by credit card (Attach form PTO-2038)

❑ The Director is hereby authorized to charge the required fee(s), any deficiency, or credit any overpayment to Deposit Account No. _____

5. **Change in Entity Status** (from status indicated above)

❑ Applicant certifying micro entity status. See 37 CFR 1.29

❑ Applicant asserting small entity status. See 37 CFR 1.27

❑ Applicant changing to regular undiscounted fee status.

NOTE: Absent a valid certification of Micro Entity Status (see forms PTO/SB/15A and 15B), issue fee payment in the micro entity amount will not be accepted at the risk of application abandonment.
NOTE: If the application was previously under micro entity status, checking this box will be taken to be a notification of loss of entitlement to micro entity status.
NOTE: Checking this box will be taken to be a notification of loss of entitlement to small or micro entity status, as applicable.

NOTE: This form must be signed in accordance with 37 CFR 1.31 and 1.33. See 37 CFR 1.4 for signature requirements and certifications.

Authorized Signature _____ Date _____

Typed or printed name _____ Registration No. _____

Petitioner Ex-1004, 1044

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
15/178,089	06/09/2016	Seyed M. A. Salehizadeh	4147.1020-002 (15-089)	7605

21005 7590 12/20/2018

HAMILTON, BROOK, SMITH & REYNOLDS, P.C.
530 VIRGINIA ROAD
P.O. BOX 9133
CONCORD, MA 01742-9133

EXAMINER	
GEDEON, BRIAN T	
ART UNIT	PAPER NUMBER
3792	

DATE MAILED: 12/20/2018

Determination of Patent Term Adjustment under 35 U.S.C. 154 (b)
(Applications filed on or after May 29, 2000)

The Office has discontinued providing a Patent Term Adjustment (PTA) calculation with the Notice of Allowance.

Section 1(h)(2) of the AIA Technical Corrections Act amended 35 U.S.C. 154(b)(3)(B)(i) to eliminate the requirement that the Office provide a patent term adjustment determination with the notice of allowance. See Revisions to Patent Term Adjustment, 78 Fed. Reg. 19416, 19417 (Apr. 1, 2013). Therefore, the Office is no longer providing an initial patent term adjustment determination with the notice of allowance. The Office will continue to provide a patent term adjustment determination with the Issue Notification Letter that is mailed to applicant approximately three weeks prior to the issue date of the patent, and will include the patent term adjustment on the patent. Any request for reconsideration of the patent term adjustment determination (or reinstatement of patent term adjustment) should follow the process outlined in 37 CFR 1.705.

Any questions regarding the Patent Term Extension or Adjustment determination should be directed to the Office of Patent Legal Administration at (571)-272-7702. Questions relating to issue and publication fee payments should be directed to the Customer Service Center of the Office of Patent Publication at 1-(888)-786-0101 or (571)-272-4200.

Petitioner Ex-1004, 1045

OMB Clearance and PRA Burden Statement for PTOL-85 Part B

The Paperwork Reduction Act (PRA) of 1995 requires Federal agencies to obtain Office of Management and Budget approval before requesting most types of information from the public. When OMB approves an agency request to collect information from the public, OMB (i) provides a valid OMB Control Number and expiration date for the agency to display on the instrument that will be used to collect the information and (ii) requires the agency to inform the public about the OMB Control Number's legal significance in accordance with 5 CFR 1320.5(b).

The information collected by PTOL-85 Part B is required by 37 CFR 1.311. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 30 minutes to complete, including gathering, preparing, and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, Virginia 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, Virginia 22313-1450. Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it displays a valid OMB control number.

Privacy Act Statement

The Privacy Act of 1974 (P.L. 93-579) requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether disclosure of these records is required by the Freedom of Information Act.
2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.
3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.
4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).
5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.
6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).
7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (i.e., GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.
8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspection or an issued patent.
9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

Petitioner Ex-1004, 1046

Notice of Allowability	Application No. 15/178,089	Applicant(s) Salehizadeh et al.	
	Examiner BRIAN T GEDEON	Art Unit 3792	AIA Status Yes

-- The MAILING DATE of this communication appears on the cover sheet with the correspondence address--

All claims being allowable, PROSECUTION ON THE MERITS IS (OR REMAINS) CLOSED in this application. If not included herewith (or previously mailed), a Notice of Allowance (PTOL-85) or other appropriate communication will be mailed in due course. **THIS NOTICE OF ALLOWABILITY IS NOT A GRANT OF PATENT RIGHTS.** This application is subject to withdrawal from issue at the initiative of the Office or upon petition by the applicant. See 37 CFR 1.313 and MPEP 1308.

1. ☑ This communication is responsive to the amendment after final filed 6 December 2018.
   ☐ A declaration(s)/affidavit(s) under **37 CFR 1.130(b)** was/were filed on _____.

2. ☐ An election was made by the applicant in response to a restriction requirement set forth during the interview on _____; the restriction requirement and election have been incorporated into this action.

3. ☑ The allowed claim(s) is/are 1-5,7-17,19-41,43-53 and 55-79 . As a result of the allowed claim(s), you may be eligible to benefit from the **Patent Prosecution Highway** program at a participating intellectual property office for the corresponding application. For more information, please see **http://www.uspto.gov/patents/init_events/pph/index.jsp** or send an inquiry to **PPHfeedback@uspto.gov.**

4. ☐ Acknowledgment is made of a claim for foreign priority under 35 U.S.C. § 119(a)-(d) or (f).

   Certified copies:

   a) ☐ All b) ☐ Some *c) ☐ None of the:

   1. ☐ Certified copies of the priority documents have been received.
   2. ☐ Certified copies of the priority documents have been received in Application No. _____ .
   3. ☐ Copies of the certified copies of the priority documents have been received in this national stage application from the International Bureau (PCT Rule 17.2(a)).

   * Certified copies not received: _____ .

Applicant has THREE MONTHS FROM THE "MAILING DATE" of this communication to file areply complying with the requirements noted below. Failure to timely comply will result in ABANDONMENT of this application.
THIS THREE-MONTH PERIOD IS NOT EXTENDABLE.

5. ☐ CORRECTED DRAWINGS (as "replacement sheets") must be submitted.
   ☐ including changes required by the attached Examiner's Amendment / Comment or in the Office action of Paper No./Mail Date _____ .

   Identifying indicia such as the application number (see 37 CFR 1.84(c)) should be written on the drawings in the front (not the back) of each sheet. Replacement sheet(s) should be labeled as such in the header according to 37 CFR 1.121(d).

6. ☐ DEPOSIT OF and/or INFORMATION about the deposit of BIOLOGICAL MATERIAL must be submitted. Note the attached Examiner's comment regarding REQUIREMENT FOR THE DEPOSIT OF BIOLOGICAL MATERIAL.

Attachment(s)

1. ☐ Notice of References Cited (PTO-892)
2. ☐ Information Disclosure Statements (PTO/SB/08), Paper No./Mail Date _____.
3. ☐ Examiner's Comment Regarding Requirement for Deposit of Biological Material _____.
4. ☐ Interview Summary (PTO-413), Paper No./Mail Date. _____.
5. ☐ Examiner's Amendment/Comment
6. ☐ Examiner's Statement of Reasons for Allowance
7. ☐ Other _____.

/BRIAN T GEDEON/
Primary Examiner, Art Unit 3792

Index of Claims	Application/Control No.	Applicant(s)/Patent Under Reexamination
	15/178,089	Salehizadeh et al.
	Examiner	Art Unit
	BRIAN T GEDEON	3792

✓	Rejected	-	Cancelled	N	Non-Elected	A	Appeal
=	Allowed	÷	Restricted	I	Interference	O	Objected

CLAIMS

☐ Claims renumbered in the same order as presented by applicant ☐ CPA ☑ T.D. ☐ R.1.47

CLAIM		DATE								
Final	Original	12/11/2018								
1	1	=								
2	2	=								
3	3	=								
4	4	=								
5	5	=								
	6	-								
6	7	=								
7	8	=								
8	9	=								
9	10	=								
10	11	=								
11	12	=								
12	13	=								
13	14	=								
14	15	=								
15	16	=								
16	17	=								
	18	-								
17	19	=								
18	20	=								
19	21	=								
20	22	=								
21	23	=								
22	24	=								
23	25	=								
24	26	=								
25	27	=								
26	28	=								
27	29	=								
28	30	=								
29	31	=								
30	32	=								
31	33	=								
32	34	=								
33	35	=								
34	36	=								
35	37	=								
36	38	=								
37	39	=								
38	40	=								
39	41	=								
	42	-								

Index of Claims	Application/Control No.	Applicant(s)/Patent Under Reexamination
	15/178,089	Salehizadeh et al.
	Examiner	Art Unit
	BRIAN T GEDEON	3792

CLAIM		DATE								
Final	Original	12/11/2018								
40	43	=								
41	44	=								
42	45	=								
43	46	=								
44	47	=								
45	48	=								
46	49	=								
47	50	=								
48	51	=								
49	52	=								
50	53	=								
	54	-								
51	55	=								
52	56	=								
53	57	=								
54	58	=								
55	59	=								
56	60	=								
57	61	=								
58	62	=								
59	63	=								
60	64	=								
61	65	=								
62	66	=								
63	67	=								
64	68	=								
65	69	=								
66	70	=								
67	71	=								
68	72	=								
69	73	=								
70	74	=								
71	75	=								
72	76	=								
73	77	=								
74	78	=								
75	79	=								

Issue Classification	Application/Control No.	Applicant(s)/Patent Under Reexamination
	15/178,089	Salehizadeh et al.
	Examiner	**Art Unit**
	BRIAN T GEDEON	3792

CPC						
Symbol					**Type**	**Version**
A61B	/	5	/	721	F	2013-01-01
A61B	/	5	/	0205	I	2013-01-01
A61B	/	5	/	725	I	2013-01-01
A61B	/	5	/	02427	I	2013-01-01
A61B	/	5	/	0245	I	2013-01-01
A61B	/	5	/	04012	I	2013-01-01
A61B	/	5	/	7239	I	2013-01-01
A61B	/	5	/	02438	I	2013-01-01
A61B	/	5	/	7253	I	2013-01-01
A61B	/	5	/	02416	I	2013-01-01
A61B	/	5	/	7275	A	2013-01-01
A61B	/	5	/	0077	A	2013-01-01
A61B	/	5	/	1102	A	2013-01-01
A61B	/	5	/	14552	A	2013-01-01
A61B	/	2562	/	0219	A	2013-01-01
A61B	/	5	/	02405	A	2013-01-01
A61B	/	5	/	046	A	2013-01-01
A61B	/	5	/	0464	A	2013-01-01
A61B	/	5	/	6824	A	2013-01-01
A61B	/	2503	/	10	A	2013-01-01
A61B	/	2505	/	07	A	2013-01-01
A61B	/	2505	/	09	A	2013-01-01

CPC Combination Sets								
Symbol					**Type**	**Set**	**Ranking**	**Version**
	/		/					

NONE		**Total Claims Allowed:**	
(Assistant Examiner)	(Date)	75	
/BRIAN T GEDEON/ Primary Examiner, Art Unit 3792	11 December 2018	O.G. Print Claim(s)	O.G. Print Figure
(Primary Examiner)	(Date)	1	4

Issue Classification	Application/Control No.	Applicant(s)/Patent Under Reexamination
	15/178,089	Salehizadeh et al.
	Examiner	**Art Unit**
	BRIAN T GEDEON	3792

INTERNATIONAL CLASSIFICATION					
CLAIMED					
A61B	/	5	/	00	
A61B	/	5	/	0205	

NON-CLAIMED				
	/		/	

US ORIGINAL CLASSIFICATION	
CLASS	**SUBCLASS**

CROSS REFERENCES(S)						
CLASS	**SUBCLASS (ONE SUBCLASS PER BLOCK)**					

NONE		**Total Claims Allowed:**	
(Assistant Examiner)	(Date)	75	
/BRIAN T GEDEON/ Primary Examiner, Art Unit 3792	11 December 2018	O.G. Print Claim(s)	O.G. Print Figure
(Primary Examiner)	(Date)	1	4

Issue Classification	Application/Control No.	Applicant(s)/Patent Under Reexamination
	15/178,089	Salehizadeh et al.
	Examiner	**Art Unit**
	BRIAN T GEDEON	3792

☐ Claims renumbered in the same order as presented by applicant ☐ CPA ☐ T.D. ☐ R.1.47

CLAIMS

Final	Original	Final	Original	Final	Original	Final	Original	Final	Original	Final	Original	Final	Original	Final	Original
1	1	10	11	19	21	29	31	39	41	48	51	57	61	67	71
2	2	11	12	20	22	30	32		42	49	52	58	62	68	72
3	3	12	13	21	23	31	33	40	43	50	53	59	63	69	73
4	4	13	14	22	24	32	34	41	44		54	60	64	70	74
5	5	14	15	23	25	33	35	42	45	51	55	61	65	71	75
	6	15	16	24	26	34	36	43	46	52	56	62	66	72	76
6	7	16	17	25	27	35	37	44	47	53	57	63	67	73	77
7	8		18	26	28	36	38	45	48	54	58	64	68	74	78
8	9	17	19	27	29	37	39	46	49	55	59	65	69	75	79
9	10	18	20	28	30	38	40	47	50	56	60	66	70		

NONE		**Total Claims Allowed:**	
(Assistant Examiner)	(Date)	75	
/BRIAN T GEDEON/ Primary Examiner, Art Unit 3792	11 December 2018	O.G. Print Claim(s)	O.G. Print Figure
(Primary Examiner)	(Date)	1	4

Search Notes	Application/Control No.	Applicant(s)/Patent Under Reexamination
	15/178,089	Salehizadeh et al.
	Examiner	Art Unit
	BRIAN T GEDEON	3792

CPC - Searched*		
Symbol	Date	Examiner
A61B 5/02427,0002,02050,02416,02433,02439,11,1118,1123,4812,681,6843,6844,7235 (limited by keyword text search)	4/13/2018	BTG

CPC Combination Sets - Searched*		
Symbol	Date	Examiner

US Classification - Searched*			
Class	Subclass	Date	Examiner

* See search history printout included with this form or the SEARCH NOTES box below to determine the scope of the search.

Search Notes		
Search Notes	Date	Examiner
Detailed EAST search history attached.	4/13/2018	BTG
Inventor name search.	4/13/2018	BTG
Search updated.	10/17/2018	BTG

Interference Search			
US Class/CPC Symbol	US Subclass/CPC Group	Date	Examiner
	US PG-Pub, USPAT claim text search.	10/17/2018	BTG

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
15/178,089	06/09/2016	Seyed M. A. Salehizadeh	4147.1020-002 (15-089)	7605

21005 7590 01/08/2019
HAMILTON, BROOK, SMITH & REYNOLDS, P.C.
530 VIRGINIA ROAD
P.O. BOX 9133
CONCORD, MA 01742-9133

EXAMINER	
GEDEON, BRIAN T	

ART UNIT	PAPER NUMBER
3792	

NOTIFICATION DATE	DELIVERY MODE
01/08/2019	ELECTRONIC

Please find below and/or attached an Office communication concerning this application or proceeding.

The time period for reply, if any, is set in the attached communication.

Notice of the Office communication was sent electronically on above-indicated "Notification Date" to the following e-mail address(es):

docketing.department@hbsr.com
helpdesk@hbsr.com

UNITED STATES PATENT AND TRADEMARK OFFICE

Commissioner for Patents
United States Patent and Trademark Office
P.O. Box 1450
Alexandria, VA 22313-1450
www.uspto.gov

Application No. : 15178089
Applicant : Salehizadeh
Filing Date : 06/09/2016
Date Mailed : 01/08/2019

NOTICE TO FILE CORRECTED APPLICATION PAPERS

Notice of Allowance Mailed

This application has been accorded an Allowance Date and is being prepared for issuance. The application, however, is incomplete for the reasons below.

Applicant is given two (2) months from the mail date of this Notice within which to respond. This time period for reply is extendable under 37 CFR 1.136(a) for only TWO additional MONTHS.

The informalities requiring correction are indicated in the attachment(s). If the informality pertains to the abstract, specification (including claims) or drawings, the informality must be corrected with an amendment in compliance with 37 CFR 1.121 (or, if the application is a reissue application, 37 CFR 1.173). Such an amendment may be filed after payment of the issue fee if limited to correction of informalities noted herein. See Waiver of 37 CFR 1.312 for Documents Required by the Office of Patent Publication, 1280 Off. Gaz. Patent Office 918 (March 23, 2004). In addition, if the informality is not corrected until after payment of the issue fee, for purposes of 35 U.S.C. 154(b)(1)(iv), "all outstanding requirements" will be considered to have been satisfied when the informality has been corrected. A failure to respond within the above-identified time period will result in the application being ABANDONED.

See attachment(s).

A copy of this notice MUST be returned with the reply. Please address response to "Mail Stop Issue Fee, Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450".

/Daxa Patel/
Publication Branch
Office of Data Management
(571) 272-4200

Application No. 15178089

NON-COMPLIANT ILLUSTRATIONS IN SPECIFICATION OR CLAIMS

[X] **The illustration(s) in the location(s) referenced below do not come within the exceptions of 37 CFR 1.58(a). Please delete the illustration(s) from the specification or claims, provided the illustration(s) as part of the formal drawing(s) in accordance with 37 CFR 1.84, and amend the specification to provide a brief description of the drawings in accordance with 37 CFR 1.74. Please see the following item(s):**

- [X] Specification document coded SPEC dated 06/09/2016, page(s) 40-41 and 48.
- [ ] Claims document coded dated , claim(s) .
- [ ] Amendment document coded dated .
- [ ] Other: .

[X] **The chemical formula(s), mathematical formula(s), or table(s) in the location(s) referenced below contain shading (color/grayscale) and therefore do not comply with 37 CFR 1.52 and do not come within the exceptions of 37 CFR 1.58(a). Please delete chemical formula(s), mathematical formula(s), or table(s) with shading from the specification or claims, provide them as formal color drawing(s) in accordance with 37 CFR 1.84, including petition, fee, and amendment in accordance with 37 CFR 1.84(a)(2), and amend the specification to provide a brief description of the drawings in accordance with 37 CFR 1.74. Please see the following item(s):**

- [X] Specification document coded SPEC dated 06/09/2016, page(s) 42, 55, 56 and 57.
- [ ] Claims document coded dated , claim(s) .
- [ ] Amendment document coded dated .
- [ ] Other: .

DocCode – SCORE

SCORE Placeholder Sheet for IFW Content

Application Number: 15178089 Document Date: 02/14/2019

The presence of this form in the IFW record indicates that the following document type was received in electronic format on the date identified above. This content is stored in the SCORE database.

Since this was an electronic submission, there is no physical artifact folder, no artifact folder is recorded in PALM, and no paper documents or physical media exist. The TIFF images in the IFW record were created from the original documents that are stored in SCORE.

- Drawing

At the time of document entry (noted above):

- USPTO employees may access SCORE content via eDAN using the Supplemental Content tab, or via the SCORE web page.
- External customers may access SCORE content via PAIR using the Supplemental Content tab.

Form Revision Date: August 26, 2013

DocCode – SCORE

SCORE Placeholder Sheet for IFW Content

Application Number: 15178089 Document Date: 02/14/2019

The presence of this form in the IFW record indicates that the following document type was received in electronic format on the date identified above. This content is stored in the SCORE database.

Since this was an electronic submission, there is no physical artifact folder, no artifact folder is recorded in PALM, and no paper documents or physical media exist. The TIFF images in the IFW record were created from the original documents that are stored in SCORE.

- Drawing

At the time of document entry (noted above):

- USPTO employees may access SCORE content via eDAN using the Supplemental Content tab, or via the SCORE web page.
- External customers may access SCORE content via PAIR using the Supplemental Content tab.

Form Revision Date: August 26, 2013

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
15/178,089	06/09/2016	Seyed M. A. Salehizadeh	4147.1020-002 (15-089)	7605

21005 7590 01/08/2019

HAMILTON, BROOK, SMITH & REYNOLDS, P.C.
530 VIRGINIA ROAD
P.O. BOX 9133
CONCORD, MA 01742-9133

EXAMINER
GEDEON, BRIAN T

ART UNIT	PAPER NUMBER
3792	

NOTIFICATION DATE	DELIVERY MODE
01/08/2019	ELECTRONIC

Please find below and/or attached an Office communication concerning this application or proceeding.

The time period for reply, if any, is set in the attached communication.

Notice of the Office communication was sent electronically on above-indicated "Notification Date" to the following e-mail address(es):

docketing.department@hbsr.com
helpdesk@hbsr.com

UNITED STATES PATENT AND TRADEMARK OFFICE

Commissioner for Patents
United States Patent and Trademark Office
P.O. Box 1450
Alexandria, VA 22313-1450
www.uspto.gov

Application No. : 15178089
Applicant : Salehizadeh
Filing Date : 06/09/2016
Date Mailed : 01/08/2019

NOTICE TO FILE CORRECTED APPLICATION PAPERS

Notice of Allowance Mailed

This application has been accorded an Allowance Date and is being prepared for issuance. The application, however, is incomplete for the reasons below.

Applicant is given two (2) months from the mail date of this Notice within which to respond. This time period for reply is extendable under 37 CFR 1.136(a) for only TWO additional MONTHS.

The informalities requiring correction are indicated in the attachment(s). If the informality pertains to the abstract, specification (including claims) or drawings, the informality must be corrected with an amendment in compliance with 37 CFR 1.121 (or, if the application is a reissue application, 37 CFR 1.173). Such an amendment may be filed after payment of the issue fee if limited to correction of informalities noted herein. See Waiver of 37 CFR 1.312 for Documents Required by the Office of Patent Publication, 1280 Off. Gaz. Patent Office 918 (March 23, 2004). In addition, if the informality is not corrected until after payment of the issue fee, for purposes of 35 U.S.C. 154(b)(1)(iv), "all outstanding requirements" will be considered to have been satisfied when the informality has been corrected. A failure to respond within the above-identified time period will result in the application being ABANDONED.

See attachment(s).

A copy of this notice MUST be returned with the reply. Please address response to "Mail Stop Issue Fee, Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450".

/Daxa Patel/
Publication Branch
Office of Data Management
(571) 272-4200

Application No. 15178089

NON-COMPLIANT ILLUSTRATIONS IN SPECIFICATION OR CLAIMS

[X] **The illustration(s) in the location(s) referenced below do not come within the exceptions of 37 CFR 1.58(a). Please delete the illustration(s) from the specification or claims, provided the illustration(s) as part of the formal drawing(s) in accordance with 37 CFR 1.84, and amend the specification to provide a brief description of the drawings in accordance with 37 CFR 1.74. Please see the following item(s):**

- [X] Specification document coded SPEC dated 06/09/2016, page(s) 40-41 and 48.
- [ ] Claims document coded dated , claim(s) .
- [ ] Amendment document coded dated .
- [ ] Other: .

[X] **The chemical formula(s), mathematical formula(s), or table(s) in the location(s) referenced below contain shading (color/grayscale) and therefore do not comply with 37 CFR 1.52 and do not come within the exceptions of 37 CFR 1.58(a). Please delete chemical formula(s), mathematical formula(s), or table(s) with shading from the specification or claims, provide them as formal color drawing(s) in accordance with 37 CFR 1.84, including petition, fee, and amendment in accordance with 37 CFR 1.84(a)(2), and amend the specification to provide a brief description of the drawings in accordance with 37 CFR 1.74. Please see the following item(s):**

- [X] Specification document coded SPEC dated 06/09/2016, page(s) 42, 55, 56 and 57.
- [ ] Claims document coded dated , claim(s) .
- [ ] Amendment document coded dated .
- [ ] Other: .

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Inventors:	Seyed M. A. Salehizadeh, Ki H. Chon, Yeonsik Noh		
Application No.:	15/178,089	Group:	3792
Filed:	Jun 9, 2016	Examiner:	Gedeon Brian T.
Confirmation No.:	7605		
For:	Method And Apparatus For Removing Motion Artifacts From Biomedical Signals		

TRANSMITTAL OF REPLACEMENT DRAWINGS

Mail Stop ISSUE FEE
Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Commissioner:

Transmitted herewith are Replacement Drawings consisting of a total of 28 sheets, figures 1−23, for filing in the subject patent application.

These Replacement Drawings are transmitted herewith in reply to the Notice of Allowability mailed from the U.S. Patent and Trademark Office on December 20, 2018.

Respectfully submitted,

HAMILTON, BROOK, SMITH & REYNOLDS, P.C.

By /Mark B. Solomon, Reg. No. 44348/
Mark B. Solomon
Registration No. 44,348
Telephone: (978) 341-0036
Facsimile: (978) 341-0136

Concord, MA 01742-9133
Date: 2/14/2019

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Inventors:	Seyed M. A. Salehizadeh, Ki H. Chon, Yeonsik Noh		
Application No.:	15/178,089	Group:	3792
Filed:	Jun 9, 2016	Examiner:	Gedeon Brian T.
Confirmation No.:	7605		
For:	Method And Apparatus For Removing Motion Artifacts From Biomedical Signals		

STATEMENT UNDER 37 CFR § 1.125(b)

Mail Stop ISSUE FEE
Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Commissioner:

This Statement is being filed in response to the Notice to File Corrected Application Papers mailed from the U.S. Patent and Trademark Office on January 8, 2019 (hereinafter, "Notice to File Corrected Application Papers"), after mailing of the Notice of Allowance on December 20, 2018, in the above-identified application.

Applicant submits concurrently herewith a substitute specification in compliance with 37 CFR § 1.52, § 1.121(b)(3) and § 1.125 for replacement in the subject application filed on June 9, 2016 along with a copy of the Notice to File Corrected Application Papers. Pursuant to 37 CFR § 1.125(c), submitted concurrently herewith is a copy of the substitute specification marked-up relative to the original specification filed on June 9, 2016.

Further, Applicant submits concurrently herewith 28 sheets of Replacement Drawings consisting of FIGS. 1−23. The Replacement Drawings are identical to the Replacement Drawings filed August 30, 2016; however, sheets have been added for new FIGS. 11C and 14C, and sheet numbers have been applied to all sheets.

The specification is amended to remove Table 6, found at page 40 through 41 of the original specification, and to remove Table 9, found at page 48 of the original specification. Tables 6 and 9 have been added as new FIGS. 11C and 14C, respectively. The specification is amended to include brief descriptions of new FIGS. 11C and 14C. Support for the amendments can be found at least at pages 40, 41, and 48 of the original specification.

The specification is also amended to remove shading from Tables 7, 8, 13, 14, and 15, located at pages 42; 42 and 43; 55; 56; and again on 56 of the original specification, respectively, and to add lines to delineate rows and columns of Table 15. In addition, the specification is amended to correct a typographical error by replacing "comparted" with "compared," found at paragraph [00154] on page 39 of the original specification. Further, the specification is amended to change formatting from bold to normal for equations 7, 8, and 9, located at pages 54, 55, and 55, respectively, of the original specification.

Applicant respectfully submits that the above-noted amendments address each of the Office's non-compliant illustration objections raised in the Notice to File Corrected Application Papers for pages 40−42, 48, 55, and 56. Applicant respectfully submits that while the Notice to File Corrected Application Papers also listed page 57 as having a non-compliant illustration, no illustration at page 57 of the original specification could be located. As such, no amendment to page 57 was made to correct a non-compliant illustration. Page 57 is amended, however, to correct typographical errors. Specifically, page 57 is amended to replace "Time–Frequency" with "Time-Frequency." Page 10 is also amended to replace "Time–Frequency" with "Time-Frequency."

No new matter has been added.

Please charge any deficiency, including any application size fee that may be due with this submission, or credit any overpayment in the fees that may be due in this matter to Deposit Account No. 08-0380.

Respectfully submitted,

HAMILTON, BROOK, SMITH & REYNOLDS, P.C.

By /Mark B. Solomon, Reg. No. 44348/
Mark B. Solomon
Registration No.: 44,348
Telephone: (978) 341-0036
Facsimile: (978) 341-0136

Concord, MA 01742-9133
Dated: 2/14/2019

Date:_____Express Mail Label No._____

Inventors: Seyed M. A. Salehizadeh, Ki H. Chon and Yeonsik Noh

Attorney's Docket No.: 4147.1020-002 (15-089)

METHOD AND APPARATUS FOR REMOVING MOTION ARTIFACTS FROM BIOMEDICAL SIGNALS

RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 62/172,862 filed June 9, 2015 and U.S. Provisional Application No. 62/299,944 filed February 25, 2016. The entire teachings of the above applications are incorporated herein by reference.

GOVERNMENT SUPPORT

[0002] This invention was made with government support under Grant No. W81XWH-12-1-0541 from the US Army Medical Research and Material Command (USAMRMC). The government has certain rights in the invention.

BACKGROUND

[0003] Heart rate monitors have become widely-used training aids for a variety of sports. Some heart rate monitors use sensors based on photoplethysmography (PPG) technology. The PPG sensors include infrared light-emitting diodes (LEDs) and photodetectors, and offer a simple, reliable, low-cost means of monitoring pulse rate noninvasively, both at rest and during exercise.

SUMMARY

[0004] During exercise and other activities, PPG and other sensors may experience movement, such as shifting position or rotating, relative to a sensing location (*e.g.*, wrist or

finger). The movement typically results in an introduction of a motion artifact in an electrical signal produced by the sensor. The motion artifact may be interpreted by a processor as a heart-related signal if not addressed in advance of or as part of the processing in the processor. By properly addressing the motion artifact, an embodiment disclosed herein has improved accuracy in reconstructing the heart-related signal, thereby enabling processes that use the heart-related signal to have better performance.

[0005] Accordingly, a method for reconstructing a heart-related signal output by a biomedical sensor may comprise reconstructing a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal. The reconstructing may be based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and the classification of the movement may be based on (ii) a classification of the movement. The method may further comprise outputting the reconstructed representation of the heart-related signal.

[0006] The motion artifacts may be suppressed in the reconstructed representation of the heart-related signal.

[0007] The time-varying spectral analysis may include pre-processing the heart-related signal to produce a pre-processed heart-related signal. In an event the classification indicates that the movement does not rise to a level causing the motion artifacts, the reconstructed representation may be based on an average value of peak-to-peak intervals in the pre-processed heart-related signal.

[0008] The pre-processing may include filtering the heart-related signal to produce a filtered heart-related signal.

[0009] The pre-processing may further include down-sampling the filtered heart-related signal, the down-sampling being at a sampling rate less than an original sampling rate.

[0010] The time-varying spectral analysis may include computing a first time-frequency spectrum (TFS) of the heart-related signal and computing a second TFS of the motion signal.

[0011] The first TFS computed and the second TFS computed may be 3-dimensional spectra, the first TFS computed and the second TFS computed each including a respective time-varying amplitude or power distribution with respect to time and frequency.

[0012] The first TFS computed may be a first time-varying power spectral density (PSD) and the second TFS computed may be a second time-varying PSD.

[0013] The reconstructed representation may be a current reconstructed representation. Based on the classification indicating that the movement does rise to a level causing the motion artifacts and is a pseudo-periodic movement or a periodic movement, the reconstructing may include determining whether at least one spectral peak is present having a corresponding frequency within a given frequency range at a point in time in the first TFS computed, the current reconstructed representation being reconstructed for the point in time. Based on a determination that the at least one spectral peak is not present, the current reconstructed representation may be based on a prior reconstructed representation, the prior reconstructed representation associated with a previous point in time in the first TFS computed. The given frequency range may be 0.5 Hz to 3 Hz.

[0014] The reconstructing may include retaining up to a pre-determined number of candidate spectral peaks located at a first point in time in the first TFS computed. The candidate spectral peaks retained may be based on having corresponding frequencies within a given frequency range and highest amplitude or power values relative to other spectral peaks located at the first point in time, the other spectral peaks having respective frequencies within the given frequency range. The reconstructing may further include discarding each of the candidate spectral peaks retained that is associated with a same frequency as a dominant spectral peak located at a second point in time in the second TFS computed. The first point in time and the second point time may have same time values. The given frequency range may be 0.5 Hz to 3 Hz.

[0015] The representation may be a current representation and the reconstructed representation may be a current reconstructed representation. In an event the discarding discards each of the candidate spectral peaks retained, reconstructing the current representation may be based on a prior reconstructed representation, the prior reconstructed representation associated with a previous point in time in the first TFS computed, the previous point in time being an earlier point in time with respect to the first point in time.

[0016] The discarding may be a first discarding, the representation may be a current representation and, in an event the first discarding results in at least one remaining candidate spectral peak retained, reconstructing the current representation may further include second discarding. The second discarding may discard remaining candidate spectral peaks, of the at least one remaining candidate spectral peak retained, based on whether a corresponding frequency of the at least one remaining candidate spectral peak retained is distanced by at least a frequency difference threshold from a prior reconstructed representation's frequency. The prior reconstructed representation associated with a previous point in time in the first TFS computed. The previous point in time may be an earlier point in time with respect to the first point in time.

[0017] Based on each of the at least one remaining candidate spectral peak retained having been discarded by the second discarding, reconstructing the current representation may be based on the prior reconstructed representation. Based on at least one last candidate spectral peak remaining, the at least one last candidate spectral peak remaining not discarded by the second discarding, reconstructing the current representation may be based on a selected candidate spectral peak. The selected candidate spectral peak may be selected from amongst the at least one last candidate spectral peak remaining having a closest corresponding frequency to the prior reconstructed representation's frequency relative to respective frequencies of each of the at least one last candidate spectral peak remaining.

[0018] The dominant spectral peak may have a largest power or amplitude value relative to other peaks located at the second point in time in the second TFS.

[0019] The retaining and the discarding may be based on the classification indicating that the movement is a pseudo-periodic movement or a periodic movement, and determining that at least one spectral peak with a corresponding frequency in the given frequency range is present at the first point in time.

[0020] The time-varying spectral analysis may further include pre-processing the heart-related signal and the motion signal for the computing of the first TFS and the second TFS.

[0021] The pre-processing may include filtering the heart-related signal and the motion signal to produce a filtered heart-related signal and a filtered motion signal, respectively. The pre-processing may further include down-sampling both the filtered heart-related signal and the

filtered motion signal, the down-sampling being at a sampling rate less than an original sampling rate.

[0022] The method may further include classifying the classification of the movement by comparing an amount of amplitude modulation in the second TFS computed to an amplitude modulation threshold. The amplitude modulation threshold may be dependent on a type of the motion detector sensor. The classification may indicate whether the movement rises to a level causing the motion artifacts based on a result of the comparing. In an event the result indicates that the movement does rise to the level causing the motion artifacts, classifying the classification of the movement may further include determining whether the movement is either a pseudo-periodic movement or a periodic movement, versus a random movement.

[0023] In determining whether the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement, the method may further include identifying a first, second, and third frequency associated, respectively, with a first, second, and third spectral peak in the second TFS at a point in time in the second TFS. The first, second, and third peaks may have largest power or amplitude values relative to other peaks in the second TFS at the point in time. The first spectral peak may be a largest spectral peak amongst the first, second, and third spectral peaks.

[0024] In determining whether the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement, the method may further include computing a first ratio of the second frequency identified to the first frequency identified. The method may determine a first comparison result by comparing the first ratio computed to a first ratio value. The method may compute a second ratio of the third frequency identified to the first frequency identified. The method may determine a second comparison result by comparing the second ratio computed to a second ratio value. The classification may further indicate the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement, based on the first comparison result and the second comparison result. The first ratio value may be 2 and the second ratio value may be 3.

[0025] The time-varying signal analysis may include pre-processing the heart-related signal to produce a pre-processed heart-related signal and, in an event the classification of the movement indicates the random movement, the reconstructing may include computing an

average value of a number of prior reconstructed representations outputted prior to the reconstructing. The number may be based on a duration of consecutive motion artifacts, detected prior to the reconstructing. The time-varying signal analysis may further include computing a bandpass filter cutoff frequency based on the average value computed, and filtering the pre-processed heart-rate signal by applying the band pass filter computed to produce a filtered, pre-processed heart-related signal. The reconstructed representation may be based on an average peak-to-peak interval value of the filtered, pre-processed heart-rate signal.

[0026] The heart-related signal and the motion signal may be produced, concurrently.

[0027] The method may comprise segmenting the heart-related signal into a plurality of windowed heart-related signal data segments and segmenting the motion signal into a corresponding plurality of windowed motion signal data segments. The method may comprise repeating the reconstructing and the outputting for each windowed heart-related signal data segment and each corresponding motion signal data segment. The time window may be a value in a range from 2 to 32 seconds.

[0028] The biomedical sensor may be at least one of: a photoplethysmogram (PPG) sensor, piezoelectric sensor, Light Emitting Diode (LED) based sensor, camera sensor, and pulse oximeter sensor, and the motion sensor may be an accelerometer.

[0029] The biomedical sensor and the motion sensor may be co-located.

[0030] The method may further comprise employing the reconstructed representation to determine a heart rate estimate.

[0031] The method may further comprise employing the reconstructed representation to determine an arterial oxygen saturation (SpO2) estimate.

[0032] The method may further comprise employing the reconstructed representation to detect or predict a heart-related ailment. The heart-related ailment may include at least one of a heart rate variability (HRV) condition, atrial fibrillation condition, congestive heart failure condition, and tachycardia condition.

[0033] The reconstructing and the outputting may be performed in real-time with respect to production of the heart-related signal and the motion signal.

[0034] The reconstructing and the outputting may be performed in non-real-time with respect to production of the heart-related signal and the motion signal.

[0035] According to another embodiment, an apparatus for reconstructing a heart-related signal output by a biomedical sensor may comprise a reconstruction unit. The reconstruction unit may be configured to reconstruct a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal, the reconstructing based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of the movement. The apparatus may further comprise an output unit configured to output the reconstructed representation of the heart-related signal.

[0036] Yet another example embodiment may include a non-transitory computer-readable medium having stored thereon a sequence of instructions which, when loaded and executed by a processor, causes the processor to complete methods disclosed herein.

[0037] It should be understood that embodiments disclosed herein can be implemented in the form of a method, apparatus, system, or computer readable medium with program codes embodied thereon.

BRIEF DESCRIPTION OF THE DRAWINGS

[0038] The patent or application file contains at least one drawing executed in color. Copies of this patent or patent application publication with color drawing(s) will be provided by the Office upon request and payment of the necessary fee.

[0039] The foregoing will be apparent from the following more particular description of example embodiments of the invention, as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating embodiments of the present invention.

[0040] FIG. 1 is a block diagram of an example application for which embodiments disclosed herein may be applied.

[0041] FIG. 2 is a flow diagram of an example embodiment of a method for reconstructing a heart-related signal output by a biomedical sensor.

[0042] FIGS. 3A-C are flow diagrams of example embodiments of a method for reconstructing a heart-related signal output by a biomedical sensor.

[0043] FIG. 4 is a block diagram of an example embodiment of a system.

[0044] FIG. 5 is a block diagram of an example embodiment of an apparatus for reconstructing a heart-related signal output by a biomedical sensor.

[0045] FIGS. 6A-6C show Time-Frequency spectra of a recording from a dataset.

[0046] FIG. 7 is a filtered time-frequency spectral plot of a photoplethysmogram (PPG) signal.

[0047] FIGS. 8A-8B show motion artifact detection in a PPG spectrum according to embodiments disclosed herein.

[0048] FIG. 9 shows a comparison of reconstructed heart rate (HR) obtained, according to embodiments disclosed herein, to reference HR obtained from simultaneous electrocardiogram (ECG) recordings.

[0049] FIG. 10A is an example embodiment of PPG signal reconstruction according to embodiments disclosed herein.

[0050] FIG. 10B is a zoomed-in version of FIG. 10A.

[0051] FIGS. 11A-B show comparisons of heart rate variability (HRV) spectra between a reference and a reconstructed HRV time series (*e.g.*, as shown in FIGS. 10A-B) from a motion artifact-contaminated PPG signal for a given dataset.

[0052] FIG. 11C is a performance comparison table of a spectral approach for filtering motion artifacts (SpaMA) method to alternative methods.

[0053] FIGS. 12A, 12B, 13A, 13B, 14A, and 14B show the reconstructed HR and corresponding power spectral density (PSD) of a sample-sample windowed HR, according to embodiments disclosed herein, in comparison to a reference HR from an ECG.

[0054] FIG. 14C is a table that includes PPG datasets and experiments settings.

[0055] FIGS. 15A-B show an example resultant variable frequency complex demodulation (VFCDM) time-frequency spectrum of recordings from a given subject.

[0056] FIG. 16 shows twelve components corresponding to the Infrared (IR) and Red signal for the given subject.

[0057] FIGS. 17A-C are example spectra plots corresponding to three scenarios.

[0058] FIG. 18A shows a representative filtered time-frequency spectral plot of PPG recording from subject #5.

[0059] FIG. 18B shows tracking of HR based on embodiments disclosed herein.

[0060] FIGS. 19A-B represent comparisons of an estimated 8 second moving average HR from a spectral approach for filtering motion artifacts for oxygen saturation estimation (OxiMA) method to a reference HR, and an HR calculated from a motion-corrupted PPG signal compared to a reference HR from an ECG, respectively.

[0061] FIGS. 20A-C are example plots of data showing less motion-corrupted data that can be used for oxygen saturation estimation.

[0062] FIGS. 21A-C and FIGS. 22A-B show reconstructed arterial oxygen saturation (SpO2) and HR in comparison to the reference HR from ECG recordings for the given subject.

[0063] FIG. 23 is a block diagram of an example internal structure of a computer optionally within an embodiment disclosed herein.

DETAILED DESCRIPTION

[0064] A description of example embodiments of the invention follows.

[0065] Accurate estimation of a heart rate (HR) and changing arterial oxygen saturation (SpO2) from a heart-related signal, such as a photoplethysmogram (PPG) signal, during intense physical activity is a very challenging problem. This is because strenuous and high intensity exercise can result in severe motion artifacts (MAs) in the heart-related signal, making accurate HR and SpO2 estimation difficult.

[0066] HR monitoring using PPG signals has many advantages compared to using traditional ECG sensors, such as simpler hardware implementation, lower cost, and no need for daily application of electrodes (Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263). Fluctuations of the PPG signal are caused by changes in arterial blood volume associated with each heartbeat, where the magnitude of the fluctuations depends on the amount of blood rushing into the peripheral vascular bed, the optical absorption of the blood, skin, and tissue, and the wavelength used to illuminate the blood. The pulse oximeter signal contains not only the

blood oxygen saturation and heart rate (HR) data, but also other vital physiological information (Chon, K.H., S. Dash, and J. Kihwan, Estimation of Respiratory Rate From Photoplethysmogram Data Using ~~Time–Frequency~~ Time-Frequency Spectral Estimation. Biomedical Engineering, IEEE Transactions on, 2009. 56(8): p. 2054-2063; Lee, J. and K.H. Chon, Respiratory Rate Extraction Via an Autoregressive Model Using the Optimal Parameter Search Criterion. Annals of Biomedical Engineering, 2010. 38(10): p. 3218-3225; Dash, S., et al., Estimation of Respiratory Rate From ECG, Photoplethysmogram, and Piezoelectric Pulse Transducer Signals: A Comparative Study of ~~Time–Frequency~~ Time-Frequency Methods. Biomedical Engineering, IEEE Transactions on, 2010. 57(5): p. 1099-1107; Jinseok, L. and K.H. Chon, Time-Varying Autoregressive Model-Based Multiple Modes Particle Filtering Algorithm for Respiratory Rate Extraction From Pulse Oximeter. Biomedical Engineering, IEEE Transactions on, 2011. 58(3): p. 790-794). The fluctuations of PPG signals contain the influences of arterial, venous, autonomic and respiratory systems on the peripheral circulation. Utilizing a pulse oximeter as a multi-purpose vital sign monitor has clinical appeal, since it is familiar to the clinician and comfortable for the patient (Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263). Even simple knowledge of HR patterns would provide more useful clinical information than just HR and blood oxygenation, especially in situations in which a pulse oximeter is the sole monitor available. One major example of such benefits can be seen in a study by Chong et al. which shows that accurate detection of atrial fibrillation can be obtained from PPG data (Jo Woon, C., et al., Arrhythmia Discrimination Using a Smart Phone. Biomedical and Health Informatics, IEEE Journal of, 2015. 19(3): p. 815-824). In addition to the acquisition of HR in response to exercise, research has recently focused on obtaining HRV information from wearable sensors including devices that use PPGs (Achten, J. and A.E. Jeukendrup, Heart rate monitoring: applications and limitations. Sports medicine (Auckland, N.Z.), 2003. 33(7): p. 517-538). Increased HRV has been associated with lower mortality rates and is affected by both age and sex (Achten, J. and A.E. Jeukendrup, Heart rate monitoring: applications and limitations. Sports medicine (Auckland, N.Z.), 2003. 33(7): p. 517-538). During graded exercise, the majority of studies show that HRV decreases progressively up

to moderate intensities, after which it stabilizes (Laughlin, M.H., Cardiovascular response to exercise. Am J Physiol, 1999. 277(6 Pt 2): p. S244-59). Although there are many promising and attractive features of using pulse oximeters for vital sign monitoring, currently they are mainly used on stationary patients. This is because motion artifacts (MAs) result in unreliable HR and SpO_2 estimation (Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263). Clinicians have cited motion artifacts in pulse oximetry as the most common cause of false alarms, loss of signal, and inaccurate readings (Jubran, A., Pulse oximetry. Crit Care, 1999. 3(2): p. R11-r17). During physical activities, MA contamination in PPG signals seriously interferes with HR estimation. The MAs are mainly caused by ambient light leaking into the gap between the PPG sensor surface and skin surface. Besides, the change in blood flow due to movements is another MA source (Maeda, Y., M. Sekine, and T. Tamura, Relationship between measurement site and motion artifacts in wearable reflected photoplethysmography. J Med Syst, 2011. 35(5): p. 969-76). In practice, MAs are difficult to remove because they do not have a predefined narrow frequency band and their spectrum often overlaps that of the desired signal (Thakor, N.V. and Y.S. Zhu, Applications of adaptive filtering to ECG analysis: noise cancellation and arrhythmia detection. IEEE Trans Biomed Eng, 1991. 38(8): p. 785-94). Consequently, development of methods capable of reconstructing the corrupted signal and removing artifacts is challenging. There are a number of general techniques used for artifact detection and removal. One of the methods used to remove motion artifacts is adaptive filtering (Diniz, P., Adaptive filtering: algorithms and practical implementation. 2008: . Springer Science, Business Media L.L.C., Kalman, R.E., A New Approach to Linear Filtering and Prediction Problems Transactions of the ASME – Journal of Basic Engineering, 1960. Series D(82); Morbidi, F., et al., Application of Kalman Filter to Remove TMS-Induced Artifacts from EEG Recordings. Control Systems Technology, IEEE Transactions on, 2008. 16(6): p. 1360-1366; Seyedtabaii, S.S.a.L., Kalman filter based adaptive reduction of motion artifact from photoplethysmographic signal. World Academy of Science, Engineering and Technology, 2008. 37). An adaptive filter is easy to implement and it also can be used in real-time applications, though the requirement of additional sensors to provide reference inputs is the major drawback of such methods. There are many

motion and noise artifact reduction techniques based on the concept of blind source separation (BSS). The aim of BSS is to estimate a set of uncorrupted signals from a set of mixed signals which is assumed to contain both the clean and noisy sources (Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263). Some of the popular BSS techniques are independent component analysis (ICA) (Comon, P., Independent component analysis, A new concept? Signal Processing, 1994. 36(3): p. 287-314), canonical correlation analysis (CCA) (Thompson, B., Canonical Correlation Analysis: Uses and Interpretation. 1984: SAGE Publications), principle component analysis (PCA) (Jolliffe, I.T., Principal Component Analysis. 2 ed. Springer Series in Statistics. 2002: Springer-Verlag New York. 488), and singular spectrum analysis (SSA) (Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263; Elsner, J.B. and A.A. Tsonis, Singular Spectrum Analysis: A New Tool in Time Series Analysis. 1996: Springer). Kim and Yoo (Kim, B.S. and S.K. Yoo, Motion artifact reduction in photoplethysmography using independent component analysis. IEEE Trans Biomed Eng, 2006. 53(3): p. 566-8) suggested using a basic ICA method and block interleaving to remove MA. Krishnan et al. (Krishnan, R., B. Natarajan, and S. Warren, Two-Stage Approach for Detection and Reduction of Motion Artifacts in Photoplethysmographic Data. Biomedical Engineering, IEEE Transactions on, 2010. 57(8): p. 1867-1876) later proposed using frequency-domain-based ICA. However, the key assumption in ICA, namely statistical independence or uncorrelation, does not hold in PPG signals contaminated by MA (Yao, J. and S. Warren, A short study to assess the potential of independent component analysis for motion artifact separation in wearable pulse oximeter signals. Conf Proc IEEE Eng Med Biol Soc, 2005. 4: p. 3585-8). Salehizadeh et al. (Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263) proposed a motion artifact removal method using SSA. In Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II:

Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263, SSA is used to decompose the corrupted segment adjacent to the clean segment and the SSA components are chosen in the corrupted segment that have a similar frequency range to that of the adjunct clean components. Although Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263 reports good performance, the method cannot be applied in scenarios where the HR and SpO_2 are varying rapidly due to corruption and movement. Acceleration data are also shown to be helpful to remove MA. For example, Fukushima et al. (Fukushima, H., et al., Estimating heart rate using wrist-type Photoplethysmography and acceleration sensor while running. Conf Proc IEEE Eng Med Biol Soc, 2012. 2012: p. 2901-4) suggested a spectral subtraction technique to remove the spectrum of acceleration data from that of a PPG signal. Acceleration data can be also used to reconstruct the observation model for Kalman filtering (Boreom Lee, J.H., Hyun Jae Baek, Jae Hyuk Shin, Kwang Suk Park and Won Jin Yi, Improved elimination of motion artifacts from a photoplethysmographic signal using a Kalman smoother with simultaneous accelerometry. Physiological Measurement, 2010. 31(12): p. 1585) to remove MA.

[0067] Two noteworthy methods are TROIKA and JOSS (Zhilin, Z., P. Zhouyue, and L. Benyuan, TROIKA: A General Framework for Heart Rate Monitoring Using Wrist-Type Photoplethysmographic Signals During Intensive Physical Exercise. Biomedical Engineering, IEEE Transactions on, 2015. 62(2): p. 522-531; Zhang, Z., Photoplethysmography-Based Heart Rate Monitoring in Physical Activities via Joint Sparse Spectrum Reconstruction. Biomedical Engineering, IEEE Transactions on, 2015. PP(99): p. 1-1) in which sparsity-based spectrum estimation and spectral peak tracking with verification, are used to estimate and monitor heart rate during intensive physical activity, respectively. Both approaches make use of PPG and accelerometer information to obtain an accurate estimation of heart rate while running on a treadmill. TROIKA has two extra stages of signal decomposition and reconstruction using singular spectrum analysis (SSA) and then applies temporal difference operations on the SSA-reconstructed PPG. SSA components are compared to the accelerometer signals and those components with close frequencies to the accelerometer signals are discarded and the rest are used to reconstruct the signal. In JOSS and TROIKA, spectral peak tracking with verification

aims to select the spectral peaks corresponding to HR. JOSS, which has been shown to estimate HR more accurately than TROIKA, is based on the idea that the spectra of PPG signals and simultaneous acceleration signals have some common spectrum structures, and, thus, formulates the spectrum estimation of these signals into a joint sparse signal recovery model using the multiple measurement vector (MMV) model. MMV is used for joint spectrum estimation based on PPG and accelerometer data, which is in contrast to the single measurement vector (SMV) model that was used in TROIKA and was based on only a single PPG signal. Although JOSS has been shown to be much more accurate than previous methods for reconstruction of heart rate from MA-contaminated PPG signals, the main disadvantage of the method is it can merely provide smoothed HR reconstruction estimations. Neither time-domain PPG signal reconstruction nor heart rate variability analysis can be done using JOSS or TROIKA. Temko proposed an approach to HR estimation based on Wiener Filtering and the Phase Vocoder (WFPV) (Temko, A. Estimation of Heart Rate from Photoplethysmography during Physical Exercise using Wiener Filtering and the Phase Vocoder. in IEEE EMBS International Conference on Engineering in Medicine and Biology. 2015. Milan, Italy: IEEE). This work showed that WFPV on average can perform better than JOSS. The main idea of WFPV is to estimate motion artifacts from accelerometer signals and then use a Weiner filter to attenuate the motion components in the PPG signal. Phase vocoder is also applied to overcome the limited resolution of the Fourier transform and to refine the initial dominant frequency estimation.

[0068] According to embodiments disclosed herein, a motion-corrupted heart-related signal, such as a PPG signal, may be reconstructed by employing a method that is based on a time-varying spectral analysis. A method for reconstructing a heart-related signal based on the time-varying spectral analysis for HR estimation may be referred to interchangeably herein as a spectral approach for filtering motion artifacts (SpaMA) method or SpaMA. A method for reconstructing the heart-related signal based on the time-varying spectral analysis for SpO2 estimation may be referred to interchangeably herein as a spectral approach for filtering motion artifacts for oxygen saturation estimation (OxiMA) method or OxiMA.

[0069] FIG. 1 is a block diagram 100 of an example application for which embodiments disclosed herein may be applied. In FIG. 1, a subject 102 is running on a treadmill 104. The subject 102 is wearing a wrist band 106 that includes a biomedical sensor 108 that produces a

heart-related signal 110. The heart-related signal 110 that is produced by the biomedical sensor 108 includes motion artifacts that are signal artifacts produced by movement of the biomedical sensor 108 relative to a sensing location (not shown). The wrist band 106 may be any suitable type of wrist band, for example, the wrist band 106 may be a smart watch.

[0070] The biomedical sensor 108 may be a PPG sensor, or any other suitable biomedical sensor, and the heart-related signal 110 may be a PPG signal, or any other suitable heart-related signal. The sensing location may a skin surface of an area on the subject's wrist where the wrist band 106 is worn, or any other suitable sensing location at which the biomedical sensor 108 senses the heart-related signal 110. For example, the sensing location may be a skin surface on the subject's forehead, and a head band including the biomedical sensor 108 or maintain the biomedical sensor 108 at the sensing location may be used instead of the wrist band 106.

[0071] Physical activity of the subject 102 may cause movement of the wrist band 106, and, thus, movement of the biomedical sensor 108, resulting in a gap between the PPG sensor and the sensing location. Ambient light may leak into the gap inducing spectrum corruption in the PPG signal. This is because the power of the PPG signal is dependent on a depth and reflection of the PPG light from the PPG sensor to the subject's skin. As such, strenuous and high intensity exercise of the subject 102, such as running or any other suitable activity, may result in movement that rises to a level causing motion artifacts in the heart-related signal 110. According to embodiments disclosed herein, the heart-related signal 110 may be reconstructed 112, producing a reconstructed heart-related signal with the motion artifacts suppressed 114. The reconstructed heart-related signal with the motion artifacts suppressed 114 may be used to accurately estimate HR, SpO2, or any other suitable heart-related estimate. As such, the reconstructed heart-related signal may be employed to detect or predict a heart-related ailment. The heart-related ailment may include at least one of a heart rate variability (HRV) condition, atrial fibrillation condition, congestive heart failure condition, and tachycardia condition.

[0072] It should be understood that the PPG sensor is one example of a biomedical sensor, the PPG signal is one example of a heart-related signal, and that any suitable type of biomedical sensor may be employed to produce any suitable type of a heart-related signal. Further, movement of the biomedical sensor 108 relative to the sensing location may be caused by any suitable source of the movement that causes movement of the biomedical sensor 108 relative to

the sensing location. It should also be understood that a subject referred to herein may be any living being, such as a person or an animal, and may be referred to interchangeably herein as a user.

[0073] FIG. 2 is a flow diagram 200 of an example embodiment of a method for reconstructing a heart-related signal output by a biomedical sensor. The example embodiment of the method of FIG. 2 may be applied to either SpaMA or OxiMA and may be applied to other applications that produce a heart-related estimate. The method may start (202) and reconstruct a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal. The reconstructing may be based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of movement (204). The method may output the reconstructed representation of the heart-related signal (206), and the method thereafter ends (208) in the example embodiment.

[0074] The method may comprise segmenting the heart-related signal into a plurality of windowed heart-related signal data segments and the motion signal into a corresponding plurality of windowed motion signal data segments and repeating the reconstructing and the outputting for each windowed heart-related signal data segment and each corresponding motion signal data segment. The time window may be a value in a range from 2 to 32 seconds. For example, the *window[k]* of raw PPG data of FIG. 3A, element 304, disclosed below, and the *window[k]* of raw accelerometer data shown in FIG. 3A, element 310, disclosed below, may each include data from the respective PPG and accelerometer signals that may be collected over a time window from 2 to 32 seconds. According to one embodiment, the time window may be 8 seconds.

[0075] The method may employ the reconstructed representation to determine a heart rate estimate. The method may employ the reconstructed representation to determine an arterial oxygen saturation (SpO2) estimate. The method may employ the reconstructed representation to detect or predict a heart-related ailment. The heart-related ailment may include at least one of a heart rate variability (HRV) condition, atrial fibrillation condition, congestive heart failure condition, and tachycardia condition.

[0076] The heart-related signal and the motion signal may be produced, concurrently.

[0077] According to some embodiments, the biomedical sensor may be at least one of: a photoplethysmogram (PPG) sensor, piezoelectric sensor, Light Emitting Diode (LED) based sensor, camera sensor, and pulse oximeter sensor. The motion sensor may be an accelerometer, or any other suitable device that produces a motion signal. If an accelerometer, the accelerometer may be a 3-axial type accelerometer, or any other suitable type of accelerometer. The biomedical sensor and the motion sensor may be co-located. For example, the wrist band 106 of FIG. 1, disclosed above, may be a smartwatch and the biomedical sensor and motion sensor may be a PPG sensor and an accelerometer, respectively, that are both disposed in the smartwatch or other suitable wearable device.

[0078] FIGS. 3A-C are flow diagrams of example embodiments of a method for reconstructing a heart-related signal output by a biomedical sensor based on embodiments disclosed in Tables 1-3, disclosed below. The method may be either a SpaMA or OxiMA method.

Table 1. Stages 1 and 2

Stage 1. Time-Varying Spectral analysis (*see* FIG. 3A)

1.1. Filter the PPG and Accelerometer signal with cutoff frequency [1, 50]/Fs/2 Hz.
1.2. Down sample the PPG and Accelerometer signal to ¼ of original sampling rate (Fs).
1.3. Compute the time frequency spectrum of both PPG and Accelerometers [0-10 Hz].

Stage 2. Movement Classification (*see* FIG. 3A)

2.1. Check each accelerometer (X, Y or Z) amplitude modulation at each window and compare to a pre-defined motion amplitude threshold. (The threshold varies depending on the type of accelerometer sensor).

Signal is clean if $AM[Acc_{x\ or\ y\ or\ z}(k)] < Motion\_Threshold$ and the signal is corrupted by motion otherwise. If the signal is clean calculate the Heart Rate from peak-to-peak intervals, otherwise go to step 2.2.

2.2. If the signal is corrupted check if the movement is pseudo-periodic (e.g. during walk, jog, run) or non-periodic (e.g. any random movements)

The assumption is when movement is pseudo-periodic the accelerometer data should comprised of a fundamental frequency component and harmonics of the fundamental frequency at its double and third frequency band. This means the ratio of the first harmonic to the fundamental frequency should be almost 2 and the second harmonic to the fundamental should be around 3.

2.2.1. Extract the fundamental frequency component, the 1st and 2nd harmonics from (*e.g.*,VFCDM) time-frequency spectrum of accelerometers. The first three highest peaks in spectral array should represent the fundamental, 1st and 2nd harmonics as long as the movement is pseudo-periodic.

2.2.2. Calculate the ratio of the extracted 1st and 2nd fundamental frequency to the extracted fundamental frequency. If the ratios are close to 2 and 3, this indicates that the movement is most likely pseudo-periodic otherwise it is non-periodic.

2.2.3. If the movement is pseudo-periodic do the Stages 3-5 (*See* Table 2 and FIG. 3B), otherwise go to Stage 6 (*See* Table 3 and FIG. 3C).

Table 2. Stages 3-5

Stage 3. Spectral Filtering (*see* FIG. 3B)

3.1. Assume HR to be in the frequency range of [0.5Hz – 3Hz], this accounts for both low and high heart rates.
3.2. The first highest three peaks and their corresponding frequencies in the PPG filtered spectrum are assumed to have HR information.
3.3. Only the largest frequency peak (that represents the fundamental frequency of movement) of the accelerometers' spectra is used for motion artifact detection in Stage 4.

Stage 4. Motion Artifact Detection (*see* FIG. 3B)

4.1. Compare the frequencies of the three peaks in the PPG spectrum with the frequency of the largest peak in the accelerometers' spectra. If the first or second largest peaks in the PPG spectrum are similar to that of the accelerometers' peaks, then motion artifact is present in the PPG.
4.2. If motion artifact is detected from 3.1, then the corresponding frequency peak (usually the first or second largest peak) in the PPG spectrum should be discarded.

Stage 5. Heart Rate Tracking and Extraction from PPG Spectrum (*see* FIG. 3B)

Case (1): From 3.1- if the spectrum is corrupted by movement and only the first largest peak is corrupted, then the HR frequency should be the frequency of the second peak in the spectrum.
Case (2): From 3.1- if the spectrum is corrupted by movement and both the first and second largest peaks have similar frequencies to those of the accelerometers' peaks, then the HR frequency should be the frequency of the third peak in the spectrum.
Case (3): Due to a gap between the pulse oximeter and a subject's skin, the HR frequency cannot be extracted from the spectrum and in this case the previous HR frequency is used or for offline implementation a cubic spline interpolation can be applied to fill in the missing HR information.

Table 3. Stage 6

Stage 6. Adaptive Bandpass Filtering (non-periodic movements) (*see* FIG. 3C)

When the movement is random and non-periodic it is difficult or not possible to identify HR trace from time-frequency spectrum (for example if stage 5 is not applicable). In this case which may happen more often, a new procedure is adopted that is called adaptive bandpass filtering. The assumption here is that HR does not deviate more than 10 bpm from the average of previous m HR values within 2 seconds.

6.1. Set averaging window length to m (e.g. m=5) and calculate the average of recent m estimated HR values.

$$HR_{mavg} = \frac{1}{m}\sum_{j=1}^{m} HR(k-j)$$

Where k is the current window. The window length m=5 should only be used for up to 10 seconds of consecutive motion artifact corrupted datapoints. If motion corrupted data last more than 10 seconds, m should be increased to more than 5.

6.2. Take the most recent estimated HR value and calculate bandpass filter cutoff frequency.

$$F_{CutOff} = [HR_{mavg} - 10, HR_{mavg} + 10\ ]/60/Fs/2$$

Design a bandpass filter of order 4 with cutoff frequency (F_{CutOff}). Apply the filter on the PPG segment.

6.3. Calculate HR from peak-to-peak intervals of the filtered data segment obtained from 6.2. Take the average of the instantaneous HR as estimated HR value at window k.

[0079] FIG. 3A is a flow diagram (300) of an example embodiment of a method for a time-varying spectral analysis and movement classification, as disclosed in Stage 1 (time-varying spectral analysis) and Stage 2 (movement classification), respectively, in Table 1, for reconstructing the representation. The method may start (302) and the time-varying spectral analysis may be employed on a first windowed segment *window[k]* of raw PPG data (304) and a second windowed segment *window [k]* of raw accelerometer (ACC) data (310). The raw PPG data (304) and the raw ACC data (310) may be extracted from a heart-related signal that is a PPG signal and a motion signal that is an accelerometer signal, respectively.

[0080] As disclosed in Stage 1 of Table 1, the time-varying spectral analysis of FIG. 3A may include pre-processing the heart-related signal (306) to produce a pre-processed heart-related signal. The pre-processing (306) may include filtering the heart-related signal to produce a

filtered heart-related signal. The pre-processing (306) may further include down-sampling the filtered heart-related signal, the down-sampling being at a sampling rate less than an original sampling rate, to produce a down-sampled, filtered heart-rate signal. The time-varying spectral analysis may further include pre-processing the motion signal (312) to produce a pre-processed motion signal. The pre-processing (312) may include filtering the motion signal to produce a filtered motion signal. The pre-processing (312) may further include down-sampling the filtered motion signal, the down-sampling being at a sampling rate less than an original sampling rate, to produce a down-sampled, filtered motion signal.

[0081] As further disclosed in Stage 1 of Table 1, the time-varying spectral analysis of FIG. 3A may include computing a first time-frequency spectrum (TFS) to produce a first TFS (308) of the down-sampled, filtered heart-related signal and computing a second TFS to produce a second TFS (314) of the down-sampled, filtered motion signal. According to some embodiments, filtering and down-sampling of the heart-related signal and motion signal for computing the first TFS (308) and the second TFS (314), respectively, may be optional. The first TFS (308) (also referred to interchangeably herein as the first TFS computed) and the second TFS (314) (also referred to interchangeably herein as the second TFS computed) may be 3-dimensional spectra, the first TFS computed and the second TFS computed each including a respective time-varying amplitude or power distribution with respect to time and frequency.

[0082] For example, the first TFS computed may be a first time-varying power spectral density (PSD) and the second TFS computed may be a second time-varying PSD. A time-frequency technique, such as a variable frequency complex demodulation (VFCDM), disclosed in U.S. Patent No. 8,388,543 B2, incorporated herein in its entirety by reference, may be used for computing the first TFS (308), that is, a TFS of the PPG signal, and the second TFS (314), that is, a TFS of the accelerometer signal. However, it should be understood that any suitable time-frequency technique may be used, such as a smoothed pseudo wigner-ville method, or a wavelet based method.

[0083] As disclosed in Stage 2 of Table 1, classifying the classification of the movement (316) in FIG. 3A may include comparing an amount of amplitude modulation in the second TFS (314) computed to an amplitude modulation threshold. The amplitude modulation threshold may be dependent on a type of the motion detector sensor, such as a type of the accelerometer. The

classification of the movement may indicate whether the movement rises to a level causing motion artifacts in the heart-related signal, that is, the PPG signal, based on a result of the comparing, as disclosed in Stage 2 of Table 1.

[0084] In an event the movement classification (316) of FIG. 3A indicates that the movement does not rise to a level causing the motion artifacts (322), a peak-peak interval (PP) of the filtered heart-related signal, or alternatively, the filtered, down-sampled heart-rate signal, may be computed (318) and the reconstructed representation *HR(k)* may be based on an average value of peak-to-peak intervals (320) in the pre-processed heart-related signal, and the method thereafter ends (325) in the example embodiment.

[0085] In an event the movement classification (316) indicates that the movement does rise to the level causing the motion artifacts (323), classifying the classification of the movement may further include determining (324) whether the movement is either a pseudo-periodic movement or a periodic movement, versus a random movement, as disclosed in Stage 2 of Table 1.

[0086] With reference to Stage 2 of Table 1, in determining whether the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement, the method may further include identifying a first, second, and third frequency associated, respectively, with a first, second, and third spectral peak in the second TFS at a point in time in the second TFS. The first, second, and third peaks may have largest power or amplitude values relative to other peaks in the second TFS at the point in time. The first spectral peak may be a largest spectral peak amongst the first, second, and third spectral peaks.

[0087] In determining whether the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement, the method may compute a first ratio of the second frequency identified to the first frequency identified. The method may determine a first comparison result by comparing the first ratio computed to a first ratio value. The method may compute a second ratio of the third frequency identified to the first frequency identified and determine a second comparison result by comparing the second ratio computed to a second ratio value. The classification may further indicate the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement, based on the first comparison result and the second comparison result. The first ratio value may be 2 and the

second ratio value may be 3. The classification of the movement may be periodic if the first ratio and the second ratio are exactly 2 and 3, respectively, while the classification of the movement may be pseudo-periodic if the first ratio and the second ratio are approximately 2 and 3, respectively, within a pre-determined level of accuracy.

[0088] In an event the classification of the movement is periodic or pseudo-periodic, the method of FIG. 3A may continue with the method of FIG. 3B, disclosed below. In an event the classification of the movement is random, the method of FIG. 3A continues to the method of FIG. 3C, disclosed below.

[0089] FIG. 3B is a flow diagram (330) of an example embodiment of a method for spectral filtering, motion artifact detection, and heart rate tracking and extraction, as disclosed in Stages 3, 4, and 5, respectively, of Table 2, for reconstructing the representation. The reconstructed representation may be referred to herein as a current reconstructed representation or *HR(k)*. As disclosed above with regard to FIG. 3A, in an event the classification of the movement (316) is periodic or pseudo-periodic, the method of FIG. 3A may continue with the method of FIG. 3B.

[0090] The method of FIG. 3B may start (331) and retain (332) up to a pre-determined number *N* of candidate spectral peaks located at a first point in time in the first TFS, that is, the first TFS from FIG. 3A. It should be understood that the method of FIG. 3B may be performed for each point in time of the first TFS and the second TFS. According to one embodiment, the pre-determined number *N* may be 3. The candidate spectral peaks retained may be based on having corresponding frequencies within a given frequency range. The candidate spectral peaks may be *N* peaks in the given frequency range that have highest amplitude or power values relative to other spectral peaks, that is, the first *N* highest peaks. It should be understood that the other spectral peaks have respective frequencies also within the given frequency range and are peaks located at the first point in time in the first TFS. The given frequency range may be 0.5 Hz to 3 Hz. As such, the *N* first highest peak in the range 0.5 Hz to 3 Hz in the first TFS may be retained at the first time point. Since no peaks in the given frequency range may be present at the first time point, the method may determine (336) whether at least one spectral peak is present.

[0091] Based on the determination (336) that no peak is present, the current reconstructed representation *HR(k)* may be based on a prior reconstructed representation *HR(k-1)* (340), the

prior reconstructed representation *HR(k-1)* associated with a previous point in time, such as the previous window *k-1*, in the first TFS computed, and the method thereafter ends (354) in the example embodiment.

[0092] Based on a determination (336) that the at least one spectral peak is present, the method may discard (338) each of the candidate spectral peaks retained, that is, each peak of the *N* first highest peaks determined at (332), if the peak is associated with a same frequency as a dominant spectral peak located at a second point in time in the second TFS (314) computed as disclosed above with regard to FIG. 3A. The first point in time and the second point time may have same time values. The dominant spectral peak may have a largest power or amplitude value relative to other peaks located at the second point in time in the second TFS. The method may determine (342) whether any peaks are retained after the discarding (338). The discarding (338) may be referred to herein as a first discarding.

[0093] In an event the discarding (338) discards each of the candidate spectral peaks retained, reconstructing the current representation *HR(k)* may be based on the prior reconstructed representation, *HR(k-1)* (340), and the method thereafter ends (354) in the example embodiment.

[0094] In an event the first discarding (338) results in at least one remaining candidate spectral peak retained, reconstructing the current representation may further include second discarding (348). The second discarding (348) may discard remaining candidate spectral peaks, of the at least one remaining candidate spectral peak retained, based on whether a corresponding frequency of the at least one remaining candidate spectral peak retained is distanced (346) by at least a frequency difference threshold, such as 10bpm, from a prior reconstructed representation's frequency, that is, a frequency associated with, for example, *HR(k-1)*.

[0095] Based on each at least one remaining candidate spectral peak retained having been discarded by the second discarding (348), reconstructing the current representation may be based on the prior reconstructed representation *HR(k-1)* (350), and the method thereafter ends (354) in the example embodiment.

[0096] Based on at least one last candidate spectral peak remaining from the second discarding (348), reconstructing the current representation may be based on a selected candidate spectral peak (352). The selected candidate spectral peak may be selected from amongst the at least one last candidate spectral peak remaining having a closest corresponding frequency to the

prior reconstructed representation's frequency relative to respective frequencies of each of the at least one last candidate spectral peak remaining, and the method thereafter ends (354) in the example embodiment.

[0097] As disclosed above with regard to FIG. 3A, in an event the classification of the movement (316) is random, the method of FIG. 3A may continue with the method of FIG. 3C.

[0098] FIG. 3C is a flow diagram (330) of an example embodiment of a method for adaptive bandpass filtering of non-periodic movements, that is, random movements, for reconstructing the representation, as disclosed in Stage 6 of Table 3. The method of FIG. 3C may start (362) and compute an average value of a number *m* of prior reconstructed representations outputted prior to the reconstructing (362). The number *m* may be based on a duration of consecutive motion artifacts, detected prior to the reconstructing of the representation $HR(k)$. For example, if motion artifacts were detected for windows *k-1*, *k-2*, and *k-3*, *m* may be understood to be 3.

[0099] The method may compute a bandpass filter cutoff frequency (366). The cutoff frequency F_c may be based on the average value computed HR_{mavg}. The method may filter the pre-processed heart-rate signal (306), disclosed in FIG. 3A, above, by applying the band pass filter computed (368) to produce a filtered, pre-processed heart-related signal. The reconstructed representation *HR(k)* may be based on an average peak-to-peak interval value (372) of the filtered, pre-processed heart-rate signal, and the method thereafter ends (374) in the example embodiment.

[00100] FIG. 4 is a block diagram of an example embodiment of a system (400). The system includes an apparatus 420 for reconstructing a heart-related signal 410c output by a biomedical sensor (not shown). The apparatus 420 includes a reconstruction unit 416 and an output unit 418. The reconstruction unit 416 may be configured to produce a reconstructed representation of the heart-related signal 414c. The reconstructing may be based on (i) a time-varying spectral analysis of the heart-related signal 410c and a motion signal 411c, the motion signal 411c output by a motion sensor (not shown) and representative of motion artifacts in the heart-related signal 410c, the motion artifacts being signal artifacts produced by movement of the biomedical sensor (not shown) relative to a sensing location (not shown), and (ii) a classification of the movement. The output unit 418 may be configured to output the reconstructed representation of heart-related signal 414c.

[00101] The apparatus 420 may be communicatively coupled to a network 401 to receive the heart related signal 410c and the motion signal 411c. The network may be a wireless network or any other suitable network. The reconstructing and the outputting may be performed in near real-time with respect to production of the heart-related signal 410c and the motion signal 411c. Alternatively, the apparatus may be coupled to a database (not shown) storing representations of the heart related signal 410c and the motion signal 411c, and the reconstructing and the outputting may be performed in non-real-time with respect to production of the heart-related signal 410c and the motion signal 414c.

[00102] The heart-related signal 410c may include raw heart-related signal data that includes the raw heart-related signal data 410a and the raw heart-related signal data 410b produced by biometric sensors (not shown) that sense the heart-related signal data 410a and the raw heart-related signal data 410b from sensing locations (not shown) on a first user 406a and a second user 406b, respectively. The motion signal 411c may include raw motion signal data that includes the raw motion signal data 411a and the raw motion signal data 411b from motion sensors (not shown). The raw motion signal data 411a and the raw motion signal data 411b may represent motion artifacts in the heart-related signal data 410a and the raw heart-related signal data 410b, respectively.

[00103] It should be understood that the raw heart-related signal data 410a-b and the raw motion signal data 411a-b may be sent to the apparatus 420 in any suitable way. For example, the raw heart-related signal data 410a and the raw motion signal data 411a may be sent in a payload of a packet; alternatively the raw heart-related signal data 410a and the raw motion signal data 411a may be sent in payloads of different packets. Similarly, the raw heart-related signal data 410b and the raw motion signal data 411b may be sent in a payload of a packet; alternatively, the raw heart-related signal data 410b and the raw motion signal data 411b may be sent in payloads of different packets.

[00104] The user 406a may be at a gym where the user 406a is exercising, and such physical activity by the user 406a may cause motion artifacts in the raw heart-related signal data 410a. The user 406b may be in a different location, such as a hospital. The user 406b may perform movements out of boredom, such wrist shaking, causing motion artifacts in the raw heart-related signal data 410b. As such, the corresponding motion artifacts may be suppressed in the

reconstructed representations 414a and 414b of the heart-related signals 414a and 414b, respectively, according to embodiments disclosed herein. The reconstructed representations 414a and 414b, or information derived therefrom, may sent to biometric devices or other devices communicatively coupled to the network 401 the user 406a and 406 may have access to such device, respectively. Alternatively, the reconstructed representations 414a and 414b, or information derived therefrom, may sent in any suitable manner to another device communicatively coupled to the network 401 such that the reconstructed representations 414a and 414b, or information derived therefrom, may be accessible to a third party, such as doctor, or any other suitable party.

[00105] FIG. 5 is a block diagram 500 of an example embodiment of an apparatus (520) for reconstructing a heart-related signal 510 output by a biomedical sensor 508. The apparatus 520 includes a reconstruction unit 516 and an output unit 518. The reconstruction unit 516 may be configured to produce a reconstructed representation of the heart-related signal 514. The reconstructing based on (i) a time-varying spectral analysis of the heart-related signal 510 and a motion signal 511, the motion signal 511 output by a motion sensor 509 and representative of motion artifacts in the heart-related signal 510. The motion artifacts may be signal artifacts produced by movement of the biomedical sensor 508 relative to a sensing location (not shown), and (ii) a classification of the movement.

[00106] The output unit 518 may be configured to output the reconstructed representation of the heart-related signal 514. The apparatus 520 may include the biomedical sensor 508 and the motion sensor 509. The reconstructing and the outputting may be performed in real-time with respect to production of the heart-related signal 510 and the motion signal 511.

[00107] The apparatus 520 may be a wearable device, such as a smartwatch, or any other suitable device, such as a wearable personal biometric monitoring device. The apparatus 520 may have a user interface (not shown) to present the reconstructed representation of the heart-related signal 514 or information derived therefrom, such as a characteristic, notification, alarm, or any other suitable information. The reconstructed representation of heart-related signal 514 or the information derived therefrom may be presented to a user via a user interface that may be a visual or audio based user interface.

[00108] According to one embodiment, the apparatus 520 may include a heart rate unit (not shown) configured to employ the reconstructed representation of the heart-related signal 514 to determine a heart rate estimate. According to another embodiment, the apparatus 520 may include an arterial oxygen saturation (SpO2) unit (not shown) configured to employ the reconstructed representation of the heart-related signal 514 to determine a SpO2 estimate. According to yet another embodiment, the apparatus may include an ailment unit (not shown) configured to employ the reconstructed representation of the heart-related signal 514 to detect or predict a heart-related ailment, the heart-related ailment including at least one of a heart rate variability (HRV) condition, an atrial fibrillation condition, a congestive heart failure condition, and a tachycardia condition. It should be understand that any combination of the heart rate unit, SpO2 unit, and ailment unit may be included in the apparatus 520 in combination with any other units disclosed herein.

[00109] SpaMA Results

[00110] According to embodiments disclosed herein, HR reconstruction and PPG signal reconstruction may be based on a time-varying spectral analysis. As disclosed above with reference to FIGS. 3A-F, embodiments disclosed herein may be based on power spectral densities (PSDs) of both PPG and accelerometer signals for each time shift of a corresponding windowed data segment of the respective signal. According to embodiments disclosed herein, by comparing time-varying spectra of the PPG and accelerometer data, those frequency peaks resulting from motion artifacts may be suppressed from the PPG spectrum.

[00111] According to some embodiments, the method may be comprised of six stages, such as the six stages disclosed above in reference to FIGS. 3A-F. According to another embodiment the method may have five distinct stages: (1) time-varying power spectral density (PSD) calculation, (2) spectral filtering, (3) motion artifact detection, (4) HR reconstruction and (5) signal reconstruction. According to embodiments disclosed herein, the method may include computing a window-segmented power spectral density of both PPG and accelerometer signals in real-time to scale each estimate of the PSD by the equivalent noise bandwidth of the window (Stoica, P. and R.L. Moses, Introduction to Spectral Analysis. 1997: Prentice Hall).

[00112] The simplest way to approach the PSD calculation may be to employ a periodogram. However, a periodogram has drawbacks in that it is an inconsistent spectrum estimator, has high

variance, and has leakage effects (Stoica, P. and R.L. Moses, Introduction to Spectral Analysis. 1997: Prentice Hall). Thus, a dominant spectral peak can lead to an estimated spectrum that contains power in frequency bands where there should be no power. However, both problems can be solved by down-sampling the raw signal, as disclosed above with reference to FIGS. 3A-F, and then using a sufficiently small frequency step by setting a large number of frequency points. Thus, embodiments disclosed herein may resample the signal from the original sampling frequency to, for example 1/4 of it, that is, down-sample the signal, and then apply a periodogram method with frequency resolution of 0.001.

[00113] Embodiments disclosed herein may limit the spectrum to the heart rate frequency range of [0.5Hz – 3 Hz], as disclosed above with reference to FIGS. 3A-F, and take the frequency and power information of the first three peaks in the PSD at each window and signal segment. Embodiments disclosed herein may be based on an understanding that the heart rate component in a typical clean (motion free) PPG signal is always the dominant frequency component in the time-varying power spectrum, thus, the highest peak of the spectrum corresponds to the HR frequency. Thus, when movement happens the dominant component can be replaced by movement components which shift the HR to the second or third peak in the spectrum. As such, embodiments disclosed herein may compare the first N peaks, such as 3 peaks, disclosed above, and corresponding frequencies of the PPG spectrum to the first peak and frequency of the accelerometers' spectra at each window and choose the frequency components (out of three) that are different from the accelerometers' frequency.

[00114] Embodiments disclosed herein may be further based on an understanding that there is coherence between a spectral peak in the PPG and the accelerometers' spectra that signifies a motion noise artifact in the PPG signal and that peak should be discarded in the HR reconstruction. After discarding these movement peaks in the spectrum, the next highest peak that is closest to the estimated HR of the previous window may be chosen at each window. By reconstructing the HR frequency at each window, simultaneously, the PPG signal may be reconstructed by using the power, frequency and phase of the signal that corresponds to the HR frequency. That is, the time-domain signals may be reconstructed from the time-frequency domain.

[00115] The SpaMA method was applied to three different datasets and 4 types of activities. The three different datasets included: 1) training datasets from the 2015 IEEE Signal Processing Cup Database recorded from 12 subjects while performing treadmill exercise from 1 km/h to 15 km/h; 2) test datasets from the 2015 IEEE Signal Processing Cup Database recorded from 11 subjects while performing forearm and upper arm exercise; and 3) Chon Lab dataset including 10 min recordings from 10 subjects during treadmill exercise.

[00116] Electrocardiogram (ECG) signals from all three datasets provided the reference HRs which were used to determine the accuracy of the SpaMA method. The performance of the SpaMA method was calculated by computing the mean absolute error between the estimated HR from the PPG and the reference HR from the ECG. The average estimation errors using the SpaMA method on the first, second and third datasets are 0.89, 1.93 and 1.38 beats/min respectively, while the overall error on all 33 subjects is 1.86 beats/min and the performance on only treadmill experiment datasets (22 subjects) is 1.11 beats/min. Moreover, it was found that dynamics of heart rate variability (HRV) can be accurately captured using the SpaMA method where the mean Pearson's correlation coefficient was found to be 0.98 between the power spectral densities of the reference and the reconstructed heart rate time series. These results show that the SpaMA method has a potential for PPG-based HR monitoring in wearable devices for fitness tracking and health monitoring during intense physical activities.

[00117] Embodiments disclosed herein not only provide PPG signal and HR reconstruction but also the potential to do heart rate variability analysis on the results. As disclosed below, embodiments disclosed herein can outperform the JOSS technique in heart rate estimation by providing less error to the reference, which yields higher accuracy.

[00118] Embodiments disclosed herein were evaluated on three different datasets. The first two datasets were provided for the IEEE Signal Processing Cup and are publically available. The three datasets are: 1.) 12 PPG training datasets (running on treadmill) from an IEEE signal processing competition (Available from: http://www.signalprocessingsociety.org/spcup2015/index.html) which was initially used in (Zhilin, Z., P. Zhouyue, and L. Benyuan, TROIKA: A General Framework for Heart Rate Monitoring Using Wrist-Type Photoplethysmographic Signals During Intensive Physical Exercise. Biomedical Engineering, IEEE Transactions on, 2015. 62(2): p. 522-531; Zhang, Z.,

Photoplethysmography-Based Heart Rate Monitoring in Physical Activities via Joint Sparse Spectrum Reconstruction. Biomedical Engineering, IEEE Transactions on, 2015. PP(99): p. 1-1, 2.) 11 PPG test datasets (e.g., arm exercise) from the IEEE signal processing competition and 3.) 10 PPG recordings from the Chon lab (running on treadmill).

[00119] (1) IEEE Signal Processing Competition Training Dataset: A single-channel PPG signal, a three-axis acceleration signal, and an ECG signal simultaneously recorded from 12 Asian male subjects ranging in age from 18 to 35. For each subject, the PPG signal was recorded from their wrist using a pulse oximeter (PO) with green LED (wavelength: 609 nm). The acceleration signal was also recorded from each subject's wrist using a three-axis accelerometer. Both the PO and the accelerometer were embedded in a wristband, which was comfortably worn. The ECG signal was recorded from the chest and it is used as the reference heart rate. All signals were sampled at 125 Hz.

[00120] (2) IEEE Signal Processing Competition Test Dataset: The dataset consists of 11 five minute recordings which were collected from 19 to 58 year old subjects performing intensive arm movements (e.g. boxing). For each subject, PPG signals were recorded with a sensing location at the wrist using a pulse oximeter with green LEDs (wavelength: 515nm). The acceleration signal was also recorded from at the sensing location at the wrist using a three-axis accelerometer. Both the PO and the accelerometer were embedded in a wristband. An ECG signal was recorded simultaneously from each subject's chest using wet ECG sensors. All signals were sampled at 125 Hz and sent to a nearby computer via Bluetooth.

[00121] (3) Chon Lab Dataset: This dataset was recorded in the Chon Lab from 10 healthy subjects (9 male/1 female), with ages ranging from 26 to 55. For each subject, the PPG signal was recorded from their forehead using a PO with red and infrared LED (wavelength: 660 and 940 nm). The acceleration signal was also recorded from each subject's forehead using a three-axis accelerometer. Both the pulse oximeter and the accelerometer were embedded in a headband and the signals were sampled at 80 Hz. The ECG signal was recorded as a reference from the chest using ECG sensors, sampled at 400Hz. During data recording, the subjects walked, jogged and ran on a treadmill with speeds of 3, 5 and 7 mph, respectively, for 9 min. At the end, all experimental subjects were asked to perform random arbitrary movements for 1 min.

[00122] For all three datasets, the data was down-sampled to 20 Hz since the estimation of heart rate is carried out in the frequency domain and this sampling rate is sufficiently high to obtain even heart rates that are as high as 240 beats/min or 4 Hz. Moreover, this down-sampling enables a focus on heart rates in the lower frequencies rather than in the physiologically irrelevant higher frequency ranges. Further details of this study's databases are given in Table 4, below. Four types of activities were involved:

- Type (1): activity involved walking or running on a treadmill for intervals of 0.5 min-1 min-1 min-1 min-1 min-0.5 min with speeds of 1-2 km/h, 6-8 km/h, 12-15 km/h, 6-8 km/h, 12-15 km/h, 1-2 km/h, respectively. The subjects were asked to purposely move the hand with the wristband to generate motion artifacts.
- Type (2): activity included various forearm and upper arm exercise which are common arm motions (*e.g.*, shaking hands, stretching, pushing objects, running, jumping, and push-ups).
- Type (3): activity consisted of intensive forearm and upper arm movements (*e.g.*, boxing).
- Type (4): activity involved 1 min rest, 1 min walking (3 mph), 1 min rest, 2 min jogging (5 mph), 1 min rest, 2 min running (7 mph), 1 min rest, 1 min arbitrary movement. The ECG-based reference HR was recorded in order to assess the performance of the methods under test.

[00123] In summary, the first dataset includes only Type (1) activities, the second dataset includes both Type (1) and (2) activities, and the third dataset includes only Type (4) activities.

Table 4. PPG Datasets and Experiments Settings

Subject	Dataset	Activity Type	Pulse Oximeter Type	Subject's Age/Sex
1	1 (IEEE Cup)	Type (1)	Wrist: green LED (wavelength: 609nm)	18-38 y (All Male)
2				
3				
4				
5				
6				
7				
8				
9				

10				
11				
12				
13	2 (IEEE Cup)	Type (2)	Wrist: green LED (wavelength: 515nm)	19-58 y (9 Male, 1 Female)
14				
15				
16		Type (3)		
17				
18				
19				
20		Type (2)		
21		Type (3)		
22				
23		Type (2)		
24	3 (Chon Lab)	Type (4)	Forehead: Red and Infrared LED (wavelength: 660 nm, 940nm)	26-55 y (9 Male, 1 Female)
25				
26				
27				
28				
29				
30				
31				
32				
33				

[00124] An example embodiment for reconstructing a heart-related signal during intensive movements is disclose by the HR monitoring method presented below in Table 5. Details of each stage are described in subsections *i* to *v*.

Table 5. HR and PPG signal reconstruction method

Stage 1. Time-Varying Spectral analysis 1.1. Down sample the PPG and Accelerometer signal to 20 Hz. 1.2. Compute the power spectral density of both PPG and Accelerometers [0-10 Hz]. Stage 2. Spectral Filtering 2.1. Assume HR to be in the frequency range of [0.5Hz – 3Hz], this accounts for both low and high heart rates. 2.2. The first highest three peaks and their corresponding frequencies in the PPG filtered spectrum are assumed to have HR information.

2.3. Only the largest frequency peak of the accelerometers' spectra is used for MA detection in stage 3.

Stage 3. Motion Artifact Detection

3.1. Compare the frequencies of the three peaks in the PPG spectrum with the frequency of the largest peak in the accelerometers' spectra. If the first or second largest peaks in the PPG spectrum are similar to that of the accelerometers' peaks, then motion artifact is present in the PPG.
3.2. If motion artifact is detected from 3.1, then the corresponding frequency peak (usually the first or second largest peak) in the PPG spectrum should be discarded.

Stage 4. Heart Rate Tracking and Extraction from PPG Spectrum

Case (1): From 3.1- if the spectrum is corrupted by movement and only the first largest peak is corrupted, then the HR frequency should be the frequency of the second peak in the spectrum.
Case (2): From 3.1- if the spectrum is corrupted by movement and both the first and second largest peaks have similar frequencies to those of the accelerometers' peaks, then the HR frequency should be the frequency of the third peak in the spectrum.
Case (3): Due to a gap between the pulse oximeter and a subject's skin, the HR frequency cannot be extracted from the spectrum and in this case the previous HR frequency is used or for offline implementation a cubic spline interpolation can be applied to fill in the missing HR information.

Stage 5. PPG Signal Reconstruction

5.1. The PPG signal is reconstructed by using the amplitude, frequency and phase information corresponding to the HR components (extracted in stage 4) that are calculated from the spectrum at each window.

- Heart Rate Variability Analysis

By using a sample-by-sample windowing strategy, HR can be extracted, from which dynamics of heart rate variability analysis can be obtained on the motion artifact-removed reconstructed HR time series.

[00125] i. Time-Varying Spectral Analysis of PPG and Accelerometer Data

[00126] Embodiments disclosed herein may produce a time-varying spectrum by taking a *T*-sec window of the signal and computing the power spectral density (PSD) of the segment and then sliding the window through the whole dataset which yields a time-frequency matrix in

which each array represents the power of the signal corresponding to a specific frequency and sliding time-step (shift) of *S*-sec. The sliding process and frequency step specify the resolution and dimension of the time-frequency matrix. According to embodiments disclosed herein, two different sliding window approaches may be used, depending on the application. For estimating either heart rates or heart rate variability, data may be shifted sample-by-sample with no overlap for the entire dataset. Such an approach enables capturing beat-to-beat dynamics of HRV which requires sample-to-sample estimation of PSD. Since some data is down-sampled data to 20 Hz in some of the database, as disclosed above, each data point may be shifted by 0.05 seconds. For estimating only the heart rates, the shift may be a data segment-by-segment shift rather than a sample-by-sample shift. This coarse-grain windowing approach has less computational cost and it can provide good tracking of heart rates, but does not apply well to HRV.

[00127] As such, according to some embodiments, a window segment length *T* may be set to 8 seconds and shifted by 2 seconds. The 8 second data segment and a shift of 2 seconds was chosen to compare results according to embodiments disclosed herein to other methods (TROIKA, JOSS and WFPV) which have used this chosen data segment length and time shift (Zhilin, Z., P. Zhouyue, and L. Benyuan, TROIKA: A General Framework for Heart Rate Monitoring Using Wrist-Type Photoplethysmographic Signals During Intensive Physical Exercise. Biomedical Engineering, IEEE Transactions on, 2015. 62(2): p. 522-531; Zhang, Z., Photoplethysmography-Based Heart Rate Monitoring in Physical Activities via Joint Sparse Spectrum Reconstruction. Biomedical Engineering, IEEE Transactions on, 2015. PP(99): p. 1-1). Moreover, the assumption of 8 second data length largely stems from the fact that heart rates do not change instantaneously, hence, an 8 second duration is a reasonable choice.

[00128] As a representative example, the resultant frequency components in the time-frequency matrix of recordings from subject #8 from the competition training dataset, for a window length of 8 seconds that is shifted by every 2 seconds, is shown in FIG. 6A, disclosed below.

[00129] FIGS. 6A-6C show Time-Frequency spectra of recording #8 from dataset (1).

[00130] FIG. 6A shows the PPG signal.

[00131] FIG. 6B shows the simultaneous Accelerometer-Z signal.

[00132] FIG. 6C (Top-Left) shows the TF spectrum of the PPG signal. FIG. 6C (Top-Right) shows the TF spectrum of ACC(x). FIG. 6C (Bottom-Left) shows the TF spectrum of ACC(y),. FIG. 6C (Bottom-Right) shows the TF spectrum of ACC(z); all computed from stage (1) of Table 5. The blue circles and letters represent movement elements in all four spectra.

[00133] The panels of FIG. 6A and FIG. 6B show a PPG time series and the z-axis accelerometer data, respectively. From the upper left panel of FIG. 6C, which represents the time-frequency plot of the PPG signal, it is observed that there are three dominant frequency components - one of them represents HR and the other two are similar to those of the accelerometers' spectra shown in the upper right and lower left and right panels of FIG. 6C. FIG. 6C illustrates 4 motion artifact elements (A, B, C, D) that are present in exactly the same areas among all spectra. By comparing the time-frequency (TF) spectrum of PPG to those of the accelerometers' spectra, the marked dynamics (A, B, C and D) in the PPG spectrum can be detected as sharing the same frequency dynamics as those of the accelerometer spectra marked in circles. Hence, both the top and bottom marked lines in the PPG spectrum most likely represent the motion artifacts, and the unmarked frequency represents the HR. The next section details how these motion artifact frequency dynamics may be detected and filtered according to embodiments disclosed herein.

[00134] ii. Spectral Filtering

[00135] After obtaining the power spectral density at each window, as disclosed above, embodiments disclosed herein may confine the HR frequency to the range [0.5 Hz – 3 Hz], which takes into account both at rest and high HR due to either tachycardia or exercise scenarios. Hence, for HR estimation, the strategy is to eliminate frequencies that are outside of this HR frequency range as they are most likely due to motion artifacts or harmonics of the HR frequency.

[00136] In general, HR frequency in the power spectral density of PPG at each window can have three different scenarios: (1) PPG is devoid of MA and there is no spatial gap between the sensor and the subject's skin during recording, (2) PPG is corrupted by MA and there is no spatial gap between the sensor and the subject's skin during recording and (3) There is a spatial gap between the sensor and the subject's skin during recording. For the ideal case (1), HR can be extracted and it is most likely represented as the highest peak in the PPG spectrum. For case

(2), MA dynamics can result in predominately either one or two dominant peaks depending on the severity of repetitive motions, and the HR peak may be relegated to either the second or third highest peak. Non-repetitive motion artifacts will show up as a broadband spectrum without a dominant peak if they are not severe (Marmarelis, V.Z., et al., Nonlinear analysis of renal autoregulation under broadband forcing conditions. Ann Biomed Eng, 1993. 21(6): p. 591-603). The only scenario that makes it difficult to extract HR from the spectrum is scenario (3) when there is a spatial gap between the PPG sensor and the subject's skin during recording. In this scenario, assuming that the motion artifacts are short lasting, the missing HR values can be interpolated using a cubic spline approach.

[00137] FIG. 7 is an example embodiment of spectral filtering. FIG. 7 shows a representative filtered time-frequency spectral plot of a PPG signal. As disclosed above, embodiments disclosed herein may retain only the three largest frequency peaks at each time point within the defined HR range (30-180 bpm) and such retained frequency peaks are represented as blue, green and red colors, respectively. Retaining only the three largest frequency peaks at each time point may be reasonable for the first two cases, as outlined above. In the PPG time-frequency spectrum of FIG. 7, the Blue, Green and Red circles correspond to the first three highest peaks in the defined HR frequency range of (30-180 bpm), respectively, at each sliding window.

[00138] iii. Motion Artifact Detection

[00139] FIGS. 8A-8B show motion artifact detection in the PPG spectrum according to embodiments disclosed herein.

[00140] FIG. 8A shows a filtered PPG spectrum with movement and HR components. FIG. 8A is an example embodiment of a PPG spectrum which is identical to FIG. 7, but it also identifies the frequencies associated with accelerometers, as marked by the shaded areas and the letters A-D, in the top left and two bottom panels of FIG. 6C, disclosed above. The shaded yellow elements (A, B, C, D) of FIG. 8A represent motion frequency components in the PPG spectrum, and the light blue line is the reference HR from a clean reference ECG signal. By removing the accelerometers' related frequencies in FIG. 8A, the remaining frequency dynamics which should represent HR frequency and its harmonics are shown in FIG 8B.

[00141] FIG. 8B shows a filtered PPG spectrum after removing motion artifact frequency components.

[00142] iv. Heart Rate Tracking & Extraction

[00143] A flow diagram for heart rate tracking and extraction is disclosed above, with reference to FIG. 3B. Embodiments disclosed herein may identify HR frequencies with time, such as HR frequencies from FIG. 8B. Note that in FIG. 8B, there are three peaks at each time instance (also referred to interchangeably herein as a time point). Embodiments disclosed herein may identify which of the three peaks represents the HR at each time point. For the initial time window of 8 seconds, a clean data segment may be used so that true HR can be determined. This scenario is case (1), disclosed above, in the spectral filtering section, and the detection of HR is simply the highest peak in the spectrum. Embodiments disclosed herein may estimate HR for each sliding window of data. Embodiments disclosed herein may choose a HR peak in the PPG spectrum with the knowledge of estimated HR values in previous time windows. Two main scenarios may present: (1) no peak exists in the spectrum that can represent HR, and (2) there is a spectral peak among the first three highest peaks of spectrum that belongs to the HR component.

[00144] In case (1), where HR is not detectable in the window (*e.g.*, due to spatial gap between the PO sensor and skin), in real-time implementation embodiments disclosed herein may take a previous window's HR value as the current HR (or simply use a moving average of several past HR beats or some other variant). In post-processing, or offline processing, a cubic spline interpolation may be used to fill in the missing HR information. In the more general case (2), where the HR peak is among the first three highest peaks in the spectrum, three possible scenarios can occur: (2-A) the windowed PPG signal is clean and the first highest peak in the spectrum represents the HR fundamental frequency, (2-B) the windowed PPG signal is corrupted by movement and at most two of the spectral peaks represent the accelerometers' frequency components, thus, the second or the third peak corresponds to HR, (2-C) while the HR spectral peak is detectable, the difference between its value and that of the previous HR is more than 10 bpm, as such, embodiments disclosed herein may replace the HR by the most recent HR value from a previous window segment (or a moving average of several past HR beats or some other variant).

[00145] According to embodiments disclosed herein, criterion may be set that the HR value cannot change more than 10 BPM from a previous time window. In FIG. 8B, these cases are

illustrated. For example, in most cases, the blue circle which represents the largest spectral peak is chosen but in other cases, either green or red circles are chosen for certain time points. For the HR peaks associated with either the green or red circles, embodiments disclosed herein may choose those peaks because either the first two highest peaks are related to accelerometers or the highest magnitude peak deviates more than 10 BPM from the previous HR value.

[00146] FIG. 9 shows a comparison of reconstructed HR obtained, according to embodiments disclosed herein, to reference HR obtained from simultaneous ECG recordings. In FIG. 9, the extracted HR (red color) from PPG spectra of recording#8 from the competition training dataset, according to embodiments disclosed herein, is shown in red color and the reference ECG-derived HR is shown in black color. In order to calculate the performance of HR reconstruction according to embodiments disclosed herein, the error value in each time window was calculated from the estimated HR to the reference ECG-derived HR. Two measurement indices of absolute error similar to the indices in (Krishnan, R., B. Natarajan, and S. Warren, Two-Stage Approach for Detection and Reduction of Motion Artifacts in Photoplethysmographic Data. Biomedical Engineering, IEEE Transactions on, 2010. 57(8): p. 1867-1876) were used.

$$Error(1) = \frac{1}{W}\sum_{k=1}^{w} |HR_{SpaMA}(k) - HR_{ref}(k)| \tag{1}$$

$$Error(2) = \frac{1}{W}\sum_{k=1}^{w} \frac{|HR_{SpaMA}(k) - HR_{ref}(k)|}{HR_{ref}(k)} \times 100\% \tag{2}$$

where W is the total number of windows.

[00147] v. PPG Signal Reconstruction for HRV analysis

[00148] For an HRV analysis application, the above-disclosed embodiments are identical except that the beat-by-beat shift is of data rather than the 8 second data segment shift or its variant. According to embodiments disclosed herein, the PPG signal may be reconstructed using heart rate frequency, amplitude and phase changes, window-by-window using the sample-by-sample windowing process:

$$Rec_{Signal}(k) = A_{HR}(k) \times \sin\left(2\pi t(k) f_{HR}(k) + \varphi_{HR}(k)\right) \tag{3}$$

where $k = 1,\ldots, N$ and N is number of signal samples and total number of windows. $A_{HR}(k)$ and $\varphi_{HR}(k)$ are calculated according to the power of the signal for HR frequencies in the PSD and phase

angles of complex elements in a Fast Fourier Transform (FFT) matrix that correspond to HR frequencies.

[00149] FIG. 10A is an example embodiment of PPG signal reconstruction according to embodiments disclosed herein. FIG. 10A shows a comparison between reconstructed PPG and original recording #8 from IEEE competition training dataset. The left and right panels of FIGS. 10A-B show the reconstructed PPG versus the original PPG and their HRV time series, respectively.

[00150] FIG. 10B is a zoomed-in version of FIG. 10A.

[00151] Given that embodiments disclosed herein estimate quite accurate heart rates, it is not surprising to observe similar frequency dynamics between the reference and reconstructed HRV time series, as shown in FIGS. 11A-B.

[00152] FIGS. 11A-B show comparisons of HRV spectra between the reference and the reconstructed HRV time series (*e.g.*, as shown in FIGS. 10A-B) from the MA-contaminated PPG signal for dataset #8. Note that for computing HRV, matching the amplitude of the reference HR is not a concern, as the focus is only in the dynamics of the fluctuations in the heart rates.

[00153] FIG. 11A shows a time-domain comparison of a reconstructed HR and a reference HR.

[00154] FIG. 11B shows a spectral comparison of heart rate variability between reconstructed HR and reference HR calculated from the reference ECG using Pan & Tompkins peak detection approach (Pan J, T.W., A real-time QRS detection algorithm. IEEE Trans Biomed Eng, 1985. 32(3): p. 230-236).

[00155] Results

[00156] FIG. 11C is a "SpaMA Method Performance Comparison" table, Table 6, also referred to interchangeably herein as Table 6. Table 6 represents the average absolute error (E1) and the average absolute error percentage (E2) of embodiments disclosed herein as applied to all 3 datasets, respectively. Embodiments disclosed herein are compared to three methods: TROIKA, JOSS and WFPV. The results in Table 6 show that better performance from embodiments disclosed herein as ~~comparted~~compared to JOSS and TROIKA for all 12 subjects in the first datasets. In comparison to WFPV, [[]]embodiments disclosed herein outperform WFPV on average across all 23 subjects in both datasets (1) and (2). The total average of E1 for

embodiments disclosed herein is less than 2 beats per minutes for all 33 subjects. The average of E1 across the treadmill experiment recordings (activity Type 1- IEEE dataset and Type 4- Chon Lab dataset) is around 1 beat per minute for all 22 subjects.

Table 6. SpaMA Method Performance Comparison

Subject	Dataset	Activity Type	TROIKA		JOSS		WFPV		SpaMA	
			E1	**E2%**	**E1**	**E2%**	**E1**	**E2%**	**E1**	**E2%**
1	1 (IEEE Cup)	Type (1)	2.87	2.18	1.33	1.19	1.23	-	**1.23**	**1.14**
2			2.75	2.37	1.75	1.66	1.26	-	1.59	1.30
3			1.91	1.50	1.47	1.27	0.72	-	**0.57**	**0.45**
4			2.25	2.00	1.48	1.41	0.98	-	**0.44**	**0.31**
5			1.69	1.22	0.69	0.51	0.75	-	**0.47**	**0.31**
6			3.16	2.51	1.32	1.09	0.91	-	**0.61**	**0.45**
7			1.72	1.27	0.71	0.54	0.67	-	**0.54**	**0.40**
8			1.83	1.47	0.56	0.47	0.91	-	**0.40**	**0.33**
9			1.58	1.28	0.49	0.41	0.54	-	**0.40**	**0.32**
10			4.00	2.49	3.81	2.43	2.61	-	2.63	1.59
11			1.96	1.29	0.78	0.51	0.94	-	**0.64**	**0.42**
12			3.33	2.30	1.04	0.81	0.98	-	1.20	0.86
mean ± std			2.42 ± 0.8	1.82 ± 0.5	1.28 ± 0.9	1.02 ± 0.6	1.04 ± 0.5	-	**0.89 ± 0.6**	**0.65 ± 0.4**
13	2 (IEEE Cup)	Type (2)					3.58	-	**3.41**	**4.25**
14							9.66	-	**7.29**	**9.80**
15							2.31	-	2.73	2.21
16		Type (3)					4.93	-	**3.18**	**2.11**
17							3.07	-	**3.01**	**2.52**
18							2.67	-	4.46	3.23
19							3.11	-	3.58	3.98
20		Type (2)					2.10	-	**1.94**	**1.66**
21		Type (3)					3.22	-	**2.56**	**2.02**
22							4.35	-	**3.12**	**3.28**
23		Type (2)					0.75	-	1.72	1.97
mean ± std							3.61 ± 2.2	-	**3.36 ± 1.5**	**3.33 ± 2.2**
Type (1,2) mean ± std							2.27 ± 2.0	-	**1.93 ± 2.0**	**2.07 ± 1.7**
24	3 (Chon Lab)	Type (4)							**0.88**	**0.91**
25									**1.03**	**0.83**
26									**1.10**	**0.90**
27									**1.64**	**1.54**
28									**1.41**	**1.12**
29									**0.82**	**0.70**
30									**0.63**	**0.58**
31									**4.78**	**3.87**
32									**0.95**	**0.79**
33									**0.62**	**0.52**
mean ± std									**1.38 ± 1.2**	**1.17 ± 1.0**

Total: mean ± std		**1.86 ± 1.6**	**1.70 ± 1.8**

[00157] FIGS. 12A, 12B, 13A, 13B, 14A, and 14B show the reconstructed HR and corresponding PSD of a sample-sample windowed HR, according to embodiments disclosed herein, in comparison to a reference HR from an ECG. The results for recording #9 from the first dataset (IEEE Competition Training dataset) and activity Type 1 (*e.g.*, running on treadmill) are shown in FIGS. 13A-B. As shown, E1 for this particular subject is as low as 0.4 bpm and the correlation between the PSD of reconstructed HR and reference HR is as high as 96%.

[00158] FIG. 12A shows a reconstructed HR vs. reference HR. FIG. 12B shows a spectral comparison of reconstructed HR and reference HR (estimated from reference ECG).

[00159] FIG. 13A illustrates the comparison between the reconstructed HR and the reference HR for Subject #14 (IEEE Competition Test Dataset) which has the highest errors. Subject #14 belongs to the second dataset (IEEE Competition Test dataset) and Type 2 activities (e.g. jumping). It can be seen that the largest error is obtained when both the physiological HR and the motion artifacts change rapidly so that the true HR cannot be reliably estimated.

[00160] FIG. 13B shows a reconstructed HR vs. reference HR for Subject 16 (IEEE Competition Test Dataset). FIG. 13B shows the comparison results of reconstructed HR and reference HR for recording #16 of the second dataset (IEEE Competition Test dataset) which has the Type 3 activities (*e.g.*, arm exercise).

[00161] FIG. 14A shows a reconstructed HR vs. reference HR for Subject #30 (Chon Lab Dataset). FIG. 14B shows a spectral comparison of reconstructed HR and reference HR (estimated from reference ECG). The results for recording #30 from the third datasets (Chon Lab datasets) and activity Type 4 (*e.g.*, running on treadmill) are shown in FIGS. 14A-B. It can be seen that the E1 for this subject is around 0.6 bpm and the correlation between the PSD of reconstructed HR and reference HR is as high as 99% for LF and 0.96 for HF frequency range. All subjects' results are provided in Table 7, disclosed below.

[00162] Table 7 represents the correlation and statistical difference using the student's t-test between PSD of estimated and reference HRV in both LF (0.04-0.15 Hz) and HF (0.15-0.4 Hz)

frequency ranges. The correlation values in the table are calculated based on Pearson's linear correlation coefficient. As shown in Table 7, there was no difference between the reference and the derived HRV for LF, according to embodiments disclosed herein, and a difference was seen in only 4 out of 10 subjects for HF.

Table 7. Frequency Domain HRV analysis Comparison: PSD of SpaMA Method vs. reference

Subjects	**Correlation**	
	LF (LF is [0.04-0.15] Hz and HF is [0.15-0.4] Hz)	**HF**
1	0.99	0.98
2	0.99	0.96
3	0.99	0.95* (*) indicates significantly different (P-value>0.05)
4	1.00	0.99
5	1.00	0.99
6	0.99	0.96*
7	0.98	0.92*
8	0.97	0.90*
9	1.00	0.99
10	1.00	0.99
mean	0.99	0.96

[00163] Table 8 shows some of the widely-reported time-domain HRV parameters such as the mean HR, standard-deviation (SDNN) of the normal-to-normal (NN) interval, root-mean-square of successive difference (RMSSD) of the NN interval, and the number of interval differences of successive NN intervals greater than 50 ms divided by the total number of NN intervals (pNN50) estimated from embodiments disclosed herein in comparison to the reference ECG NN interval. None of these parameters were found to be significantly different between those derived according to embodiments disclosed herein and the reference HRV.

Table 8. Time Domain HRV analysis Comparison: SpaMA Method vs. reference HRV

Subjects	**SDNN**		**meanNN**		**RMSSD**		**pNN50**	
	SpaMA	Reference	SpaMA	Reference	SpaMA	Reference	SpaMA	Reference
1	2620.75	2566.47	10481.89	10480.72	33.24	18.05	0.001	0.020
2	2115.44	2079.58	9908.00	10020.00	25.93	16.32	0.011	0.019
3	3173.73	3177.68	10764.20	10829.06	89.70	56.15	0.019	0.207
4	2517.78	2533.20	10376.95	10426.26	13.54	19.58	0.001	0.030
5	2654.42	2670.32	10846.04	10990.08	11.88	18.59	0.003	0.018
6	2012.53	1974.65	9737.35	9827.63	39.64	21.17	0.004	0.025
7	3056.36	2925.19	12519.74	13134.05	27.66	30.61	0.015	0.071

8	3133.76	2756.66	10504.00	10530.00	32.57	36.38	0.002	0.003
9	2195.08	2142.53	10499.81	10470.06	8.23	13.01	0.002	0.004
10	2454.57	2406.96	12936.62	12981.21	41.52	20.28	0.006	0.024
p-value	> 0.05		> 0.05		> 0.05		> 0.05	

[00164] As such, the SpaMA method, according to embodiments disclosed herein, that may be based on time-varying spectral analysis of the PPG signal addresses Heart Rate monitoring in the real world with challenges ranging from a subject who makes sudden movements but is otherwise sedate, to intensive physical activities. Embodiments disclosed herein compare spectral changes in PPG and accelerometer signals. As disclosed above, three different datasets have been used to verify the SpaMA performance. Each dataset reflects different types of activities and movements. In all of the experiments, the reference HR was calculated from an ECG signal that was collected simultaneously with the PPG signal. The estimated HR was calculated from the spectrum of PPG in 8 second time windows. Based on the results, disclosed above, the SpaMA method may be used for tracking HR changes during severe motion artifacts with an average error of just 1.86 bpm compared to that of the reference ECG; these results are superior to three other methods tested: TROIKA, JOSS and WFPV (Zhilin, Z., P. Zhouyue, and L. Benyuan, TROIKA: A General Framework for Heart Rate Monitoring Using Wrist-Type Photoplethysmographic Signals During Intensive Physical Exercise. Biomedical Engineering, IEEE Transactions on, 2015. 62(2): p. 522-531; Zhang, Z., Photoplethysmography-Based Heart Rate Monitoring in Physical Activities via Joint Sparse Spectrum Reconstruction. Biomedical Engineering, IEEE Transactions on, 2015. PP(99): p. 1-1).

[00165] Out of 33 recordings, 23 are from a wrist pulse oximeter, and the rest of the data were recorded by a forehead pulse oximeter. The results from Table 8, disclosed above, show that the SpaMA method can be applied to monitor HR from both wrist and forehead pulse oximeters. By comparing the performance of the method for treadmill experiments (dataset 1 and dataset 3), the error is lower by almost 1 beat using a wrist pulse oximeter. However, it should be noted that from this result a conclusion that the wrist PPG provides less error than the forehead should not be drawn, as the experiments used different subjects and were two separate studies. The prior methods (TROIKA, JOSS and WFPV) were tested using only on the wrist-based PPG signals as

the implementers of those methods did not have access to forehead PPG sensors. The SpaMA method, according to embodiment disclosed herein, was tested on data from both PPG sensor locations, and proved to be effective regardless of the location of the PPG sensor.

[00166] Several observations were made while analyzing the data, disclosed above. The tracking ability of the SpaMA method decreased as the frequency changes during recordings increased. This phenomenon mostly was observed while dealing with the second set of datasets from the IEEE competition, which involved Type (2) and Type (3) activities. These types of exercises involved more abrupt movements which consequently made it more difficult to track the HR-related frequencies in the spectrum. In the three datasets that have been analyzed, recordings #10 and 14 are examples of this phenomenon.

[00167] A strength of the PPG's LED is one of the most important factors determining the SpaMA method performance. Movement induces much less spectrum corruption (shift) in the PPG if the LED is sufficiently strong. A reduction in the strength of the PPG signal can also be caused by ambient light leaking into the gap between a PPG sensor and the skin surface (Zhang, Z., Photoplethysmography-Based Heart Rate Monitoring in Physical Activities via Joint Sparse Spectrum Reconstruction. Biomedical Engineering, IEEE Transactions on, 2015. PP(99): p. 1-1). This is because the power of the signal is dependent on the depth and reflection of the light from the pulse oximeter to the subject's skin. This gap between skin and the planar substrate where the LEDs and PD are mounted may be the result of movement during physical activities or the shape of tissue that the sensors touch. Among the three datasets, low performance for recordings #16 and 31 is the result of a weak PPG signal most likely due to a gap between the sensor and skin caused by motion artifacts.

[00168] By using the sample-by-sample windowing process, SpaMA, according to embodiments disclosed herein, can be utilized for both Heart Rate monitoring and HRV analysis in both frequency- and time-domains. From the results, disclosed above, it can be observed that embodiments disclosed here are able to replicate both the low frequency (0.04-0.15Hz) and the high frequency (0.15-0.4) dynamics well, albeit better the former than the latter, when compared to a reference HRV. For time-domain HRV measures, the mean HR, SDNN, RMSSD, and pNN50 based on embodiments disclosed herein were all found to be not significantly different than the reference HRV. It has long been shown that during dynamic exercise, heart rate

increases due to both a parasympathetic withdrawal and an augmented sympathetic activity (Iellamo, F., Neural mechanisms of cardiovascular regulation during exercise. Auton Neurosci, 2001. 90(1-2): p. 66-75; Bernardi, L. and M.F. Piepoli, [Autonomic nervous system adaptation during physical exercise]. Ital Heart J Suppl, 2001. 2(8): p. 831-9). The relative role of the two drives depends on the exercise intensity (Perini, R., et al., The influence of exercise intensity on the power spectrum of heart rate variability. Eur J Appl Physiol Occup Physiol, 1990. 61(1-2): p. 143-8; Sarmiento, S., et al., Heart rate variability during high-intensity exercise. Journal of Systems Science and Complexity, 2013. 26(1): p. 104-116; Roure, R., et al., Autonomic nervous system responses correlate with mental rehearsal in volleyball training. Eur J Appl Physiol Occup Physiol, 1998. 78(2): p. 99-108). Analysis of HRV permits insight into this control mechanism (Aubert, A.E., B. Seps, and F. Beckers, Heart rate variability in athletes. Sports Med, 2003. 33(12): p. 889-919). Also, being able to do HRV analysis from PPG even during movement and physical activities would be an advantage for detecting and diagnosing many cardiovascular diseases using only PPG recordings.

[00169] The SpaMA method, according to embodiments disclosed herein, can be potentially implemented in real time. The method written in Matlab®, version R2014 and CPU 3.4 GHz takes only 110 msec per 8 second segments. Therefore, given the high accuracy of the method in estimating HR despite severe motion artifacts, the SpaMA method, according to embodiments disclosed herein, has the potential to be applicable for implementation on wearable devices such as smart watches and PPG-based fitness sensors.

[00170] As disclosed above, accurate estimation of changing arterial oxygen saturation (SpO2) from photoplethysmogram (PPG) signals during movement is a very challenging problem. This is because strenuous and high intensity movements can result in severe motion artifacts (MA), making accurate SpO2 estimation from PPG signals difficult. As such, embodiment disclosed herein may applied the methods for reconstructing a PPG signal, as disclosed above, and include an additional stage of SpO2 estimation.

[00171] According to one embodiment, OxiMA may be comprised of the 6 stages disclosed above, with reference to FIGS. 3A-F, and include Stage 7, that is SpO2 Estimation.

[00172] According to another embodiment, OxiMA may be comprised of 6 stages: (1) Time-frequency Spectral Analysis, (2) Signal Decomposition, (3) Spectral Filtering, (4) Heart Rate (HR) extraction and tracking, (5) Signal Reconstruction, (6) SpO2 Estimation.

[00173] OxiMA

[00174] According to some embodiments, OxiMA may decompose the PPG signal into its frequency components by using a complex demodulation-based technique and may choose the components with frequencies close to the HR frequency for reconstructing the clean PPG signal. Next, SpO2 may be estimated from the reconstructed PPG signal. Such a method is applied to 22 minute datasets recorded from 10 subjects. A Nellcor OxiMax transmission sensor was used to collect analog PPG signals, while reference SpO2 and HR were collected simultaneously from the FDA approved Masimo SET Radical RDS-1 pulse oximeter. The performance of the OxiMA method according to embodiments disclosed herein, was determined by computing the mean absolute error between the estimated HR/SpO2 from the PPG and reference HR [Masimo]/SpO2[Masimo] oximeter. The results show the average estimation error using OxiMA are only 2.4 beats/minute for HR and 1.8% for SpO2, respectively. As such, the OxiMA method has great potential for MA reduction for both SpO2 and HR monitoring.

[00175] Vital signs and clinical symptoms have been shown to be poor predictors of hypoxia, and in order to rationalize oxygen therapy, measurement of arterial oxygen saturation by pulse oximetry is being increasingly recommended (Laman, M., et al., Can clinical signs predict hypoxaemia in Papua New Guinean children with moderate and severe pneumonia? Ann Trop Paediatr, 2005. 25(1): p. 23-7) Arterial oxygen saturation (SpO2) reflects the relative amount of oxyhemoglobin in the arterial blood. The most common method to measure SpO2 is based on pulse oximetry, whereby oxidized hemoglobin and reduced hemoglobin have significantly different optical spectra.

[00176] Specifically, at a red wavelength of about 660 nm, there is a significant difference in light absorbance between reduced (Hb) and oxidized hemoglobin (HbO2). A measurement of the percent oxygen saturation of blood is defined as the ratio of oxyhemoglobin to the total concentration of hemoglobin present in the blood. Pulse oximetry assumes that the fluctuations of the PPG signal are caused by changes in arterial blood volume associated with each heartbeat, where the magnitude of the fluctuations depends on the amount of arterial blood rushing into the

peripheral vascular bed, the optical absorption of the blood, skin and tissue, and the wavelengths used to illuminate the blood. The photoplethysmogram (PPG) can be used to derive not only the SpO2 and heart rate (HR) data, but also other vital physiological information (Laman, M., et al., Can clinical signs predict hypoxaemia in Papua New Guinean children with moderate and severe pneumonia? Ann Trop Paediatr, 2005. 25(1): p. 23-7; Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263; Tamisier, R., et al., A new model of chronic intermittent hypoxia in humans: effect on ventilation, sleep, and blood pressure. J Appl Physiol (1985), 2009. 107(1): p. 17-24; Jubran, A., Pulse oximetry. Crit Care, 1999. 3(2): p. R11-r17). As disclosed above, utilizing a pulse oximeter as a multi-purpose vital sign monitor has clinical appeal, since it is familiar to clinicians and comfortable for the patient (Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263).

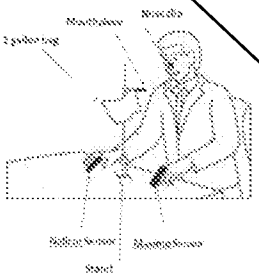
[00177] In healthy persons, SpO2 is typically near 98%. A lower reading indicates a level of hypoxia. SpO2 readings below 95% are usually a cause for concern, indicating the need for supplemental oxygen therapy. In certain individuals, such as those with chronic respiratory or cardiac diseases, SpO2 readings below 95% may be considered normal. However, in general, SpO2 readings between 90%-95% represent mild hypoxia, while 85%-90% indicates serious hypoxia, and readings below 85% are considered critical hypoxia (Tamisier, R., et al., A new model of chronic intermittent hypoxia in humans: effect on ventilation, sleep, and blood pressure. J Appl Physiol (1985), 2009. 107(1): p. 17-24).

[00178] As disclosed below, the OxiMA method according to embodiments disclosed herein, provides HR reconstruction with accurate SpO2 estimation even during movement. The most recent methods as noted above (e.g., TROIKA and JOSS) do not show their ability to obtain SpO2 estimates as they were mainly designed for HR calculations in the presence of intense motion artifacts.

[00179] The OxiMA method was evaluated on a lab controlled dataset that was recorded during voluntary induced hypoxia. In an IRB approved study which recruited 10 subjects, one

set of data was collected from each subject for a duration of 22 min. Reference arterial SpO2 and HR were collected from the FDA approved Masimo SET Radical RDS-1 pulse oximeter (mounted on the left hand), while a Nellcor OxiMax sensor (mounted on the right hand) was used to collect analog PPG signals, simultaneously ~~(Table 9)~~, as shown in Table 9 of FIG. 14C, disclosed below.

TABLE 9
PPG DATASETS AND EXPERIMENTS SETTINGS

Scenario	Sensor Type	Age/Sex Ethnicity
Oxygen Saturation Variations 	[Actual PPG] Finger Pulse Oximeter Nellcor [Ref SpO_2] Finger Pulse Oximeter [Ref HR] SilverRest ECG Electrode	23-58 yr (10 Males) 3 Asian 2 Hispanic 3 American 2 White

[00180] FIG. 14C is a table, Table 9, that includes PPG datasets and experiments settings. Each subject sat in a chair and was asked to re-breathe into a 1-gallon bag four times for approximately two minutes each time. During the first and third time the subject rebreathed into the bag, subjects were asked to remain still. During the second and fourth time the subject rebreathed into the bag, subjects were asked to introduce motion artifacts into the measurement by shaking their right hand. Each subject wore a disposable nose clip to prevent accidental breathing of room air. The Masimo reference sensor placed in the left hand remained motionless for the entire duration of the study. Subjects had at least two minutes of rest between successive breathing maneuvers, with more time if requested. The protocol for this experiment is presented in Table 10. Worcester Polytechnic Institute IRB approved the study protocol and informed consent was required by all subjects prior to data recording.

[00181] This sequence of data recording allowed us to test the efficacy of the OxiMA method while a subject experienced different levels of short lasting hypoxia during motion artifacts. For reference, other clinical studies showed that SpO2 levels in patients suffering from mild to moderate sleep apnea can drop to about 80% for short periods of time until the patient is awakened without irreversible physiological effects (Maeda, Y., M. Sekine, and T. Tamura, Relationship between measurement site and motion artifacts in wearable reflected photoplethysmography. J Med Syst, 2011. 35(5): p. 969-76).

[00182] Methodology

[00183] The protocol for testing performance of the OxiMA method is presented in Table 10.

TABLE 10
EXPERIMENT PROTOCOL

End Time (min)	Event
2	Rest (baseline)
4	Bag breathing (motion)
5	Rest (oxygen recovery)
7	Rest
9	Bag breathing (motion)
10	Rest (oxygen recovery)
12	Rest
14	Bag breathing (no motion)
15	Rest (oxygen recovery)
17	Rest
19	Bag breathing (motion)
20	Rest (oxygen recovery)
22	Rest

[00184] Details of each stage of the OxiMA method as applied in the experiment are disclosed below.

[00185] Time-Varying Spectral Analysis of PPG and Accelerometer Data

[00186] To compute the time-frequency spectrum, a variable frequency complex demodulation technique was employed. Table 11, disclosed below, presents the OxiMA method, according to one embodiment.

[00187] The time-varying spectrum is estimated by taking a T-sec window of the PPG signal and computing the VFCDM time-frequency of the segment and then sliding the window through the whole dataset. There is no overlapping between the sliding time windows. The window

segment length T was set to 8 seconds and was shifted by 8 seconds. The assumption of 8 second data length largely stems from the fact that SpO2 and heart rates do not change instantaneously; hence, an 8 second duration is a reasonable choice.

TABLE 11
OXIMA METHOD: HR AND SPO2 RECONSTRUCTION

Stage 1. VFCDM Time-Frequency Spectrum
1.1. Downsample the PPG signal to ¼ of the original sampling frequency.
1.2. Compute the VFCDM based time-frequency spectrum (TFS)

Stage 2. Signal Decomposition
2.1. Decompose the PPG signal into its frequency components according to frequency bands in the TFS

Stage 3. Spectral Filtering
3.1. Assume HR to be in the frequency range of [0.5Hz – 3Hz], to account for both low and high HR values.
3.2. The first highest two peaks and their corresponding frequencies in the PPG filtered spectrum are assumed to have HR information.

Stage 4. Heart Rate Tracking and Extraction from PPG Spectrum
Case (1): From 3.1- if the spectrum is corrupted by movement and only the first largest peak is corrupted, then the HR frequency should be the frequency of the second peak in the spectrum.
Case (2): Due to the sensor-skin interface interruption, which could be a result of gap between the pulse oximeter and a subject's skin or slight sensor alignment variations relative to skin, the HR frequency cannot be extracted from the spectrum and in this case the previous HR frequency is used or for offline implementation a cubic spline interpolation can be applied to fill in the missing HR information.

Stage 5. PPG Signal Reconstruction
5.1. The PPG signal is reconstructed by using the summation of VFCDM components with frequency close to the HR frequency at each window.

Stage 6. Oxygen Saturation Estimation
6.1. Calculate the SpO2 estimations from reconstructed infrared and red PPG signals using the following empirical calibration equation [2]

$$SpO_2(\%) = (110 - 25R)$$

where,

$$R = \frac{AC_{Red}/DC_{Red}}{AC_{IR}/DC_{IR}}$$

[00188] FIGS. 15A-B show the resultant VFCDM time-frequency spectrum of recordings from subject #5, as a representative example.

[00189] The panels in FIGS. 15A-B show infrared PPG time series data. FIG. 15B represents the time-frequency plot of the infrared PPG signal. The next section details how the PPG data is decomposed into its frequency components using VFCDM.

[00190] Signal Decomposition

[00191] The original PPG signal was decomposed into sinusoidal modulations using a VFCDM method, as disclosed in Table 12 below.

$$x(t) = \sum_{i=1}^{N} Component\{i\} = \sum_{i=1}^{N} dc_i(t)A_i(t)cos(2\pi f_i(t) + \phi_i(t)) \qquad (4)$$

[00192] By assuming N=12 fixed frequency bands each with a distinct central frequency, the PPG and accelerometer signals may be decomposed using the VFCDM method of Table 12 which yields 12 components.

TABLE 12
VFCDM METHOD

Consider a sinusoidal signal $x(t)$ to be a narrow band oscillation with a time-varying center frequency $f(\tau)$, instantaneous amplitude $A(t)$, phase $\phi(t)$, and the direct current component $dc(t)$:

$$\boldsymbol{x(t) = dc(t) + A(t)\cos\left(\int_0^t 2\pi f(\tau)d\tau + \phi(t)\right)}$$

Step (1) For a given center frequency, we can extract the instantaneous amplitude information $A(t)$ and phase information $\phi(t)$ by multiplying (1) by $e^{-j\int_0^t 2\pi f(\tau)d\tau}$ which results in the following:

$$z(t) = x(t)e^{-j\int_0^t 2\pi f(\tau)d\tau} = dc(t)e^{-j\int_0^t 2\pi f(\tau)d\tau} + \frac{A(t)}{2}e^{j\phi(t)} + \frac{A(t)}{2} e^{-j\left(\int_0^t 4\pi f(\tau)d\tau + \phi(t)\right)}$$

Step (2) From (2), if $z(t)$ is filtered with an ideal low-pass filter (LPF) with a cutoff frequency $f_c < f_0$, where f_0 is the center frequency of interest. Then the filtered signal $z_{lp}(t)$ will contain only the component of interest $z_{lp}(t) = \frac{A(t)}{2}e^{j\phi(t)}$.

Step (3) By changing the center frequency followed by using the variable frequency approach as well as the LPF, the signal, $x(t)$, will be decomposed into the sinusoid modulations, d_i, by the CDM technique as follows:

$$\boldsymbol{x(t) = \sum_i d_i = dc(t) + \sum_i A_i(t)\cos\left(\int_0^t 2\pi f_i(\tau)d\tau + \phi_i(t)\right)}$$

Step (4) The instantaneous frequency and amplitude of d_i can be calculated using the Hilbert transform

$$A(t) = 2|z_{lp}(t)| = [X^2(t) + Y^2(t)]^{1/2}$$
$$X(t) = real(z_{lp}(t))$$
$$Y(t) = imag(z_{lp}(t)) = H[X(t)] = \frac{1}{\pi}\int \frac{X(t')}{t - t'}dt'$$

[00193] FIG. 16 shows the twelve components corresponding to the IR and Red signal for subject #5. Among the twelve frequency bands, bands 1 to 5 correspond to frequency range of [0.5 Hz to 3 Hz], which is typically the HR frequency range accounting for both normal and elevated heart rates. Embodiments disclosed herein select a component of these 5 components to reconstruct the signal that preserves the HR and is less corrupted by the motion artifacts. For the selection, an accurate HR may be estimated by selecting the components that match closest to the actual HR frequency in order to reconstruct a less noisy PPG signal than the original motion corrupted data.

[00194] Spectral Filtering

[00195] After obtaining the power spectral density at each window, HR frequency may be assumed to be confined in the range [0.5 Hz – 3 Hz], which takes into account both at rest and high HR values due to either tachycardia or exercise scenarios. Next, for HR estimation, the strategy is to keep only frequencies that correspond to the first and second peak at each column of time-frequency matrix, as disclosed above, with reference to FIG. 3B.

[00196] In general, HR frequency in the VFCDM based power spectral density of the PPG at each window can have three different scenarios: (1) PPG is devoid of MA and there is no sensor-skin interface problems like a spatial gap between the sensor and the subject's skin during recording, (2) PPG is corrupted by MA and there is no spatial gap between the sensor and the subject's skin during recording and (3) There is a spatial gap between the sensor and the subject's skin during recording. For the ideal case (1), HR can be extracted and it is most likely represented as the highest peak in the PPG spectrum. For case (2), MA dynamics can result in the dominant peak and HR frequency peak's magnitude become smaller than the MA frequency peak in the spectrum. The only scenario that makes it difficult to extract HR from the spectrum is scenario (3) when there is a spatial gap between the PPG sensor and the subject's skin during recording. In this scenario, assuming that the motion artifacts are short lasting, the missing HR values can be interpolated using the cubic spline approach.

[00197] FIGS. 17A-C are plots of the above three scenarios. In FIG. 17A and FIG. 17B, the true HR frequency is close to the first and second peak respectively, while in FIG. 17C, the true HR frequency is far from the dominant peaks in the spectrum. As long as the PPG data is clean, an assumption may be made that the HR frequency belongs to the frequency component with the

highest power (peak) at the each column of the TFS matrix. On the other hand, when the data becomes corrupted by MA, it might shift the HR frequency to the next highest peak in the spectrum or might lose the dominant HR frequency.

[00198] Embodiments disclosed herein employ a TFS filtering step to search for N first highest spectral peaks and their associated frequencies in each column of the TFS. Hence, the original TFS of FIG. 15B can be filtered to select only N, for example, 2, in the example embodiments, highest spectral peaks.

[00199] FIG. 18A shows a representative filtered time-frequency spectral plot of PPG recording from subject #5. This portion of the OxiMA method involves retaining only the two largest frequency peaks at each time point within the defined HR range (30-180 bpm) and they are represented as blue and green traces, respectively.

[00200] Heart Rate Tracking and Extraction

[00201] After filtering the TFS, the HR may be extracted. The HR tracking method may be summarized as: Assume there is only knowledge of the initial HR, the HR at each window is extracted by comparing the peaks to the previous HR value.

[00202] As disclosed above with reference to FIG. 3B, if the largest peak is within the 10 bpm range from the previous value of HR, it is chosen; if not, the second largest peak is checked for compliance of this scenario. If the HR value deviates by more than 10 bpm, the HR from the previous window may be adopted by the method.

[00203] FIG. 18B illustrates the tracking of HR based on OxiMA method, disclosed above.

[00204] FIGS. 19A and 19B represent comparisons, of the estimated 8 second moving averaged HR from the OxiMA method, to the reference HR, and the HR calculated from the motion-corrupted PPG signal, compared to the reference HR from the ECG, respectively. In order to calculate the performance of the OxiMA method for HR reconstruction, the error value in each time window was calculated from the estimated HR to the reference ECG-derived HR. Two measurement indices of absolute and normalized errors similar to the indices in (Wang, H., et al., A high resolution approach to estimating time-frequency spectra and their amplitudes. Ann Biomed Eng, 2006. 34(2): p. 326-3) were used.

$$Error(1) = \frac{1}{W}\Sigma_{k=1}^{W}\left|HR_{OxiMA}(k) - HR_{ref}(k)\right| \quad (5)$$

$$Error(2) = \frac{1}{W}\sum_{k=1}^{w}\frac{|HR_{OxiMA}(k) - HR_{ref}(k)|}{HR_{OxiMA}(k)} \times 100\% \quad (6)$$

where, W is the total number of windows.

[00205] PPG signal reconstruction

[00206] Now that HR values at each time window are estimated from the time-frequency spectrum, the signal reconstruction phase of the OxiMA method may be performed. An assumption may be made that the signal components corresponding to the HR frequency are more robust against motion and, thus, a less corrupted signal can be reconstructed using the summation of these components.

[00207] By calculating the components from the Signal Decomposition, using Eq (4) and the time-frequency spectrum of the PPG, at each 8-sec window a signal component may be chosen that has a frequency close to estimated HR frequency and that component may be employed to reconstruct infrared and red PPG data at each window. This yields a less motion-corrupted data that can be used for oxygen saturation estimation, as disclosed in FIG. 20A and FIG. 20B.

[00208] Oxygen Saturation Estimation

[00209] In order to calculate SpO2 from PPG signals, red and infrared PPG signals with clearly separable DC and AC components are required. Let the pulsatile components of the red and infrared PPG signals be denoted as AC_{Red} and AC_{IR}, respectively, then the "ratio-of-ratio" R is estimated (Thakor, N.V. and Y.S. Zhu, Applications of adaptive filtering to ECG analysis: noise cancellation and arrhythmia detection. IEEE Trans Biomed Eng, 1991. 38(8): p. 785-94; Diniz, P., Adaptive filtering: algorithms and practical implementation. 2008: . Springer Science, Business Media L.L.C) as

$$\boldsymbol{R} = \frac{\boldsymbol{AC_{Red}/DC_{Red}}}{\boldsymbol{AC_{IR}/DC_{IR}}} \quad (7)$$

[00210] Accordingly, SpO2 may be computed by substituting the R value in an empirical linear approximated relation given by $SpO_2(\%) = (110 - 25R)$.

[00211] FIG. 20C represents the reconstructed SpO2 values obtained from OxiMA in comparison to the reference SpO2 values and the estimated values before reconstruction.

[00212] OxiMA Results

[00213] Table 13 represents the average absolute error (E1) and the average absolute error percentage (E2) of HR and SpO2 estimations of the OxiMA method on the varying hypoxia level dataset.

TABLE 13
OXIMA METHOD PERFORMANCE COMPARISON (HR ESTIMATIONS)

Subject	Actual HR estimation error		OxiMA HR estimation error	
	E1	E2%	E1	E2%
1	3.84	4.83	**1.53**	**2.10**
2	6.84	9.57	**2.72**	**3.97**
3	8.15	9.59	**1.69**	**2.29**
4	4.55	5.39	**2.61**	**3.18**
5	10.53	11.96	**4.04**	**4.60**
6	4.46	5.52	**2.04**	**2.66**
7	12.41	19.65	**2.81**	**4.37**
8	3.84	4.35	**2.10**	**2.46**
9	3.80	4.13	**2.57**	**2.83**
10	3.65	4.20	**1.85**	**2.41**
mean ± std	6.20 ± 3.2	7.91 ± 5.0	2.40 ± 0.73	3.09 ± 0.90

[00214] The OxiMA method is compared to the HR and SpO2 estimations prior to the reconstruction method, where both pre- and post-reconstruction estimations are compared to the reference HR and reference SpO2 values obtained from the Masimo pulse oximeter.

[00215] The results presented in Table 13 show that OxiMA on average improves the HR and SpO2 estimations by 100% and 105%, respectively when compared to those estimations without the reconstruction method. Improvement rates are calculated as follow:

$$\boldsymbol{ImRate1}(\%) = \frac{1}{W}\sum_{k=1}^{W} \frac{|Error1_{OxiMA}(k) - Error1_{Act}(k)|}{Error1_{OxiMA}(k)} \times 100\% \quad (8)$$

$$\boldsymbol{ImRate2}(\%) = \frac{1}{W}\sum_{k=1}^{W} \frac{|Error2_{OxiMA}(k) - Error2_{Act}(k)|}{Error2_{OxiMA}(k)} \times 100\% \quad (9)$$

[00216] FIGS. 21A-C and FIGS. 22A-B show the reconstructed SpO2 and HR in comparison to the reference HR from ECG recordings for subject #5. The largest error among all recordings was found to be from this recording, as shown in Tables 13 and 14. The larger error could be due to rapid movements or skin-sensor gap during the recordings.

TABLE 14
OXIMA METHOD PERFORMANCE COMPARISON (SpO_2 ESTIMATIONS)

Subject	Actual SpO_2 estimation error		OxiMA SpO_2 estimation error	
	E1	E2%	E1	E2%
1	2.51	2.63	**0.86**	**0.90**
2	7.14	9.63	**2.45**	**3.10**
3	6.21	6.59	**1.61**	**1.67**
4	1.89	2.46	**0.95**	**1.16**
5	7.13	7.80	**3.25**	**3.47**
6	2.85	2.99	**1.10**	**1.14**
7	5.83	9.09	**2.57**	**4.52**
8	3.51	4.63	**1.73**	**2.22**
9	1.81	2.10	**1.50**	**1.61**
10	4.85	5.91	**1.93**	**2.07**
mean ± std	4.37 ± 2.1	5.38 ± 2.8	1.79 ± 0.8	2.19 ± 1.2

[00217] As such, the E1 (HR) for this particular subject is as low as 4.05 bpm while the E1 (SpO2) is as low as 3.25%. It can be seen from Table 15, disclosed below, that HR and SpO2 both improved by 160% and 119%, respectively, post reconstruction method.

TABLE 15
OXIMA METHOD PERFORMANCE COMPARISON (SpO_2 ESTIMATIONS)

Subject	HR Improvement Rate		SpO_2 Improvement Rate	
	ImRate1%	ImRate2%	ImRate1%	ImRate2%
1	150.90	130.00	191.86	192.22
2	151.47	141.05	191.43	210.64
3	323.08	318.78	285.71	294.61
4	74.33	69.50	98.95	112.07
5	160.17	160.66	119.38	124.78
6	118.63	107.52	159.09	162.28
7	377.22	372.54	126.85	101.10
8	82.86	76.83	102.89	108.55
9	47.86	45.94	20.67	30.43
10	97.30	74.27	151.30	185.5
mean ±	158.38 ±	149.71 ±	144.81 ±	152.2 ±

V. Conclusions

[00218] As such, the OxiMA method that may be based on time-varying spectral analysis of the PPG signal combats motion artifacts that can degrade the accuracy of SpO2 and HR estimations. According to embodiments disclosed herein, the OxiMA method may decompose

the PPG signal into many frequency bands using a VFCDM method (Chon, K.H., S. Dash, and J. Kihwan, Estimation of Respiratory Rate From Photoplethysmogram Data Using ~~Time–Frequency~~ Time-Frequency Spectral Estimation. Biomedical Engineering, IEEE Transactions on, 2009. 56(8): p. 2054-2063), or any other suitable time-frequency technique, such as a wavelet analysis (Chon, K.H., S. Dash, and J. Kihwan, Estimation of Respiratory Rate From Photoplethysmogram Data Using ~~Time–Frequency~~ Time-Frequency Spectral Estimation. Biomedical Engineering, IEEE Transactions on, 2009. 56(8): p. 2054-2063). According to embodiments disclosed herein, those components that are within the heart rate ranges including both extreme ranges of the low and high heart rates may be decomposed and used to reconstruct the PPG signal based on those components. As such, frequencies that are not within the prescribed HR ranges may be removed. From this reconstructed time series HR may be estimated and SpO2 may be estimated, as disclosed above.

[00219] The dataset used to verify the OxiMA method's performance was collected from 10 subjects during hypoxic experiments. The results show accurate estimation of both HR and SpO2 even during the presence of severe motion artifacts where the average error was only 2.4 bpm. More importantly, the average improvements in these estimates are astoundingly high for both HR (149%) and SpO2 (152%) when the reconstruction method applied, according to embodiments disclosed herein. Other methods for estimates of HR during severe motion artifacts for PPG signal Zhilin, Z., P. Zhouyue, and L. Benyuan, TROIKA: A General Framework for Heart Rate Monitoring Using Wrist-Type Photoplethysmographic Signals During Intensive Physical Exercise. Biomedical Engineering, IEEE Transactions on, 2015. 62(2): p. 522-531; Zhang, Z., Photoplethysmography-Based Heart Rate Monitoring in Physical Activities via Joint Sparse Spectrum Reconstruction. Biomedical Engineering, IEEE Transactions on, 2015. PP(99): p. 1-1; Salehizadeh, S., et al., A Novel Time-Varying Spectral Filtering Algorithm for Reconstruction of Motion Artifact Corrupted Heart Rate Signals During Intense Physical Activities Using a Wearable Photoplethysmogram Sensor. Sensors, 2015. 16(1): p. 10) produced good results (Kalman, R.E., A New Approach to Linear Filtering and Prediction Problems Transactions of the ASME – Journal of Basic Engineering, 1960. Series D (82)). However, these methods are only confined to HR estimation and not SpO2. Specifically, previous PPG reconstruction methods, such as (Salehizadeh, S.M.A., et al., Photoplethysmograph Signal

Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263; Kim, B.S. and S.K. Yoo, Motion artifact reduction in photoplethysmography using independent component analysis. IEEE Trans Biomed Eng, 2006. 53(3): p. 566-8), have been tested under MA conditions but not with concomitant hypoxia. The results, disclosed abele, illustrate the efficacy of a method which provides accurate estimates of both SpO2 and HR even when there are significant MA and concomitant low oxygen saturation values.

[00220] Observations were made while analyzing the OxiMA data. The tracking ability of the OxiMA method decreased as the frequency changes during recordings increased. This is mostly likely because OxiMA tracks a dominant frequency through an 8-second window. Since each subjects' motion varied throughout each hypoxic maneuver, the dominant frequency can change within the observed window. The strength of the PPG's LED is one of the most important factors determining the performance. A reduction in the strength of the PPG signal can be caused by ambient light leaking into the gap between a PPG sensor and the skin surface (Zhang, Z., Photoplethysmography-Based Heart Rate Monitoring in Physical Activities via Joint Sparse Spectrum Reconstruction. Biomedical Engineering, IEEE Transactions on, 2015. PP(99): p. 1-1). This is because the power of the signal is dependent on the depth and reflection of the light from the pulse oximeter sensor to the subject's skin. This gap between the skin and the sensor may be the result of movement during physical activities or the shape of tissue that the sensors touch. In the datasets that have been analyzed, recordings #5 and #7 are examples of the above two scenarios.

[00221] Additionally, the local blood perfusion of the monitored region affects the signal-to-noise ratio of the PPG signal. When performing the hypoxic maneuvers, subjects' HR and breathing rate normally increase as oxygen saturation decreases. These physiologic changes cause more distinct pulsations in the digits, which increase the signal-to-noise ratio.

[00222] The OxiMA method can be easily implemented in real-time. Execution time of the method has been found to be only 180 msec on data divided into 8 second segments using Matlab® R2014a and CPU 3.6GHz. Therefore, given the high accuracy of the OxiMA method in estimating HR and SpO2 despite severe motion artifacts, this method has the potential to be

applicable for implementation on wearable devices such as smart watches and PPG-based fitness sensors.

[00223] FIG. 23 is a block diagram of an example of the internal structure of a computer 2300 in which various embodiments of the present disclosure may be implemented. The computer 2300 contains a system bus 2302, where a bus is a set of hardware lines used for data transfer among the components of a computer or processing system. The system bus 2302 is essentially a shared conduit that connects different elements of a computer system (*e.g.*, processor, disk storage, memory, input/output ports, network ports, *etc.*) that enables the transfer of information between the elements. Coupled to the system bus 2302 is an I/O device interface 2404 for connecting various input and output devices (*e.g.*, keyboard, mouse, displays, printers, speakers, *etc.*) to the computer 2300. A network interface 2306 allows the computer 2300 to connect to various other devices attached to a network. Memory 2308 provides volatile storage for computer software instructions 2310 and data 2312 that may be used to implement embodiments of the present disclosure. Disk storage 2314 provides non-volatile storage for computer software instructions 2310 and data 2312 that may be used to implement embodiments of the present disclosure. A central processor unit 2318 is also coupled to the system bus 2302 and provides for the execution of computer instructions.

[00224] Further example embodiments disclosed herein may be configured using a computer program product; for example, controls may be programmed in software for implementing example embodiments. Further example embodiments may include a non-transitory computer-readable medium containing instructions that may be executed by a processor, and, when loaded and executed, cause the processor to complete methods described herein. It should be understood that elements of the block and flow diagrams, such as the reconstruction unit 416, output unit 418, reconstruction unit 516, output unit 518, heart rate unit, arterial oxygen saturation (SpO2) unit, and ailment unit, disclosed above, may be implemented in software, hardware, such as via one or more arrangements of circuitry of FIG. 23, disclosed above, or equivalents thereof, firmware, a combination thereof, or other similar implementation determined in the future. In addition, the elements of the block and flow diagrams described herein may be combined or divided in any manner in software, hardware, or firmware. If implemented in software, the software may be written in any language that can support the

example embodiments disclosed herein. The software may be stored in any form of computer readable medium, such as random access memory (RAM), read only memory (ROM), compact disk read-only memory (CD-ROM), and so forth. In operation, a general purpose or application-specific processor or processing core loads and executes software in a manner well understood in the art. It should be understood further that the block and flow diagrams may include more or fewer elements, be arranged or oriented differently, or be represented differently. It should be understood that implementation may dictate the block, flow, and/or network diagrams and the number of block and flow diagrams illustrating the execution of embodiments disclosed herein.

[00225] The teachings of all patents, published applications and references cited herein are incorporated by reference in their entirety.

[00226] While this invention has been particularly shown and described with references to example embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the invention encompassed by the appended claims.

Date:_____Express Mail Label No._____

Inventors: Seyed M. A. Salehizadeh, Ki H. Chon and Yeonsik Noh

Attorney's Docket No.: 4147.1020-002 (15-089)

METHOD AND APPARATUS FOR REMOVING MOTION ARTIFACTS FROM BIOMEDICAL SIGNALS

RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 62/172,862 filed June 9, 2015 and U.S. Provisional Application No. 62/299,944 filed February 25, 2016. The entire teachings of the above applications are incorporated herein by reference.

GOVERNMENT SUPPORT

[0002] This invention was made with government support under Grant No. W81XWH-12-1-0541 from the US Army Medical Research and Material Command (USAMRMC). The government has certain rights in the invention.

BACKGROUND

[0003] Heart rate monitors have become widely-used training aids for a variety of sports. Some heart rate monitors use sensors based on photoplethysmography (PPG) technology. The PPG sensors include infrared light-emitting diodes (LEDs) and photodetectors, and offer a simple, reliable, low-cost means of monitoring pulse rate noninvasively, both at rest and during exercise.

SUMMARY

[0004] During exercise and other activities, PPG and other sensors may experience movement, such as shifting position or rotating, relative to a sensing location (*e.g.*, wrist or

finger). The movement typically results in an introduction of a motion artifact in an electrical signal produced by the sensor. The motion artifact may be interpreted by a processor as a heart-related signal if not addressed in advance of or as part of the processing in the processor. By properly addressing the motion artifact, an embodiment disclosed herein has improved accuracy in reconstructing the heart-related signal, thereby enabling processes that use the heart-related signal to have better performance.

[0005] Accordingly, a method for reconstructing a heart-related signal output by a biomedical sensor may comprise reconstructing a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal. The reconstructing may be based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and the classification of the movement may be based on (ii) a classification of the movement. The method may further comprise outputting the reconstructed representation of the heart-related signal.

[0006] The motion artifacts may be suppressed in the reconstructed representation of the heart-related signal.

[0007] The time-varying spectral analysis may include pre-processing the heart-related signal to produce a pre-processed heart-related signal. In an event the classification indicates that the movement does not rise to a level causing the motion artifacts, the reconstructed representation may be based on an average value of peak-to-peak intervals in the pre-processed heart-related signal.

[0008] The pre-processing may include filtering the heart-related signal to produce a filtered heart-related signal.

[0009] The pre-processing may further include down-sampling the filtered heart-related signal, the down-sampling being at a sampling rate less than an original sampling rate.

[0010] The time-varying spectral analysis may include computing a first time-frequency spectrum (TFS) of the heart-related signal and computing a second TFS of the motion signal.

[0011] The first TFS computed and the second TFS computed may be 3-dimensional spectra, the first TFS computed and the second TFS computed each including a respective time-varying amplitude or power distribution with respect to time and frequency.

[0012] The first TFS computed may be a first time-varying power spectral density (PSD) and the second TFS computed may be a second time-varying PSD.

[0013] The reconstructed representation may be a current reconstructed representation. Based on the classification indicating that the movement does rise to a level causing the motion artifacts and is a pseudo-periodic movement or a periodic movement, the reconstructing may include determining whether at least one spectral peak is present having a corresponding frequency within a given frequency range at a point in time in the first TFS computed, the current reconstructed representation being reconstructed for the point in time. Based on a determination that the at least one spectral peak is not present, the current reconstructed representation may be based on a prior reconstructed representation, the prior reconstructed representation associated with a previous point in time in the first TFS computed. The given frequency range may be 0.5 Hz to 3 Hz.

[0014] The reconstructing may include retaining up to a pre-determined number of candidate spectral peaks located at a first point in time in the first TFS computed. The candidate spectral peaks retained may be based on having corresponding frequencies within a given frequency range and highest amplitude or power values relative to other spectral peaks located at the first point in time, the other spectral peaks having respective frequencies within the given frequency range. The reconstructing may further include discarding each of the candidate spectral peaks retained that is associated with a same frequency as a dominant spectral peak located at a second point in time in the second TFS computed. The first point in time and the second point time may have same time values. The given frequency range may be 0.5 Hz to 3 Hz.

[0015] The representation may be a current representation and the reconstructed representation may be a current reconstructed representation. In an event the discarding discards each of the candidate spectral peaks retained, reconstructing the current representation may be based on a prior reconstructed representation, the prior reconstructed representation associated with a previous point in time in the first TFS computed, the previous point in time being an earlier point in time with respect to the first point in time.

[0016] The discarding may be a first discarding, the representation may be a current representation and, in an event the first discarding results in at least one remaining candidate spectral peak retained, reconstructing the current representation may further include second discarding. The second discarding may discard remaining candidate spectral peaks, of the at least one remaining candidate spectral peak retained, based on whether a corresponding frequency of the at least one remaining candidate spectral peak retained is distanced by at least a frequency difference threshold from a prior reconstructed representation's frequency. The prior reconstructed representation associated with a previous point in time in the first TFS computed. The previous point in time may be an earlier point in time with respect to the first point in time.

[0017] Based on each of the at least one remaining candidate spectral peak retained having been discarded by the second discarding, reconstructing the current representation may be based on the prior reconstructed representation. Based on at least one last candidate spectral peak remaining, the at least one last candidate spectral peak remaining not discarded by the second discarding, reconstructing the current representation may be based on a selected candidate spectral peak. The selected candidate spectral peak may be selected from amongst the at least one last candidate spectral peak remaining having a closest corresponding frequency to the prior reconstructed representation's frequency relative to respective frequencies of each of the at least one last candidate spectral peak remaining.

[0018] The dominant spectral peak may have a largest power or amplitude value relative to other peaks located at the second point in time in the second TFS.

[0019] The retaining and the discarding may be based on the classification indicating that the movement is a pseudo-periodic movement or a periodic movement, and determining that at least one spectral peak with a corresponding frequency in the given frequency range is present at the first point in time.

[0020] The time-varying spectral analysis may further include pre-processing the heart-related signal and the motion signal for the computing of the first TFS and the second TFS.

[0021] The pre-processing may include filtering the heart-related signal and the motion signal to produce a filtered heart-related signal and a filtered motion signal, respectively. The pre-processing may further include down-sampling both the filtered heart-related signal and the

filtered motion signal, the down-sampling being at a sampling rate less than an original sampling rate.

[0022] The method may further include classifying the classification of the movement by comparing an amount of amplitude modulation in the second TFS computed to an amplitude modulation threshold. The amplitude modulation threshold may be dependent on a type of the motion detector sensor. The classification may indicate whether the movement rises to a level causing the motion artifacts based on a result of the comparing. In an event the result indicates that the movement does rise to the level causing the motion artifacts, classifying the classification of the movement may further include determining whether the movement is either a pseudo-periodic movement or a periodic movement, versus a random movement.

[0023] In determining whether the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement, the method may further include identifying a first, second, and third frequency associated, respectively, with a first, second, and third spectral peak in the second TFS at a point in time in the second TFS. The first, second, and third peaks may have largest power or amplitude values relative to other peaks in the second TFS at the point in time. The first spectral peak may be a largest spectral peak amongst the first, second, and third spectral peaks.

[0024] In determining whether the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement, the method may further include computing a first ratio of the second frequency identified to the first frequency identified. The method may determine a first comparison result by comparing the first ratio computed to a first ratio value. The method may compute a second ratio of the third frequency identified to the first frequency identified. The method may determine a second comparison result by comparing the second ratio computed to a second ratio value. The classification may further indicate the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement, based on the first comparison result and the second comparison result. The first ratio value may be 2 and the second ratio value may be 3.

[0025] The time-varying signal analysis may include pre-processing the heart-related signal to produce a pre-processed heart-related signal and, in an event the classification of the movement indicates the random movement, the reconstructing may include computing an

average value of a number of prior reconstructed representations outputted prior to the reconstructing. The number may be based on a duration of consecutive motion artifacts, detected prior to the reconstructing. The time-varying signal analysis may further include computing a bandpass filter cutoff frequency based on the average value computed, and filtering the pre-processed heart-rate signal by applying the band pass filter computed to produce a filtered, pre-processed heart-related signal. The reconstructed representation may be based on an average peak-to-peak interval value of the filtered, pre-processed heart-rate signal.

[0026] The heart-related signal and the motion signal may be produced, concurrently.

[0027] The method may comprise segmenting the heart-related signal into a plurality of windowed heart-related signal data segments and segmenting the motion signal into a corresponding plurality of windowed motion signal data segments. The method may comprise repeating the reconstructing and the outputting for each windowed heart-related signal data segment and each corresponding motion signal data segment. The time window may be a value in a range from 2 to 32 seconds.

[0028] The biomedical sensor may be at least one of: a photoplethysmogram (PPG) sensor, piezoelectric sensor, Light Emitting Diode (LED) based sensor, camera sensor, and pulse oximeter sensor, and the motion sensor may be an accelerometer.

[0029] The biomedical sensor and the motion sensor may be co-located.

[0030] The method may further comprise employing the reconstructed representation to determine a heart rate estimate.

[0031] The method may further comprise employing the reconstructed representation to determine an arterial oxygen saturation (SpO2) estimate.

[0032] The method may further comprise employing the reconstructed representation to detect or predict a heart-related ailment. The heart-related ailment may include at least one of a heart rate variability (HRV) condition, atrial fibrillation condition, congestive heart failure condition, and tachycardia condition.

[0033] The reconstructing and the outputting may be performed in real-time with respect to production of the heart-related signal and the motion signal.

[0034] The reconstructing and the outputting may be performed in non-real-time with respect to production of the heart-related signal and the motion signal.

[0035] According to another embodiment, an apparatus for reconstructing a heart-related signal output by a biomedical sensor may comprise a reconstruction unit. The reconstruction unit may be configured to reconstruct a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal, the reconstructing based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of the movement. The apparatus may further comprise an output unit configured to output the reconstructed representation of the heart-related signal.

[0036] Yet another example embodiment may include a non-transitory computer-readable medium having stored thereon a sequence of instructions which, when loaded and executed by a processor, causes the processor to complete methods disclosed herein.

[0037] It should be understood that embodiments disclosed herein can be implemented in the form of a method, apparatus, system, or computer readable medium with program codes embodied thereon.

BRIEF DESCRIPTION OF THE DRAWINGS

[0038] The patent or application file contains at least one drawing executed in color. Copies of this patent or patent application publication with color drawing(s) will be provided by the Office upon request and payment of the necessary fee.

[0039] The foregoing will be apparent from the following more particular description of example embodiments of the invention, as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating embodiments of the present invention.

[0040] FIG. 1 is a block diagram of an example application for which embodiments disclosed herein may be applied.

[0041] FIG. 2 is a flow diagram of an example embodiment of a method for reconstructing a heart-related signal output by a biomedical sensor.

[0042] FIGS. 3A-C are flow diagrams of example embodiments of a method for reconstructing a heart-related signal output by a biomedical sensor.

[0043] FIG. 4 is a block diagram of an example embodiment of a system.

[0044] FIG. 5 is a block diagram of an example embodiment of an apparatus for reconstructing a heart-related signal output by a biomedical sensor.

[0045] FIGS. 6A-6C show Time-Frequency spectra of a recording from a dataset.

[0046] FIG. 7 is a filtered time-frequency spectral plot of a photoplethysmogram (PPG) signal.

[0047] FIGS. 8A-8B show motion artifact detection in a PPG spectrum according to embodiments disclosed herein.

[0048] FIG. 9 shows a comparison of reconstructed heart rate (HR) obtained, according to embodiments disclosed herein, to reference HR obtained from simultaneous electrocardiogram (ECG) recordings.

[0049] FIG. 10A is an example embodiment of PPG signal reconstruction according to embodiments disclosed herein.

[0050] FIG. 10B is a zoomed-in version of FIG. 10A.

[0051] FIGS. 11A-B show comparisons of heart rate variability (HRV) spectra between a reference and a reconstructed HRV time series (*e.g.*, as shown in FIGS. 10A-B) from a motion artifact-contaminated PPG signal for a given dataset.

[0052] FIG. 11C is a performance comparison table of a spectral approach for filtering motion artifacts (SpaMA) method to alternative methods.

[0053] FIGS. 12A, 12B, 13A, 13B, 14A, and 14B show the reconstructed HR and corresponding power spectral density (PSD) of a sample-sample windowed HR, according to embodiments disclosed herein, in comparison to a reference HR from an ECG.

[0054] FIG. 14C is a table that includes PPG datasets and experiments settings.

[0055] FIGS. 15A-B show an example resultant variable frequency complex demodulation (VFCDM) time-frequency spectrum of recordings from a given subject.

[0056] FIG. 16 shows twelve components corresponding to the Infrared (IR) and Red signal for the given subject.

[0057] FIGS. 17A-C are example spectra plots corresponding to three scenarios.

[0058] FIG. 18A shows a representative filtered time-frequency spectral plot of PPG recording from subject #5.

[0059] FIG. 18B shows tracking of HR based on embodiments disclosed herein.

[0060] FIGS. 19A-B represent comparisons of an estimated 8 second moving average HR from a spectral approach for filtering motion artifacts for oxygen saturation estimation (OxiMA) method to a reference HR, and an HR calculated from a motion-corrupted PPG signal compared to a reference HR from an ECG, respectively.

[0061] FIGS. 20A-C are example plots of data showing less motion-corrupted data that can be used for oxygen saturation estimation.

[0062] FIGS. 21A-C and FIGS. 22A-B show reconstructed arterial oxygen saturation (SpO2) and HR in comparison to the reference HR from ECG recordings for the given subject.

[0063] FIG. 23 is a block diagram of an example internal structure of a computer optionally within an embodiment disclosed herein.

DETAILED DESCRIPTION

[0064] A description of example embodiments of the invention follows.

[0065] Accurate estimation of a heart rate (HR) and changing arterial oxygen saturation (SpO2) from a heart-related signal, such as a photoplethysmogram (PPG) signal, during intense physical activity is a very challenging problem. This is because strenuous and high intensity exercise can result in severe motion artifacts (MAs) in the heart-related signal, making accurate HR and SpO2 estimation difficult.

[0066] HR monitoring using PPG signals has many advantages compared to using traditional ECG sensors, such as simpler hardware implementation, lower cost, and no need for daily application of electrodes (Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263). Fluctuations of the PPG signal are caused by changes in arterial blood volume associated with each heartbeat, where the magnitude of the fluctuations depends on the amount of blood rushing into the peripheral vascular bed, the optical absorption of the blood, skin, and tissue, and the wavelength used to illuminate the blood. The pulse oximeter signal contains not only the

blood oxygen saturation and heart rate (HR) data, but also other vital physiological information (Chon, K.H., S. Dash, and J. Kihwan, Estimation of Respiratory Rate From Photoplethysmogram Data Using Time-Frequency Spectral Estimation. Biomedical Engineering, IEEE Transactions on, 2009. 56(8): p. 2054-2063; Lee, J. and K.H. Chon, Respiratory Rate Extraction Via an Autoregressive Model Using the Optimal Parameter Search Criterion. Annals of Biomedical Engineering, 2010. 38(10): p. 3218-3225; Dash, S., et al., Estimation of Respiratory Rate From ECG, Photoplethysmogram, and Piezoelectric Pulse Transducer Signals: A Comparative Study of Time-Frequency Methods. Biomedical Engineering, IEEE Transactions on, 2010. 57(5): p. 1099-1107; Jinseok, L. and K.H. Chon, Time-Varying Autoregressive Model-Based Multiple Modes Particle Filtering Algorithm for Respiratory Rate Extraction From Pulse Oximeter. Biomedical Engineering, IEEE Transactions on, 2011. 58(3): p. 790-794). The fluctuations of PPG signals contain the influences of arterial, venous, autonomic and respiratory systems on the peripheral circulation. Utilizing a pulse oximeter as a multi-purpose vital sign monitor has clinical appeal, since it is familiar to the clinician and comfortable for the patient (Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263). Even simple knowledge of HR patterns would provide more useful clinical information than just HR and blood oxygenation, especially in situations in which a pulse oximeter is the sole monitor available. One major example of such benefits can be seen in a study by Chong et al. which shows that accurate detection of atrial fibrillation can be obtained from PPG data (Jo Woon, C., et al., Arrhythmia Discrimination Using a Smart Phone. Biomedical and Health Informatics, IEEE Journal of, 2015. 19(3): p. 815-824). In addition to the acquisition of HR in response to exercise, research has recently focused on obtaining HRV information from wearable sensors including devices that use PPGs (Achten, J. and A.E. Jeukendrup, Heart rate monitoring: applications and limitations. Sports medicine (Auckland, N.Z.), 2003. 33(7): p. 517-538). Increased HRV has been associated with lower mortality rates and is affected by both age and sex (Achten, J. and A.E. Jeukendrup, Heart rate monitoring: applications and limitations. Sports medicine (Auckland, N.Z.), 2003. 33(7): p. 517-538). During graded exercise, the majority of studies show that HRV decreases progressively up to moderate intensities, after which it stabilizes (Laughlin, M.H., Cardiovascular response to

exercise. Am J Physiol, 1999. 277(6 Pt 2): p. S244-59). Although there are many promising and attractive features of using pulse oximeters for vital sign monitoring, currently they are mainly used on stationary patients. This is because motion artifacts (MAs) result in unreliable HR and SpO_2 estimation (Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263). Clinicians have cited motion artifacts in pulse oximetry as the most common cause of false alarms, loss of signal, and inaccurate readings (Jubran, A., Pulse oximetry. Crit Care, 1999. 3(2): p. R11-r17). During physical activities, MA contamination in PPG signals seriously interferes with HR estimation. The MAs are mainly caused by ambient light leaking into the gap between the PPG sensor surface and skin surface. Besides, the change in blood flow due to movements is another MA source (Maeda, Y., M. Sekine, and T. Tamura, Relationship between measurement site and motion artifacts in wearable reflected photoplethysmography. J Med Syst, 2011. 35(5): p. 969-76). In practice, MAs are difficult to remove because they do not have a predefined narrow frequency band and their spectrum often overlaps that of the desired signal (Thakor, N.V. and Y.S. Zhu, Applications of adaptive filtering to ECG analysis: noise cancellation and arrhythmia detection. IEEE Trans Biomed Eng, 1991. 38(8): p. 785-94). Consequently, development of methods capable of reconstructing the corrupted signal and removing artifacts is challenging. There are a number of general techniques used for artifact detection and removal. One of the methods used to remove motion artifacts is adaptive filtering (Diniz, P., Adaptive filtering: algorithms and practical implementation. 2008: . Springer Science, Business Media L.L.C., Kalman, R.E., A New Approach to Linear Filtering and Prediction Problems Transactions of the ASME – Journal of Basic Engineering, 1960. Series D(82); Morbidi, F., et al., Application of Kalman Filter to Remove TMS-Induced Artifacts from EEG Recordings. Control Systems Technology, IEEE Transactions on, 2008. 16(6): p. 1360-1366; Seyedtabaii, S.S.a.L., Kalman filter based adaptive reduction of motion artifact from photoplethysmographic signal. World Academy of Science, Engineering and Technology, 2008. 37). An adaptive filter is easy to implement and it also can be used in real-time applications, though the requirement of additional sensors to provide reference inputs is the major drawback of such methods. There are many motion and noise artifact reduction techniques based on the concept of blind source separation

(BSS). The aim of BSS is to estimate a set of uncorrupted signals from a set of mixed signals which is assumed to contain both the clean and noisy sources (Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263). Some of the popular BSS techniques are independent component analysis (ICA) (Comon, P., Independent component analysis, A new concept? Signal Processing, 1994. 36(3): p. 287-314), canonical correlation analysis (CCA) (Thompson, B., Canonical Correlation Analysis: Uses and Interpretation. 1984: SAGE Publications), principle component analysis (PCA) (Jolliffe, I.T., Principal Component Analysis. 2 ed. Springer Series in Statistics. 2002: Springer-Verlag New York. 488), and singular spectrum analysis (SSA) (Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263; Elsner, J.B. and A.A. Tsonis, Singular Spectrum Analysis: A New Tool in Time Series Analysis. 1996: Springer). Kim and Yoo (Kim, B.S. and S.K. Yoo, Motion artifact reduction in photoplethysmography using independent component analysis. IEEE Trans Biomed Eng, 2006. 53(3): p. 566-8) suggested using a basic ICA method and block interleaving to remove MA. Krishnan et al. (Krishnan, R., B. Natarajan, and S. Warren, Two-Stage Approach for Detection and Reduction of Motion Artifacts in Photoplethysmographic Data. Biomedical Engineering, IEEE Transactions on, 2010. 57(8): p. 1867-1876) later proposed using frequency-domain-based ICA. However, the key assumption in ICA, namely statistical independence or uncorrelation, does not hold in PPG signals contaminated by MA (Yao, J. and S. Warren, A short study to assess the potential of independent component analysis for motion artifact separation in wearable pulse oximeter signals. Conf Proc IEEE Eng Med Biol Soc, 2005. 4: p. 3585-8). Salehizadeh et al. (Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263) proposed a motion artifact removal method using SSA. In Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-

2263, SSA is used to decompose the corrupted segment adjacent to the clean segment and the SSA components are chosen in the corrupted segment that have a similar frequency range to that of the adjunct clean components. Although Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263 reports good performance, the method cannot be applied in scenarios where the HR and SpO_2 are varying rapidly due to corruption and movement. Acceleration data are also shown to be helpful to remove MA. For example, Fukushima et al. (Fukushima, H., et al., Estimating heart rate using wrist-type Photoplethysmography and acceleration sensor while running. Conf Proc IEEE Eng Med Biol Soc, 2012. 2012: p. 2901-4) suggested a spectral subtraction technique to remove the spectrum of acceleration data from that of a PPG signal. Acceleration data can be also used to reconstruct the observation model for Kalman filtering (Boreom Lee, J.H., Hyun Jae Baek, Jae Hyuk Shin, Kwang Suk Park and Won Jin Yi, Improved elimination of motion artifacts from a photoplethysmographic signal using a Kalman smoother with simultaneous accelerometry. Physiological Measurement, 2010. 31(12): p. 1585) to remove MA.

[0067] Two noteworthy methods are TROIKA and JOSS (Zhilin, Z., P. Zhouyue, and L. Benyuan, TROIKA: A General Framework for Heart Rate Monitoring Using Wrist-Type Photoplethysmographic Signals During Intensive Physical Exercise. Biomedical Engineering, IEEE Transactions on, 2015. 62(2): p. 522-531; Zhang, Z., Photoplethysmography-Based Heart Rate Monitoring in Physical Activities via Joint Sparse Spectrum Reconstruction. Biomedical Engineering, IEEE Transactions on, 2015. PP(99): p. 1-1) in which sparsity-based spectrum estimation and spectral peak tracking with verification, are used to estimate and monitor heart rate during intensive physical activity, respectively. Both approaches make use of PPG and accelerometer information to obtain an accurate estimation of heart rate while running on a treadmill. TROIKA has two extra stages of signal decomposition and reconstruction using singular spectrum analysis (SSA) and then applies temporal difference operations on the SSA-reconstructed PPG. SSA components are compared to the accelerometer signals and those components with close frequencies to the accelerometer signals are discarded and the rest are used to reconstruct the signal. In JOSS and TROIKA, spectral peak tracking with verification aims to select the spectral peaks corresponding to HR. JOSS, which has been shown to estimate

HR more accurately than TROIKA, is based on the idea that the spectra of PPG signals and simultaneous acceleration signals have some common spectrum structures, and, thus, formulates the spectrum estimation of these signals into a joint sparse signal recovery model using the multiple measurement vector (MMV) model. MMV is used for joint spectrum estimation based on PPG and accelerometer data, which is in contrast to the single measurement vector (SMV) model that was used in TROIKA and was based on only a single PPG signal. Although JOSS has been shown to be much more accurate than previous methods for reconstruction of heart rate from MA-contaminated PPG signals, the main disadvantage of the method is it can merely provide smoothed HR reconstruction estimations. Neither time-domain PPG signal reconstruction nor heart rate variability analysis can be done using JOSS or TROIKA. Temko proposed an approach to HR estimation based on Wiener Filtering and the Phase Vocoder (WFPV) (Temko, A. Estimation of Heart Rate from Photoplethysmography during Physical Exercise using Wiener Filtering and the Phase Vocoder. in IEEE EMBS International Conference on Engineering in Medicine and Biology. 2015. Milan, Italy: IEEE). This work showed that WFPV on average can perform better than JOSS. The main idea of WFPV is to estimate motion artifacts from accelerometer signals and then use a Weiner filter to attenuate the motion components in the PPG signal. Phase vocoder is also applied to overcome the limited resolution of the Fourier transform and to refine the initial dominant frequency estimation.

[0068] According to embodiments disclosed herein, a motion-corrupted heart-related signal, such as a PPG signal, may be reconstructed by employing a method that is based on a time-varying spectral analysis. A method for reconstructing a heart-related signal based on the time-varying spectral analysis for HR estimation may be referred to interchangeably herein as a spectral approach for filtering motion artifacts (SpaMA) method or SpaMA. A method for reconstructing the heart-related signal based on the time-varying spectral analysis for SpO2 estimation may be referred to interchangeably herein as a spectral approach for filtering motion artifacts for oxygen saturation estimation (OxiMA) method or OxiMA.

[0069] FIG. 1 is a block diagram 100 of an example application for which embodiments disclosed herein may be applied. In FIG. 1, a subject 102 is running on a treadmill 104. The subject 102 is wearing a wrist band 106 that includes a biomedical sensor 108 that produces a heart-related signal 110. The heart-related signal 110 that is produced by the biomedical sensor

108 includes motion artifacts that are signal artifacts produced by movement of the biomedical sensor 108 relative to a sensing location (not shown). The wrist band 106 may be any suitable type of wrist band, for example, the wrist band 106 may be a smart watch.

[0070] The biomedical sensor 108 may be a PPG sensor, or any other suitable biomedical sensor, and the heart-related signal 110 may be a PPG signal, or any other suitable heart-related signal. The sensing location may a skin surface of an area on the subject's wrist where the wrist band 106 is worn, or any other suitable sensing location at which the biomedical sensor 108 senses the heart-related signal 110. For example, the sensing location may be a skin surface on the subject's forehead, and a head band including the biomedical sensor 108 or maintain the biomedical sensor 108 at the sensing location may be used instead of the wrist band 106.

[0071] Physical activity of the subject 102 may cause movement of the wrist band 106, and, thus, movement of the biomedical sensor 108, resulting in a gap between the PPG sensor and the sensing location. Ambient light may leak into the gap inducing spectrum corruption in the PPG signal. This is because the power of the PPG signal is dependent on a depth and reflection of the PPG light from the PPG sensor to the subject's skin. As such, strenuous and high intensity exercise of the subject 102, such as running or any other suitable activity, may result in movement that rises to a level causing motion artifacts in the heart-related signal 110. According to embodiments disclosed herein, the heart-related signal 110 may be reconstructed 112, producing a reconstructed heart-related signal with the motion artifacts suppressed 114. The reconstructed heart-related signal with the motion artifacts suppressed 114 may be used to accurately estimate HR, SpO2, or any other suitable heart-related estimate. As such, the reconstructed heart-related signal may be employed to detect or predict a heart-related ailment. The heart-related ailment may include at least one of a heart rate variability (HRV) condition, atrial fibrillation condition, congestive heart failure condition, and tachycardia condition.

[0072] It should be understood that the PPG sensor is one example of a biomedical sensor, the PPG signal is one example of a heart-related signal, and that any suitable type of biomedical sensor may be employed to produce any suitable type of a heart-related signal. Further, movement of the biomedical sensor 108 relative to the sensing location may be caused by any suitable source of the movement that causes movement of the biomedical sensor 108 relative to the sensing location. It should also be understood that a subject referred to herein may be any

living being, such as a person or an animal, and may be referred to interchangeably herein as a user.

[0073] FIG. 2 is a flow diagram 200 of an example embodiment of a method for reconstructing a heart-related signal output by a biomedical sensor. The example embodiment of the method of FIG. 2 may be applied to either SpaMA or OxiMA and may be applied to other applications that produce a heart-related estimate. The method may start (202) and reconstruct a representation of the heart-related signal to produce a reconstructed representation of the heart-related signal. The reconstructing may be based on (i) a time-varying spectral analysis of the heart-related signal and a motion signal, the motion signal output by a motion sensor and representative of motion artifacts in the heart-related signal, the motion artifacts being signal artifacts produced by movement of the biomedical sensor relative to a sensing location, and (ii) a classification of movement (204). The method may output the reconstructed representation of the heart-related signal (206), and the method thereafter ends (208) in the example embodiment.

[0074] The method may comprise segmenting the heart-related signal into a plurality of windowed heart-related signal data segments and the motion signal into a corresponding plurality of windowed motion signal data segments and repeating the reconstructing and the outputting for each windowed heart-related signal data segment and each corresponding motion signal data segment. The time window may be a value in a range from 2 to 32 seconds. For example, the *window[k]* of raw PPG data of FIG. 3A, element 304, disclosed below, and the *window[k]* of raw accelerometer data shown in FIG. 3A, element 310, disclosed below, may each include data from the respective PPG and accelerometer signals that may be collected over a time window from 2 to 32 seconds. According to one embodiment, the time window may be 8 seconds.

[0075] The method may employ the reconstructed representation to determine a heart rate estimate. The method may employ the reconstructed representation to determine an arterial oxygen saturation (SpO2) estimate. The method may employ the reconstructed representation to detect or predict a heart-related ailment. The heart-related ailment may include at least one of a heart rate variability (HRV) condition, atrial fibrillation condition, congestive heart failure condition, and tachycardia condition.

[0076] The heart-related signal and the motion signal may be produced, concurrently.

[0077] According to some embodiments, the biomedical sensor may be at least one of: a photoplethysmogram (PPG) sensor, piezoelectric sensor, Light Emitting Diode (LED) based sensor, camera sensor, and pulse oximeter sensor. The motion sensor may be an accelerometer, or any other suitable device that produces a motion signal. If an accelerometer, the accelerometer may be a 3-axial type accelerometer, or any other suitable type of accelerometer. The biomedical sensor and the motion sensor may be co-located. For example, the wrist band 106 of FIG. 1, disclosed above, may be a smartwatch and the biomedical sensor and motion sensor may be a PPG sensor and an accelerometer, respectively, that are both disposed in the smartwatch or other suitable wearable device.

[0078] FIGS. 3A-C are flow diagrams of example embodiments of a method for reconstructing a heart-related signal output by a biomedical sensor based on embodiments disclosed in Tables 1-3, disclosed below. The method may be either a SpaMA or OxiMA method.

Table 1. Stages 1 and 2

Stage 1. Time-Varying Spectral analysis (*see* FIG. 3A)

1.1. Filter the PPG and Accelerometer signal with cutoff frequency [1, 50]/Fs/2 Hz.
1.2. Down sample the PPG and Accelerometer signal to ¼ of original sampling rate (Fs).
1.3. Compute the time frequency spectrum of both PPG and Accelerometers [0-10 Hz].

Stage 2. Movement Classification (*see* FIG. 3A)

2.1. Check each accelerometer (X, Y or Z) amplitude modulation at each window and compare to a pre-defined motion amplitude threshold. (The threshold varies depending on the type of accelerometer sensor).

Signal is clean if $AM[Acc_{x\ or\ y\ or\ z}(k)] < Motion\_Threshold$ and the signal is corrupted by motion otherwise. If the signal is clean calculate the Heart Rate from peak-to-peak intervals, otherwise go to step 2.2.

2.2. If the signal is corrupted check if the movement is pseudo-periodic (e.g. during walk, jog, run) or non-periodic (e.g. any random movements)

The assumption is when movement is pseudo-periodic the accelerometer data should comprised of a fundamental frequency component and harmonics of the fundamental frequency at its double and third frequency band. This means the ratio of the first harmonic to the fundamental frequency should be almost 2 and the second harmonic to the fundamental should be around 3.

2.2.1. Extract the fundamental frequency component, the 1st and 2nd harmonics from (*e.g.*,VFCDM) time-frequency spectrum of accelerometers. The first three highest peaks in spectral array should represent the fundamental, 1st and 2nd harmonics as long as the movement is pseudo-periodic.

2.2.2. Calculate the ratio of the extracted 1st and 2nd fundamental frequency to the extracted fundamental frequency. If the ratios are close to 2 and 3, this indicates that the movement is most likely pseudo-periodic otherwise it is non-periodic.

2.2.3. If the movement is pseudo-periodic do the Stages 3-5 (*See* Table 2 and FIG. 3B), otherwise go to Stage 6 (*See* Table 3 and FIG. 3C).

Table 2. Stages 3-5

Stage 3. Spectral Filtering (*see* FIG. 3B)

3.1. Assume HR to be in the frequency range of [0.5Hz – 3Hz], this accounts for both low and high heart rates.
3.2. The first highest three peaks and their corresponding frequencies in the PPG filtered spectrum are assumed to have HR information.
3.3. Only the largest frequency peak (that represents the fundamental frequency of movement) of the accelerometers' spectra is used for motion artifact detection in Stage 4.

Stage 4. Motion Artifact Detection (*see* FIG. 3B)

4.1. Compare the frequencies of the three peaks in the PPG spectrum with the frequency of the largest peak in the accelerometers' spectra. If the first or second largest peaks in the PPG spectrum are similar to that of the accelerometers' peaks, then motion artifact is present in the PPG.
4.2. If motion artifact is detected from 3.1, then the corresponding frequency peak (usually the first or second largest peak) in the PPG spectrum should be discarded.

Stage 5. Heart Rate Tracking and Extraction from PPG Spectrum (*see* FIG. 3B)

Case (1): From 3.1- if the spectrum is corrupted by movement and only the first largest peak is corrupted, then the HR frequency should be the frequency of the second peak in the spectrum.
Case (2): From 3.1- if the spectrum is corrupted by movement and both the first and second largest peaks have similar frequencies to those of the accelerometers' peaks, then the HR frequency should be the frequency of the third peak in the spectrum.
Case (3): Due to a gap between the pulse oximeter and a subject's skin, the HR frequency cannot be extracted from the spectrum and in this case the previous HR frequency is used or for offline implementation a cubic spline interpolation can be applied to fill in the missing HR information.

Table 3. Stage 6

Stage 6. Adaptive Bandpass Filtering (non-periodic movements) (*see* FIG. 3C)

When the movement is random and non-periodic it is difficult or not possible to identify HR trace from time-frequency spectrum (for example if stage 5 is not applicable). In this case which may happen more often, a new procedure is adopted that is called adaptive bandpass filtering. The assumption here is that HR does not deviate more than 10 bpm from the average of previous m HR values within 2 seconds.

6.1. Set averaging window length to m (e.g. m=5) and calculate the average of recent m estimated HR values.

$$HR_{mavg} = \frac{1}{m}\sum_{j=1}^{m} HR(k-j)$$

Where k is the current window. The window length m=5 should only be used for up to 10 seconds of consecutive motion artifact corrupted datapoints. If motion corrupted data last more than 10 seconds, m should be increased to more than 5.

6.2. Take the most recent estimated HR value and calculate bandpass filter cutoff frequency.

$$F_{CutOff} = [HR_{mavg} - 10, HR_{mavg} + 10\ ]/60/Fs/2$$

Design a bandpass filter of order 4 with cutoff frequency (F_{CutOff}). Apply the filter on the PPG segment.

6.3. Calculate HR from peak-to-peak intervals of the filtered data segment obtained from 6.2. Take the average of the instantaneous HR as estimated HR value at window k.

[0079] FIG. 3A is a flow diagram (300) of an example embodiment of a method for a time-varying spectral analysis and movement classification, as disclosed in Stage 1 (time-varying spectral analysis) and Stage 2 (movement classification), respectively, in Table 1, for reconstructing the representation. The method may start (302) and the time-varying spectral analysis may be employed on a first windowed segment *window[k]* of raw PPG data (304) and a second windowed segment *window [k]* of raw accelerometer (ACC) data (310). The raw PPG data (304) and the raw ACC data (310) may be extracted from a heart-related signal that is a PPG signal and a motion signal that is an accelerometer signal, respectively.

[0080] As disclosed in Stage 1 of Table 1, the time-varying spectral analysis of FIG. 3A may include pre-processing the heart-related signal (306) to produce a pre-processed heart-related signal. The pre-processing (306) may include filtering the heart-related signal to produce a

filtered heart-related signal. The pre-processing (306) may further include down-sampling the filtered heart-related signal, the down-sampling being at a sampling rate less than an original sampling rate, to produce a down-sampled, filtered heart-rate signal. The time-varying spectral analysis may further include pre-processing the motion signal (312) to produce a pre-processed motion signal. The pre-processing (312) may include filtering the motion signal to produce a filtered motion signal. The pre-processing (312) may further include down-sampling the filtered motion signal, the down-sampling being at a sampling rate less than an original sampling rate, to produce a down-sampled, filtered motion signal.

[0081] As further disclosed in Stage 1 of Table 1, the time-varying spectral analysis of FIG. 3A may include computing a first time-frequency spectrum (TFS) to produce a first TFS (308) of the down-sampled, filtered heart-related signal and computing a second TFS to produce a second TFS (314) of the down-sampled, filtered motion signal. According to some embodiments, filtering and down-sampling of the heart-related signal and motion signal for computing the first TFS (308) and the second TFS (314), respectively, may be optional. The first TFS (308) (also referred to interchangeably herein as the first TFS computed) and the second TFS (314) (also referred to interchangeably herein as the second TFS computed) may be 3-dimensional spectra, the first TFS computed and the second TFS computed each including a respective time-varying amplitude or power distribution with respect to time and frequency.

[0082] For example, the first TFS computed may be a first time-varying power spectral density (PSD) and the second TFS computed may be a second time-varying PSD. A time-frequency technique, such as a variable frequency complex demodulation (VFCDM), disclosed in U.S. Patent No. 8,388,543 B2, incorporated herein in its entirety by reference, may be used for computing the first TFS (308), that is, a TFS of the PPG signal, and the second TFS (314), that is, a TFS of the accelerometer signal. However, it should be understood that any suitable time-frequency technique may be used, such as a smoothed pseudo wigner-ville method, or a wavelet based method.

[0083] As disclosed in Stage 2 of Table 1, classifying the classification of the movement (316) in FIG. 3A may include comparing an amount of amplitude modulation in the second TFS (314) computed to an amplitude modulation threshold. The amplitude modulation threshold may be dependent on a type of the motion detector sensor, such as a type of the accelerometer. The

classification of the movement may indicate whether the movement rises to a level causing motion artifacts in the heart-related signal, that is, the PPG signal, based on a result of the comparing, as disclosed in Stage 2 of Table 1.

[0084] In an event the movement classification (316) of FIG. 3A indicates that the movement does not rise to a level causing the motion artifacts (322), a peak-peak interval (PP) of the filtered heart-related signal, or alternatively, the filtered, down-sampled heart-rate signal, may be computed (318) and the reconstructed representation *HR(k)* may be based on an average value of peak-to-peak intervals (320) in the pre-processed heart-related signal, and the method thereafter ends (325) in the example embodiment.

[0085] In an event the movement classification (316) indicates that the movement does rise to the level causing the motion artifacts (323), classifying the classification of the movement may further include determining (324) whether the movement is either a pseudo-periodic movement or a periodic movement, versus a random movement, as disclosed in Stage 2 of Table 1.

[0086] With reference to Stage 2 of Table 1, in determining whether the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement, the method may further include identifying a first, second, and third frequency associated, respectively, with a first, second, and third spectral peak in the second TFS at a point in time in the second TFS. The first, second, and third peaks may have largest power or amplitude values relative to other peaks in the second TFS at the point in time. The first spectral peak may be a largest spectral peak amongst the first, second, and third spectral peaks.

[0087] In determining whether the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement, the method may compute a first ratio of the second frequency identified to the first frequency identified. The method may determine a first comparison result by comparing the first ratio computed to a first ratio value. The method may compute a second ratio of the third frequency identified to the first frequency identified and determine a second comparison result by comparing the second ratio computed to a second ratio value. The classification may further indicate the movement is either the pseudo-periodic movement or the periodic movement, versus the random movement, based on the first comparison result and the second comparison result. The first ratio value may be 2 and the

second ratio value may be 3. The classification of the movement may be periodic if the first ratio and the second ratio are exactly 2 and 3, respectively, while the classification of the movement may be pseudo-periodic if the first ratio and the second ratio are approximately 2 and 3, respectively, within a pre-determined level of accuracy.

[0088] In an event the classification of the movement is periodic or pseudo-periodic, the method of FIG. 3A may continue with the method of FIG. 3B, disclosed below. In an event the classification of the movement is random, the method of FIG. 3A continues to the method of FIG. 3C, disclosed below.

[0089] FIG. 3B is a flow diagram (330) of an example embodiment of a method for spectral filtering, motion artifact detection, and heart rate tracking and extraction, as disclosed in Stages 3, 4, and 5, respectively, of Table 2, for reconstructing the representation. The reconstructed representation may be referred to herein as a current reconstructed representation or *HR(k)*. As disclosed above with regard to FIG. 3A, in an event the classification of the movement (316) is periodic or pseudo-periodic, the method of FIG. 3A may continue with the method of FIG. 3B.

[0090] The method of FIG. 3B may start (331) and retain (332) up to a pre-determined number *N* of candidate spectral peaks located at a first point in time in the first TFS, that is, the first TFS from FIG. 3A. It should be understood that the method of FIG. 3B may be performed for each point in time of the first TFS and the second TFS. According to one embodiment, the pre-determined number *N* may be 3. The candidate spectral peaks retained may be based on having corresponding frequencies within a given frequency range. The candidate spectral peaks may be *N* peaks in the given frequency range that have highest amplitude or power values relative to other spectral peaks, that is, the first *N* highest peaks. It should be understood that the other spectral peaks have respective frequencies also within the given frequency range and are peaks located at the first point in time in the first TFS. The given frequency range may be 0.5 Hz to 3 Hz. As such, the *N* first highest peak in the range 0.5 Hz to 3 Hz in the first TFS may be retained at the first time point. Since no peaks in the given frequency range may be present at the first time point, the method may determine (336) whether at least one spectral peak is present.

[0091] Based on the determination (336) that no peak is present, the current reconstructed representation *HR(k)* may be based on a prior reconstructed representation *HR(k-1)* (340), the

prior reconstructed representation *HR(k-1)* associated with a previous point in time, such as the previous window *k-1*, in the first TFS computed, and the method thereafter ends (354) in the example embodiment.

[0092] Based on a determination (336) that the at least one spectral peak is present, the method may discard (338) each of the candidate spectral peaks retained, that is, each peak of the *N* first highest peaks determined at (332), if the peak is associated with a same frequency as a dominant spectral peak located at a second point in time in the second TFS (314) computed as disclosed above with regard to FIG. 3A. The first point in time and the second point time may have same time values. The dominant spectral peak may have a largest power or amplitude value relative to other peaks located at the second point in time in the second TFS. The method may determine (342) whether any peaks are retained after the discarding (338). The discarding (338) may be referred to herein as a first discarding.

[0093] In an event the discarding (338) discards each of the candidate spectral peaks retained, reconstructing the current representation *HR(k)* may be based on the prior reconstructed representation, *HR(k-1)* (340), and the method thereafter ends (354) in the example embodiment.

[0094] In an event the first discarding (338) results in at least one remaining candidate spectral peak retained, reconstructing the current representation may further include second discarding (348). The second discarding (348) may discard remaining candidate spectral peaks, of the at least one remaining candidate spectral peak retained, based on whether a corresponding frequency of the at least one remaining candidate spectral peak retained is distanced (346) by at least a frequency difference threshold, such as 10bpm, from a prior reconstructed representation's frequency, that is, a frequency associated with, for example, *HR(k-1)*.

[0095] Based on each at least one remaining candidate spectral peak retained having been discarded by the second discarding (348), reconstructing the current representation may be based on the prior reconstructed representation *HR(k-1)* (350), and the method thereafter ends (354) in the example embodiment.

[0096] Based on at least one last candidate spectral peak remaining from the second discarding (348), reconstructing the current representation may be based on a selected candidate spectral peak (352). The selected candidate spectral peak may be selected from amongst the at least one last candidate spectral peak remaining having a closest corresponding frequency to the

prior reconstructed representation's frequency relative to respective frequencies of each of the at least one last candidate spectral peak remaining, and the method thereafter ends (354) in the example embodiment.

[0097] As disclosed above with regard to FIG. 3A, in an event the classification of the movement (316) is random, the method of FIG. 3A may continue with the method of FIG. 3C.

[0098] FIG. 3C is a flow diagram (330) of an example embodiment of a method for adaptive bandpass filtering of non-periodic movements, that is, random movements, for reconstructing the representation, as disclosed in Stage 6 of Table 3. The method of FIG. 3C may start (362) and compute an average value of a number *m* of prior reconstructed representations outputted prior to the reconstructing (362). The number *m* may be based on a duration of consecutive motion artifacts, detected prior to the reconstructing of the representation $HR(k)$. For example, if motion artifacts were detected for windows *k-1*, *k-2*, and *k-3*, *m* may be understood to be 3.

[0099] The method may compute a bandpass filter cutoff frequency (366). The cutoff frequency F_c may be based on the average value computed HR_{mavg}. The method may filter the pre-processed heart-rate signal (306), disclosed in FIG. 3A, above, by applying the band pass filter computed (368) to produce a filtered, pre-processed heart-related signal. The reconstructed representation *HR(k)* may be based on an average peak-to-peak interval value (372) of the filtered, pre-processed heart-rate signal, and the method thereafter ends (374) in the example embodiment.

[00100] FIG. 4 is a block diagram of an example embodiment of a system (400). The system includes an apparatus 420 for reconstructing a heart-related signal 410c output by a biomedical sensor (not shown). The apparatus 420 includes a reconstruction unit 416 and an output unit 418. The reconstruction unit 416 may be configured to produce a reconstructed representation of the heart-related signal 414c. The reconstructing may be based on (i) a time-varying spectral analysis of the heart-related signal 410c and a motion signal 411c, the motion signal 411c output by a motion sensor (not shown) and representative of motion artifacts in the heart-related signal 410c, the motion artifacts being signal artifacts produced by movement of the biomedical sensor (not shown) relative to a sensing location (not shown), and (ii) a classification of the movement. The output unit 418 may be configured to output the reconstructed representation of heart-related signal 414c.

[00101] The apparatus 420 may be communicatively coupled to a network 401 to receive the heart related signal 410c and the motion signal 411c. The network may be a wireless network or any other suitable network. The reconstructing and the outputting may be performed in near real-time with respect to production of the heart-related signal 410c and the motion signal 411c. Alternatively, the apparatus may be coupled to a database (not shown) storing representations of the heart related signal 410c and the motion signal 411c, and the reconstructing and the outputting may be performed in non-real-time with respect to production of the heart-related signal 410c and the motion signal 414c.

[00102] The heart-related signal 410c may include raw heart-related signal data that includes the raw heart-related signal data 410a and the raw heart-related signal data 410b produced by biometric sensors (not shown) that sense the heart-related signal data 410a and the raw heart-related signal data 410b from sensing locations (not shown) on a first user 406a and a second user 406b, respectively. The motion signal 411c may include raw motion signal data that includes the raw motion signal data 411a and the raw motion signal data 411b from motion sensors (not shown). The raw motion signal data 411a and the raw motion signal data 411b may represent motion artifacts in the heart-related signal data 410a and the raw heart-related signal data 410b, respectively.

[00103] It should be understood that the raw heart-related signal data 410a-b and the raw motion signal data 411a-b may be sent to the apparatus 420 in any suitable way. For example, the raw heart-related signal data 410a and the raw motion signal data 411a may be sent in a payload of a packet; alternatively the raw heart-related signal data 410a and the raw motion signal data 411a may be sent in payloads of different packets. Similarly, the raw heart-related signal data 410b and the raw motion signal data 411b may be sent in a payload of a packet; alternatively, the raw heart-related signal data 410b and the raw motion signal data 411b may be sent in payloads of different packets.

[00104] The user 406a may be at a gym where the user 406a is exercising, and such physical activity by the user 406a may cause motion artifacts in the raw heart-related signal data 410a. The user 406b may be in a different location, such as a hospital. The user 406b may perform movements out of boredom, such wrist shaking, causing motion artifacts in the raw heart-related signal data 410b. As such, the corresponding motion artifacts may be suppressed in the

reconstructed representations 414a and 414b of the heart-related signals 414a and 414b, respectively, according to embodiments disclosed herein. The reconstructed representations 414a and 414b, or information derived therefrom, may sent to biometric devices or other devices communicatively coupled to the network 401 the user 406a and 406 may have access to such device, respectively. Alternatively, the reconstructed representations 414a and 414b, or information derived therefrom, may sent in any suitable manner to another device communicatively coupled to the network 401 such that the reconstructed representations 414a and 414b, or information derived therefrom, may be accessible to a third party, such as doctor, or any other suitable party.

[00105] FIG. 5 is a block diagram 500 of an example embodiment of an apparatus (520) for reconstructing a heart-related signal 510 output by a biomedical sensor 508. The apparatus 520 includes a reconstruction unit 516 and an output unit 518. The reconstruction unit 516 may be configured to produce a reconstructed representation of the heart-related signal 514. The reconstructing based on (i) a time-varying spectral analysis of the heart-related signal 510 and a motion signal 511, the motion signal 511 output by a motion sensor 509 and representative of motion artifacts in the heart-related signal 510. The motion artifacts may be signal artifacts produced by movement of the biomedical sensor 508 relative to a sensing location (not shown), and (ii) a classification of the movement.

[00106] The output unit 518 may be configured to output the reconstructed representation of the heart-related signal 514. The apparatus 520 may include the biomedical sensor 508 and the motion sensor 509. The reconstructing and the outputting may be performed in real-time with respect to production of the heart-related signal 510 and the motion signal 511.

[00107] The apparatus 520 may be a wearable device, such as a smartwatch, or any other suitable device, such as a wearable personal biometric monitoring device. The apparatus 520 may have a user interface (not shown) to present the reconstructed representation of the heart-related signal 514 or information derived therefrom, such as a characteristic, notification, alarm, or any other suitable information. The reconstructed representation of heart-related signal 514 or the information derived therefrom may be presented to a user via a user interface that may be a visual or audio based user interface.

[00108] According to one embodiment, the apparatus 520 may include a heart rate unit (not shown) configured to employ the reconstructed representation of the heart-related signal 514 to determine a heart rate estimate. According to another embodiment, the apparatus 520 may include an arterial oxygen saturation (SpO2) unit (not shown) configured to employ the reconstructed representation of the heart-related signal 514 to determine a SpO2 estimate. According to yet another embodiment, the apparatus may include an ailment unit (not shown) configured to employ the reconstructed representation of the heart-related signal 514 to detect or predict a heart-related ailment, the heart-related ailment including at least one of a heart rate variability (HRV) condition, an atrial fibrillation condition, a congestive heart failure condition, and a tachycardia condition. It should be understand that any combination of the heart rate unit, SpO2 unit, and ailment unit may be included in the apparatus 520 in combination with any other units disclosed herein.

[00109] SpaMA Results

[00110] According to embodiments disclosed herein, HR reconstruction and PPG signal reconstruction may be based on a time-varying spectral analysis. As disclosed above with reference to FIGS. 3A-F, embodiments disclosed herein may be based on power spectral densities (PSDs) of both PPG and accelerometer signals for each time shift of a corresponding windowed data segment of the respective signal. According to embodiments disclosed herein, by comparing time-varying spectra of the PPG and accelerometer data, those frequency peaks resulting from motion artifacts may be suppressed from the PPG spectrum.

[00111] According to some embodiments, the method may be comprised of six stages, such as the six stages disclosed above in reference to FIGS. 3A-F. According to another embodiment the method may have five distinct stages: (1) time-varying power spectral density (PSD) calculation, (2) spectral filtering, (3) motion artifact detection, (4) HR reconstruction and (5) signal reconstruction. According to embodiments disclosed herein, the method may include computing a window-segmented power spectral density of both PPG and accelerometer signals in real-time to scale each estimate of the PSD by the equivalent noise bandwidth of the window (Stoica, P. and R.L. Moses, Introduction to Spectral Analysis. 1997: Prentice Hall).

[00112] The simplest way to approach the PSD calculation may be to employ a periodogram. However, a periodogram has drawbacks in that it is an inconsistent spectrum estimator, has high

variance, and has leakage effects (Stoica, P. and R.L. Moses, Introduction to Spectral Analysis. 1997: Prentice Hall). Thus, a dominant spectral peak can lead to an estimated spectrum that contains power in frequency bands where there should be no power. However, both problems can be solved by down-sampling the raw signal, as disclosed above with reference to FIGS. 3A-F, and then using a sufficiently small frequency step by setting a large number of frequency points. Thus, embodiments disclosed herein may resample the signal from the original sampling frequency to, for example 1/4 of it, that is, down-sample the signal, and then apply a periodogram method with frequency resolution of 0.001.

[00113] Embodiments disclosed herein may limit the spectrum to the heart rate frequency range of [0.5Hz – 3 Hz], as disclosed above with reference to FIGS. 3A-F, and take the frequency and power information of the first three peaks in the PSD at each window and signal segment. Embodiments disclosed herein may be based on an understanding that the heart rate component in a typical clean (motion free) PPG signal is always the dominant frequency component in the time-varying power spectrum, thus, the highest peak of the spectrum corresponds to the HR frequency. Thus, when movement happens the dominant component can be replaced by movement components which shift the HR to the second or third peak in the spectrum. As such, embodiments disclosed herein may compare the first N peaks, such as 3 peaks, disclosed above, and corresponding frequencies of the PPG spectrum to the first peak and frequency of the accelerometers' spectra at each window and choose the frequency components (out of three) that are different from the accelerometers' frequency.

[00114] Embodiments disclosed herein may be further based on an understanding that there is coherence between a spectral peak in the PPG and the accelerometers' spectra that signifies a motion noise artifact in the PPG signal and that peak should be discarded in the HR reconstruction. After discarding these movement peaks in the spectrum, the next highest peak that is closest to the estimated HR of the previous window may be chosen at each window. By reconstructing the HR frequency at each window, simultaneously, the PPG signal may be reconstructed by using the power, frequency and phase of the signal that corresponds to the HR frequency. That is, the time-domain signals may be reconstructed from the time-frequency domain.

[00115] The SpaMA method was applied to three different datasets and 4 types of activities. The three different datasets included: 1) training datasets from the 2015 IEEE Signal Processing Cup Database recorded from 12 subjects while performing treadmill exercise from 1 km/h to 15 km/h; 2) test datasets from the 2015 IEEE Signal Processing Cup Database recorded from 11 subjects while performing forearm and upper arm exercise; and 3) Chon Lab dataset including 10 min recordings from 10 subjects during treadmill exercise.

[00116] Electrocardiogram (ECG) signals from all three datasets provided the reference HRs which were used to determine the accuracy of the SpaMA method. The performance of the SpaMA method was calculated by computing the mean absolute error between the estimated HR from the PPG and the reference HR from the ECG. The average estimation errors using the SpaMA method on the first, second and third datasets are 0.89, 1.93 and 1.38 beats/min respectively, while the overall error on all 33 subjects is 1.86 beats/min and the performance on only treadmill experiment datasets (22 subjects) is 1.11 beats/min. Moreover, it was found that dynamics of heart rate variability (HRV) can be accurately captured using the SpaMA method where the mean Pearson's correlation coefficient was found to be 0.98 between the power spectral densities of the reference and the reconstructed heart rate time series. These results show that the SpaMA method has a potential for PPG-based HR monitoring in wearable devices for fitness tracking and health monitoring during intense physical activities.

[00117] Embodiments disclosed herein not only provide PPG signal and HR reconstruction but also the potential to do heart rate variability analysis on the results. As disclosed below, embodiments disclosed herein can outperform the JOSS technique in heart rate estimation by providing less error to the reference, which yields higher accuracy.

[00118] Embodiments disclosed herein were evaluated on three different datasets. The first two datasets were provided for the IEEE Signal Processing Cup and are publically available. The three datasets are: 1.) 12 PPG training datasets (running on treadmill) from an IEEE signal processing competition (Available from: http://www.signalprocessingsociety.org/spcup2015/index.html) which was initially used in (Zhilin, Z., P. Zhouyue, and L. Benyuan, TROIKA: A General Framework for Heart Rate Monitoring Using Wrist-Type Photoplethysmographic Signals During Intensive Physical Exercise. Biomedical Engineering, IEEE Transactions on, 2015. 62(2): p. 522-531; Zhang, Z.,

Photoplethysmography-Based Heart Rate Monitoring in Physical Activities via Joint Sparse Spectrum Reconstruction. Biomedical Engineering, IEEE Transactions on, 2015. PP(99): p. 1-1, 2.) 11 PPG test datasets (e.g., arm exercise) from the IEEE signal processing competition and 3.) 10 PPG recordings from the Chon lab (running on treadmill).

[00119] (1) IEEE Signal Processing Competition Training Dataset: A single-channel PPG signal, a three-axis acceleration signal, and an ECG signal simultaneously recorded from 12 Asian male subjects ranging in age from 18 to 35. For each subject, the PPG signal was recorded from their wrist using a pulse oximeter (PO) with green LED (wavelength: 609 nm). The acceleration signal was also recorded from each subject's wrist using a three-axis accelerometer. Both the PO and the accelerometer were embedded in a wristband, which was comfortably worn. The ECG signal was recorded from the chest and it is used as the reference heart rate. All signals were sampled at 125 Hz.

[00120] (2) IEEE Signal Processing Competition Test Dataset: The dataset consists of 11 five minute recordings which were collected from 19 to 58 year old subjects performing intensive arm movements (e.g. boxing). For each subject, PPG signals were recorded with a sensing location at the wrist using a pulse oximeter with green LEDs (wavelength: 515nm). The acceleration signal was also recorded from at the sensing location at the wrist using a three-axis accelerometer. Both the PO and the accelerometer were embedded in a wristband. An ECG signal was recorded simultaneously from each subject's chest using wet ECG sensors. All signals were sampled at 125 Hz and sent to a nearby computer via Bluetooth.

[00121] (3) Chon Lab Dataset: This dataset was recorded in the Chon Lab from 10 healthy subjects (9 male/1 female), with ages ranging from 26 to 55. For each subject, the PPG signal was recorded from their forehead using a PO with red and infrared LED (wavelength: 660 and 940 nm). The acceleration signal was also recorded from each subject's forehead using a three-axis accelerometer. Both the pulse oximeter and the accelerometer were embedded in a headband and the signals were sampled at 80 Hz. The ECG signal was recorded as a reference from the chest using ECG sensors, sampled at 400Hz. During data recording, the subjects walked, jogged and ran on a treadmill with speeds of 3, 5 and 7 mph, respectively, for 9 min. At the end, all experimental subjects were asked to perform random arbitrary movements for 1 min.

[00122] For all three datasets, the data was down-sampled to 20 Hz since the estimation of heart rate is carried out in the frequency domain and this sampling rate is sufficiently high to obtain even heart rates that are as high as 240 beats/min or 4 Hz. Moreover, this down-sampling enables a focus on heart rates in the lower frequencies rather than in the physiologically irrelevant higher frequency ranges. Further details of this study's databases are given in Table 4, below. Four types of activities were involved:

- Type (1): activity involved walking or running on a treadmill for intervals of 0.5 min-1 min-1 min-1 min-1 min-0.5 min with speeds of 1-2 km/h, 6-8 km/h, 12-15 km/h, 6-8 km/h, 12-15 km/h, 1-2 km/h, respectively. The subjects were asked to purposely move the hand with the wristband to generate motion artifacts.
- Type (2): activity included various forearm and upper arm exercise which are common arm motions (*e.g.*, shaking hands, stretching, pushing objects, running, jumping, and push-ups).
- Type (3): activity consisted of intensive forearm and upper arm movements (*e.g.*, boxing).
- Type (4): activity involved 1 min rest, 1 min walking (3 mph), 1 min rest, 2 min jogging (5 mph), 1 min rest, 2 min running (7 mph), 1 min rest, 1 min arbitrary movement. The ECG-based reference HR was recorded in order to assess the performance of the methods under test.

[00123] In summary, the first dataset includes only Type (1) activities, the second dataset includes both Type (1) and (2) activities, and the third dataset includes only Type (4) activities.

Table 4. PPG Datasets and Experiments Settings

Subject	Dataset	Activity Type	Pulse Oximeter Type	Subject's Age/Sex
1	1 (IEEE Cup)	Type (1)	Wrist: green LED (wavelength: 609nm)	18-38 y (All Male)
2				
3				
4				
5				
6				
7				
8				
9				

10				
11				
12				
13	2 (IEEE Cup)	Type (2)	Wrist: green LED (wavelength: 515nm)	19-58 y (9 Male, 1 Female)
14				
15				
16		Type (3)		
17				
18				
19				
20		Type (2)		
21		Type (3)		
22				
23		Type (2)		
24	3 (Chon Lab)	Type (4)	Forehead: Red and Infrared LED (wavelength: 660 nm, 940nm)	26-55 y (9 Male, 1 Female)
25				
26				
27				
28				
29				
30				
31				
32				
33				

[00124] An example embodiment for reconstructing a heart-related signal during intensive movements is disclose by the HR monitoring method presented below in Table 5. Details of each stage are described in subsections *i* to *v*.

Table 5. HR and PPG signal reconstruction method

Stage 1. Time-Varying Spectral analysis 1.1. Down sample the PPG and Accelerometer signal to 20 Hz. 1.2. Compute the power spectral density of both PPG and Accelerometers [0-10 Hz]. Stage 2. Spectral Filtering 2.1. Assume HR to be in the frequency range of [0.5Hz – 3Hz], this accounts for both low and high heart rates. 2.2. The first highest three peaks and their corresponding frequencies in the PPG filtered spectrum are assumed to have HR information.

2.3. Only the largest frequency peak of the accelerometers' spectra is used for MA detection in stage 3.

Stage 3. Motion Artifact Detection

3.1. Compare the frequencies of the three peaks in the PPG spectrum with the frequency of the largest peak in the accelerometers' spectra. If the first or second largest peaks in the PPG spectrum are similar to that of the accelerometers' peaks, then motion artifact is present in the PPG.
3.2. If motion artifact is detected from 3.1, then the corresponding frequency peak (usually the first or second largest peak) in the PPG spectrum should be discarded.

Stage 4. Heart Rate Tracking and Extraction from PPG Spectrum

Case (1): From 3.1- if the spectrum is corrupted by movement and only the first largest peak is corrupted, then the HR frequency should be the frequency of the second peak in the spectrum.
Case (2): From 3.1- if the spectrum is corrupted by movement and both the first and second largest peaks have similar frequencies to those of the accelerometers' peaks, then the HR frequency should be the frequency of the third peak in the spectrum.
Case (3): Due to a gap between the pulse oximeter and a subject's skin, the HR frequency cannot be extracted from the spectrum and in this case the previous HR frequency is used or for offline implementation a cubic spline interpolation can be applied to fill in the missing HR information.

Stage 5. PPG Signal Reconstruction

5.1. The PPG signal is reconstructed by using the amplitude, frequency and phase information corresponding to the HR components (extracted in stage 4) that are calculated from the spectrum at each window.

- Heart Rate Variability Analysis

By using a sample-by-sample windowing strategy, HR can be extracted, from which dynamics of heart rate variability analysis can be obtained on the motion artifact-removed reconstructed HR time series.

[00125] i. Time-Varying Spectral Analysis of PPG and Accelerometer Data

[00126] Embodiments disclosed herein may produce a time-varying spectrum by taking a *T*-sec window of the signal and computing the power spectral density (PSD) of the segment and then sliding the window through the whole dataset which yields a time-frequency matrix in

which each array represents the power of the signal corresponding to a specific frequency and sliding time-step (shift) of *S*-sec. The sliding process and frequency step specify the resolution and dimension of the time-frequency matrix. According to embodiments disclosed herein, two different sliding window approaches may be used, depending on the application. For estimating either heart rates or heart rate variability, data may be shifted sample-by-sample with no overlap for the entire dataset. Such an approach enables capturing beat-to-beat dynamics of HRV which requires sample-to-sample estimation of PSD. Since some data is down-sampled data to 20 Hz in some of the database, as disclosed above, each data point may be shifted by 0.05 seconds. For estimating only the heart rates, the shift may be a data segment-by-segment shift rather than a sample-by-sample shift. This coarse-grain windowing approach has less computational cost and it can provide good tracking of heart rates, but does not apply well to HRV.

[00127] As such, according to some embodiments, a window segment length *T* may be set to 8 seconds and shifted by 2 seconds. The 8 second data segment and a shift of 2 seconds was chosen to compare results according to embodiments disclosed herein to other methods (TROIKA, JOSS and WFPV) which have used this chosen data segment length and time shift (Zhilin, Z., P. Zhouyue, and L. Benyuan, TROIKA: A General Framework for Heart Rate Monitoring Using Wrist-Type Photoplethysmographic Signals During Intensive Physical Exercise. Biomedical Engineering, IEEE Transactions on, 2015. 62(2): p. 522-531; Zhang, Z., Photoplethysmography-Based Heart Rate Monitoring in Physical Activities via Joint Sparse Spectrum Reconstruction. Biomedical Engineering, IEEE Transactions on, 2015. PP(99): p. 1-1). Moreover, the assumption of 8 second data length largely stems from the fact that heart rates do not change instantaneously, hence, an 8 second duration is a reasonable choice.

[00128] As a representative example, the resultant frequency components in the time-frequency matrix of recordings from subject #8 from the competition training dataset, for a window length of 8 seconds that is shifted by every 2 seconds, is shown in FIG. 6A, disclosed below.

[00129] FIGS. 6A-6C show Time-Frequency spectra of recording #8 from dataset (1).

[00130] FIG. 6A shows the PPG signal.

[00131] FIG. 6B shows the simultaneous Accelerometer-Z signal.

[00132] FIG. 6C (Top-Left) shows the TF spectrum of the PPG signal. FIG. 6C (Top-Right) shows the TF spectrum of ACC(x). FIG. 6C (Bottom-Left) shows the TF spectrum of ACC(y),. FIG. 6C (Bottom-Right) shows the TF spectrum of ACC(z); all computed from stage (1) of Table 5. The blue circles and letters represent movement elements in all four spectra.

[00133] The panels of FIG. 6A and FIG. 6B show a PPG time series and the z-axis accelerometer data, respectively. From the upper left panel of FIG. 6C, which represents the time-frequency plot of the PPG signal, it is observed that there are three dominant frequency components - one of them represents HR and the other two are similar to those of the accelerometers' spectra shown in the upper right and lower left and right panels of FIG. 6C. FIG. 6C illustrates 4 motion artifact elements (A, B, C, D) that are present in exactly the same areas among all spectra. By comparing the time-frequency (TF) spectrum of PPG to those of the accelerometers' spectra, the marked dynamics (A, B, C and D) in the PPG spectrum can be detected as sharing the same frequency dynamics as those of the accelerometer spectra marked in circles. Hence, both the top and bottom marked lines in the PPG spectrum most likely represent the motion artifacts, and the unmarked frequency represents the HR. The next section details how these motion artifact frequency dynamics may be detected and filtered according to embodiments disclosed herein.

[00134] ii. Spectral Filtering

[00135] After obtaining the power spectral density at each window, as disclosed above, embodiments disclosed herein may confine the HR frequency to the range [0.5 Hz – 3 Hz], which takes into account both at rest and high HR due to either tachycardia or exercise scenarios. Hence, for HR estimation, the strategy is to eliminate frequencies that are outside of this HR frequency range as they are most likely due to motion artifacts or harmonics of the HR frequency.

[00136] In general, HR frequency in the power spectral density of PPG at each window can have three different scenarios: (1) PPG is devoid of MA and there is no spatial gap between the sensor and the subject's skin during recording, (2) PPG is corrupted by MA and there is no spatial gap between the sensor and the subject's skin during recording and (3) There is a spatial gap between the sensor and the subject's skin during recording. For the ideal case (1), HR can be extracted and it is most likely represented as the highest peak in the PPG spectrum. For case

(2), MA dynamics can result in predominately either one or two dominant peaks depending on the severity of repetitive motions, and the HR peak may be relegated to either the second or third highest peak. Non-repetitive motion artifacts will show up as a broadband spectrum without a dominant peak if they are not severe (Marmarelis, V.Z., et al., Nonlinear analysis of renal autoregulation under broadband forcing conditions. Ann Biomed Eng, 1993. 21(6): p. 591-603). The only scenario that makes it difficult to extract HR from the spectrum is scenario (3) when there is a spatial gap between the PPG sensor and the subject's skin during recording. In this scenario, assuming that the motion artifacts are short lasting, the missing HR values can be interpolated using a cubic spline approach.

[00137] FIG. 7 is an example embodiment of spectral filtering. FIG. 7 shows a representative filtered time-frequency spectral plot of a PPG signal. As disclosed above, embodiments disclosed herein may retain only the three largest frequency peaks at each time point within the defined HR range (30-180 bpm) and such retained frequency peaks are represented as blue, green and red colors, respectively. Retaining only the three largest frequency peaks at each time point may be reasonable for the first two cases, as outlined above. In the PPG time-frequency spectrum of FIG. 7, the Blue, Green and Red circles correspond to the first three highest peaks in the defined HR frequency range of (30-180 bpm), respectively, at each sliding window.

[00138] iii. Motion Artifact Detection

[00139] FIGS. 8A-8B show motion artifact detection in the PPG spectrum according to embodiments disclosed herein.

[00140] FIG. 8A shows a filtered PPG spectrum with movement and HR components. FIG. 8A is an example embodiment of a PPG spectrum which is identical to FIG. 7, but it also identifies the frequencies associated with accelerometers, as marked by the shaded areas and the letters A-D, in the top left and two bottom panels of FIG. 6C, disclosed above. The shaded yellow elements (A, B, C, D) of FIG. 8A represent motion frequency components in the PPG spectrum, and the light blue line is the reference HR from a clean reference ECG signal. By removing the accelerometers' related frequencies in FIG. 8A, the remaining frequency dynamics which should represent HR frequency and its harmonics are shown in FIG 8B.

[00141] FIG. 8B shows a filtered PPG spectrum after removing motion artifact frequency components.

[00142] iv. Heart Rate Tracking & Extraction

[00143] A flow diagram for heart rate tracking and extraction is disclosed above, with reference to FIG. 3B. Embodiments disclosed herein may identify HR frequencies with time, such as HR frequencies from FIG. 8B. Note that in FIG. 8B, there are three peaks at each time instance (also referred to interchangeably herein as a time point). Embodiments disclosed herein may identify which of the three peaks represents the HR at each time point. For the initial time window of 8 seconds, a clean data segment may be used so that true HR can be determined. This scenario is case (1), disclosed above, in the spectral filtering section, and the detection of HR is simply the highest peak in the spectrum. Embodiments disclosed herein may estimate HR for each sliding window of data. Embodiments disclosed herein may choose a HR peak in the PPG spectrum with the knowledge of estimated HR values in previous time windows. Two main scenarios may present: (1) no peak exists in the spectrum that can represent HR, and (2) there is a spectral peak among the first three highest peaks of spectrum that belongs to the HR component.

[00144] In case (1), where HR is not detectable in the window (*e.g.*, due to spatial gap between the PO sensor and skin), in real-time implementation embodiments disclosed herein may take a previous window's HR value as the current HR (or simply use a moving average of several past HR beats or some other variant). In post-processing, or offline processing, a cubic spline interpolation may be used to fill in the missing HR information. In the more general case (2), where the HR peak is among the first three highest peaks in the spectrum, three possible scenarios can occur: (2-A) the windowed PPG signal is clean and the first highest peak in the spectrum represents the HR fundamental frequency, (2-B) the windowed PPG signal is corrupted by movement and at most two of the spectral peaks represent the accelerometers' frequency components, thus, the second or the third peak corresponds to HR, (2-C) while the HR spectral peak is detectable, the difference between its value and that of the previous HR is more than 10 bpm, as such, embodiments disclosed herein may replace the HR by the most recent HR value from a previous window segment (or a moving average of several past HR beats or some other variant).

[00145] According to embodiments disclosed herein, criterion may be set that the HR value cannot change more than 10 BPM from a previous time window. In FIG. 8B, these cases are

illustrated. For example, in most cases, the blue circle which represents the largest spectral peak is chosen but in other cases, either green or red circles are chosen for certain time points. For the HR peaks associated with either the green or red circles, embodiments disclosed herein may choose those peaks because either the first two highest peaks are related to accelerometers or the highest magnitude peak deviates more than 10 BPM from the previous HR value.

[00146] FIG. 9 shows a comparison of reconstructed HR obtained, according to embodiments disclosed herein, to reference HR obtained from simultaneous ECG recordings. In FIG. 9, the extracted HR (red color) from PPG spectra of recording#8 from the competition training dataset, according to embodiments disclosed herein, is shown in red color and the reference ECG-derived HR is shown in black color. In order to calculate the performance of HR reconstruction according to embodiments disclosed herein, the error value in each time window was calculated from the estimated HR to the reference ECG-derived HR. Two measurement indices of absolute error similar to the indices in (Krishnan, R., B. Natarajan, and S. Warren, Two-Stage Approach for Detection and Reduction of Motion Artifacts in Photoplethysmographic Data. Biomedical Engineering, IEEE Transactions on, 2010. 57(8): p. 1867-1876) were used.

$$Error(1) = \frac{1}{W}\sum_{k=1}^{w} |HR_{SpaMA}(k) - HR_{ref}(k)| \tag{1}$$

$$Error(2) = \frac{1}{W}\sum_{k=1}^{w} \frac{|HR_{SpaMA}(k) - HR_{ref}(k)|}{HR_{ref}(k)} \times 100\% \tag{2}$$

where W is the total number of windows.

[00147] v. PPG Signal Reconstruction for HRV analysis

[00148] For an HRV analysis application, the above-disclosed embodiments are identical except that the beat-by-beat shift is of data rather than the 8 second data segment shift or its variant. According to embodiments disclosed herein, the PPG signal may be reconstructed using heart rate frequency, amplitude and phase changes, window-by-window using the sample-by-sample windowing process:

$$Rec_{Signal}(k) = A_{HR}(k) \times \sin\left(2\pi t(k) f_{HR}(k) + \varphi_{HR}(k)\right) \tag{3}$$

where $k = 1,\ldots, N$ and N is number of signal samples and total number of windows. $A_{HR}(k)$ and $\varphi_{HR}(k)$ are calculated according to the power of the signal for HR frequencies in the PSD and phase

angles of complex elements in a Fast Fourier Transform (FFT) matrix that correspond to HR frequencies.

[00149] FIG. 10A is an example embodiment of PPG signal reconstruction according to embodiments disclosed herein. FIG. 10A shows a comparison between reconstructed PPG and original recording #8 from IEEE competition training dataset. The left and right panels of FIGS. 10A-B show the reconstructed PPG versus the original PPG and their HRV time series, respectively.

[00150] FIG. 10B is a zoomed-in version of FIG. 10A.

[00151] Given that embodiments disclosed herein estimate quite accurate heart rates, it is not surprising to observe similar frequency dynamics between the reference and reconstructed HRV time series, as shown in FIGS. 11A-B.

[00152] FIGS. 11A-B show comparisons of HRV spectra between the reference and the reconstructed HRV time series (*e.g.*, as shown in FIGS. 10A-B) from the MA-contaminated PPG signal for dataset #8. Note that for computing HRV, matching the amplitude of the reference HR is not a concern, as the focus is only in the dynamics of the fluctuations in the heart rates.

[00153] FIG. 11A shows a time-domain comparison of a reconstructed HR and a reference HR.

[00154] FIG. 11B shows a spectral comparison of heart rate variability between reconstructed HR and reference HR calculated from the reference ECG using Pan & Tompkins peak detection approach (Pan J, T.W., A real-time QRS detection algorithm. IEEE Trans Biomed Eng, 1985. 32(3): p. 230-236).

[00155] Results

[00156] FIG. 11C is a "SpaMA Method Performance Comparison" table, Table 6, also referred to interchangeably herein as Table 6. Table 6 represents the average absolute error (E1) and the average absolute error percentage (E2) of embodiments disclosed herein as applied to all 3 datasets, respectively. Embodiments disclosed herein are compared to three methods: TROIKA, JOSS and WFPV. The results in Table 6 show that better performance from embodiments disclosed herein as compared to JOSS and TROIKA for all 12 subjects in the first datasets. In comparison to WFPV, embodiments disclosed herein outperform WFPV on average across all 23 subjects in both datasets (1) and (2). The total average of E1 for embodiments

disclosed herein is less than 2 beats per minutes for all 33 subjects. The average of E1 across the treadmill experiment recordings (activity Type 1- IEEE dataset and Type 4- Chon Lab dataset) is around 1 beat per minute for all 22 subjects.

[00157] FIGS. 12A, 12B, 13A, 13B, 14A, and 14B show the reconstructed HR and corresponding PSD of a sample-sample windowed HR, according to embodiments disclosed herein, in comparison to a reference HR from an ECG. The results for recording #9 from the first dataset (IEEE Competition Training dataset) and activity Type 1 (*e.g.*, running on treadmill) are shown in FIGS. 13A-B. As shown, E1 for this particular subject is as low as 0.4 bpm and the correlation between the PSD of reconstructed HR and reference HR is as high as 96%.

[00158] FIG. 12A shows a reconstructed HR vs. reference HR. FIG. 12B shows a spectral comparison of reconstructed HR and reference HR (estimated from reference ECG).

[00159] FIG. 13A illustrates the comparison between the reconstructed HR and the reference HR for Subject #14 (IEEE Competition Test Dataset) which has the highest errors. Subject #14 belongs to the second dataset (IEEE Competition Test dataset) and Type 2 activities (e.g. jumping). It can be seen that the largest error is obtained when both the physiological HR and the motion artifacts change rapidly so that the true HR cannot be reliably estimated.

[00160] FIG. 13B shows a reconstructed HR vs. reference HR for Subject 16 (IEEE Competition Test Dataset). FIG. 13B shows the comparison results of reconstructed HR and reference HR for recording #16 of the second dataset (IEEE Competition Test dataset) which has the Type 3 activities (*e.g.*, arm exercise).

[00161] FIG. 14A shows a reconstructed HR vs. reference HR for Subject #30 (Chon Lab Dataset). FIG. 14B shows a spectral comparison of reconstructed HR and reference HR (estimated from reference ECG). The results for recording #30 from the third datasets (Chon Lab datasets) and activity Type 4 (*e.g.*, running on treadmill) are shown in FIGS. 14A-B. It can be seen that the E1 for this subject is around 0.6 bpm and the correlation between the PSD of reconstructed HR and reference HR is as high as 99% for LF and 0.96 for HF frequency range. All subjects' results are provided in Table 7, disclosed below.

[00162] Table 7 represents the correlation and statistical difference using the student's t-test between PSD of estimated and reference HRV in both LF (0.04-0.15 Hz) and HF (0.15-0.4 Hz)

frequency ranges. The correlation values in the table are calculated based on Pearson's linear correlation coefficient. As shown in Table 7, there was no difference between the reference and the derived HRV for LF, according to embodiments disclosed herein, and a difference was seen in only 4 out of 10 subjects for HF.

Table 7. Frequency Domain HRV analysis Comparison: PSD of SpaMA Method vs. reference

Subjects	**Correlation**	
	LF (LF is [0.04-0.15] Hz and HF is [0.15-0.4] Hz)	**HF**
1	0.99	0.98
2	0.99	0.96
3	0.99	0.95* (*) indicates significantly different (P-value>0.05)
4	1.00	0.99
5	1.00	0.99
6	0.99	0.96*
7	0.98	0.92*
8	0.97	0.90*
9	1.00	0.99
10	1.00	0.99
mean	0.99	0.96

[00163] Table 8 shows some of the widely-reported time-domain HRV parameters such as the mean HR, standard-deviation (SDNN) of the normal-to-normal (NN) interval, root-mean-square of successive difference (RMSSD) of the NN interval, and the number of interval differences of successive NN intervals greater than 50 ms divided by the total number of NN intervals (pNN50) estimated from embodiments disclosed herein in comparison to the reference ECG NN interval. None of these parameters were found to be significantly different between those derived according to embodiments disclosed herein and the reference HRV.

Table 8. Time Domain HRV analysis Comparison: SpaMA Method vs. reference HRV

Subjects	**SDNN**		**meanNN**		**RMSSD**		**pNN50**	
	SpaMA	Reference	SpaMA	Reference	SpaMA	Reference	SpaMA	Reference
1	2620.75	2566.47	10481.89	10480.72	33.24	18.05	0.001	0.020
2	2115.44	2079.58	9908.00	10020.00	25.93	16.32	0.011	0.019
3	3173.73	3177.68	10764.20	10829.06	89.70	56.15	0.019	0.207
4	2517.78	2533.20	10376.95	10426.26	13.54	19.58	0.001	0.030
5	2654.42	2670.32	10846.04	10990.08	11.88	18.59	0.003	0.018
6	2012.53	1974.65	9737.35	9827.63	39.64	21.17	0.004	0.025
7	3056.36	2925.19	12519.74	13134.05	27.66	30.61	0.015	0.071

8	3133.76	2756.66	10504.00	10530.00	32.57	36.38	0.002	0.003
9	2195.08	2142.53	10499.81	10470.06	8.23	13.01	0.002	0.004
10	2454.57	2406.96	12936.62	12981.21	41.52	20.28	0.006	0.024
p-value	> 0.05		> 0.05		> 0.05		> 0.05	

[00164] As such, the SpaMA method, according to embodiments disclosed herein, that may be based on time-varying spectral analysis of the PPG signal addresses Heart Rate monitoring in the real world with challenges ranging from a subject who makes sudden movements but is otherwise sedate, to intensive physical activities. Embodiments disclosed herein compare spectral changes in PPG and accelerometer signals. As disclosed above, three different datasets have been used to verify the SpaMA performance. Each dataset reflects different types of activities and movements. In all of the experiments, the reference HR was calculated from an ECG signal that was collected simultaneously with the PPG signal. The estimated HR was calculated from the spectrum of PPG in 8 second time windows. Based on the results, disclosed above, the SpaMA method may be used for tracking HR changes during severe motion artifacts with an average error of just 1.86 bpm compared to that of the reference ECG; these results are superior to three other methods tested: TROIKA, JOSS and WFPV (Zhilin, Z., P. Zhouyue, and L. Benyuan, TROIKA: A General Framework for Heart Rate Monitoring Using Wrist-Type Photoplethysmographic Signals During Intensive Physical Exercise. Biomedical Engineering, IEEE Transactions on, 2015. 62(2): p. 522-531; Zhang, Z., Photoplethysmography-Based Heart Rate Monitoring in Physical Activities via Joint Sparse Spectrum Reconstruction. Biomedical Engineering, IEEE Transactions on, 2015. PP(99): p. 1-1).

[00165] Out of 33 recordings, 23 are from a wrist pulse oximeter, and the rest of the data were recorded by a forehead pulse oximeter. The results from Table 8, disclosed above, show that the SpaMA method can be applied to monitor HR from both wrist and forehead pulse oximeters. By comparing the performance of the method for treadmill experiments (dataset 1 and dataset 3), the error is lower by almost 1 beat using a wrist pulse oximeter. However, it should be noted that from this result a conclusion that the wrist PPG provides less error than the forehead should not be drawn, as the experiments used different subjects and were two separate studies. The prior methods (TROIKA, JOSS and WFPV) were tested using only on the wrist-based PPG signals as

the implementers of those methods did not have access to forehead PPG sensors. The SpaMA method, according to embodiment disclosed herein, was tested on data from both PPG sensor locations, and proved to be effective regardless of the location of the PPG sensor.

[00166] Several observations were made while analyzing the data, disclosed above. The tracking ability of the SpaMA method decreased as the frequency changes during recordings increased. This phenomenon mostly was observed while dealing with the second set of datasets from the IEEE competition, which involved Type (2) and Type (3) activities. These types of exercises involved more abrupt movements which consequently made it more difficult to track the HR-related frequencies in the spectrum. In the three datasets that have been analyzed, recordings #10 and 14 are examples of this phenomenon.

[00167] A strength of the PPG's LED is one of the most important factors determining the SpaMA method performance. Movement induces much less spectrum corruption (shift) in the PPG if the LED is sufficiently strong. A reduction in the strength of the PPG signal can also be caused by ambient light leaking into the gap between a PPG sensor and the skin surface (Zhang, Z., Photoplethysmography-Based Heart Rate Monitoring in Physical Activities via Joint Sparse Spectrum Reconstruction. Biomedical Engineering, IEEE Transactions on, 2015. PP(99): p. 1-1). This is because the power of the signal is dependent on the depth and reflection of the light from the pulse oximeter to the subject's skin. This gap between skin and the planar substrate where the LEDs and PD are mounted may be the result of movement during physical activities or the shape of tissue that the sensors touch. Among the three datasets, low performance for recordings #16 and 31 is the result of a weak PPG signal most likely due to a gap between the sensor and skin caused by motion artifacts.

[00168] By using the sample-by-sample windowing process, SpaMA, according to embodiments disclosed herein, can be utilized for both Heart Rate monitoring and HRV analysis in both frequency- and time-domains. From the results, disclosed above, it can be observed that embodiments disclosed here are able to replicate both the low frequency (0.04-0.15Hz) and the high frequency (0.15-0.4) dynamics well, albeit better the former than the latter, when compared to a reference HRV. For time-domain HRV measures, the mean HR, SDNN, RMSSD, and pNN50 based on embodiments disclosed herein were all found to be not significantly different than the reference HRV. It has long been shown that during dynamic exercise, heart rate

increases due to both a parasympathetic withdrawal and an augmented sympathetic activity (Iellamo, F., Neural mechanisms of cardiovascular regulation during exercise. Auton Neurosci, 2001. 90(1-2): p. 66-75; Bernardi, L. and M.F. Piepoli, [Autonomic nervous system adaptation during physical exercise]. Ital Heart J Suppl, 2001. 2(8): p. 831-9). The relative role of the two drives depends on the exercise intensity (Perini, R., et al., The influence of exercise intensity on the power spectrum of heart rate variability. Eur J Appl Physiol Occup Physiol, 1990. 61(1-2): p. 143-8; Sarmiento, S., et al., Heart rate variability during high-intensity exercise. Journal of Systems Science and Complexity, 2013. 26(1): p. 104-116; Roure, R., et al., Autonomic nervous system responses correlate with mental rehearsal in volleyball training. Eur J Appl Physiol Occup Physiol, 1998. 78(2): p. 99-108). Analysis of HRV permits insight into this control mechanism (Aubert, A.E., B. Seps, and F. Beckers, Heart rate variability in athletes. Sports Med, 2003. 33(12): p. 889-919). Also, being able to do HRV analysis from PPG even during movement and physical activities would be an advantage for detecting and diagnosing many cardiovascular diseases using only PPG recordings.

[00169] The SpaMA method, according to embodiments disclosed herein, can be potentially implemented in real time. The method written in Matlab®, version R2014 and CPU 3.4 GHz takes only 110 msec per 8 second segments. Therefore, given the high accuracy of the method in estimating HR despite severe motion artifacts, the SpaMA method, according to embodiments disclosed herein, has the potential to be applicable for implementation on wearable devices such as smart watches and PPG-based fitness sensors.

[00170] As disclosed above, accurate estimation of changing arterial oxygen saturation (SpO2) from photoplethysmogram (PPG) signals during movement is a very challenging problem. This is because strenuous and high intensity movements can result in severe motion artifacts (MA), making accurate SpO2 estimation from PPG signals difficult. As such, embodiment disclosed herein may applied the methods for reconstructing a PPG signal, as disclosed above, and include an additional stage of SpO2 estimation.

[00171] According to one embodiment, OxiMA may be comprised of the 6 stages disclosed above, with reference to FIGS. 3A-F, and include Stage 7, that is SpO2 Estimation.

[00172] According to another embodiment, OxiMA may be comprised of 6 stages: (1) Time-frequency Spectral Analysis, (2) Signal Decomposition, (3) Spectral Filtering, (4) Heart Rate (HR) extraction and tracking, (5) Signal Reconstruction, (6) SpO2 Estimation.

[00173] OxiMA

[00174] According to some embodiments, OxiMA may decompose the PPG signal into its frequency components by using a complex demodulation-based technique and may choose the components with frequencies close to the HR frequency for reconstructing the clean PPG signal. Next, SpO2 may be estimated from the reconstructed PPG signal. Such a method is applied to 22 minute datasets recorded from 10 subjects. A Nellcor OxiMax transmission sensor was used to collect analog PPG signals, while reference SpO2 and HR were collected simultaneously from the FDA approved Masimo SET Radical RDS-1 pulse oximeter. The performance of the OxiMA method according to embodiments disclosed herein, was determined by computing the mean absolute error between the estimated HR/SpO2 from the PPG and reference HR [Masimo]/SpO2[Masimo] oximeter. The results show the average estimation error using OxiMA are only 2.4 beats/minute for HR and 1.8% for SpO2, respectively. As such, the OxiMA method has great potential for MA reduction for both SpO2 and HR monitoring.

[00175] Vital signs and clinical symptoms have been shown to be poor predictors of hypoxia, and in order to rationalize oxygen therapy, measurement of arterial oxygen saturation by pulse oximetry is being increasingly recommended (Laman, M., et al., Can clinical signs predict hypoxaemia in Papua New Guinean children with moderate and severe pneumonia? Ann Trop Paediatr, 2005. 25(1): p. 23-7) Arterial oxygen saturation (SpO2) reflects the relative amount of oxyhemoglobin in the arterial blood. The most common method to measure SpO2 is based on pulse oximetry, whereby oxidized hemoglobin and reduced hemoglobin have significantly different optical spectra.

[00176] Specifically, at a red wavelength of about 660 nm, there is a significant difference in light absorbance between reduced (Hb) and oxidized hemoglobin (HbO2). A measurement of the percent oxygen saturation of blood is defined as the ratio of oxyhemoglobin to the total concentration of hemoglobin present in the blood. Pulse oximetry assumes that the fluctuations of the PPG signal are caused by changes in arterial blood volume associated with each heartbeat, where the magnitude of the fluctuations depends on the amount of arterial blood rushing into the

peripheral vascular bed, the optical absorption of the blood, skin and tissue, and the wavelengths used to illuminate the blood. The photoplethysmogram (PPG) can be used to derive not only the SpO2 and heart rate (HR) data, but also other vital physiological information (Laman, M., et al., Can clinical signs predict hypoxaemia in Papua New Guinean children with moderate and severe pneumonia? Ann Trop Paediatr, 2005. 25(1): p. 23-7; Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263; Tamisier, R., et al., A new model of chronic intermittent hypoxia in humans: effect on ventilation, sleep, and blood pressure. J Appl Physiol (1985), 2009. 107(1): p. 17-24; Jubran, A., Pulse oximetry. Crit Care, 1999. 3(2): p. R11-r17). As disclosed above, utilizing a pulse oximeter as a multi-purpose vital sign monitor has clinical appeal, since it is familiar to clinicians and comfortable for the patient (Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II: Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263).

[00177] In healthy persons, SpO2 is typically near 98%. A lower reading indicates a level of hypoxia. SpO2 readings below 95% are usually a cause for concern, indicating the need for supplemental oxygen therapy. In certain individuals, such as those with chronic respiratory or cardiac diseases, SpO2 readings below 95% may be considered normal. However, in general, SpO2 readings between 90%-95% represent mild hypoxia, while 85%-90% indicates serious hypoxia, and readings below 85% are considered critical hypoxia (Tamisier, R., et al., A new model of chronic intermittent hypoxia in humans: effect on ventilation, sleep, and blood pressure. J Appl Physiol (1985), 2009. 107(1): p. 17-24).

[00178] As disclosed below, the OxiMA method according to embodiments disclosed herein, provides HR reconstruction with accurate SpO2 estimation even during movement. The most recent methods as noted above (e.g., TROIKA and JOSS) do not show their ability to obtain SpO2 estimates as they were mainly designed for HR calculations in the presence of intense motion artifacts.

[00179] The OxiMA method was evaluated on a lab controlled dataset that was recorded during voluntary induced hypoxia. In an IRB approved study which recruited 10 subjects, one

set of data was collected from each subject for a duration of 22 min. Reference arterial SpO2 and HR were collected from the FDA approved Masimo SET Radical RDS-1 pulse oximeter (mounted on the left hand), while a Nellcor OxiMax sensor (mounted on the right hand) was used to collect analog PPG signals, simultaneously, as shown in Table 9 of FIG. 14C, disclosed below.

[00180] FIG. 14C is a table, Table 9, that includes PPG datasets and experiments settings. Each subject sat in a chair and was asked to re-breathe into a 1-gallon bag four times for approximately two minutes each time. During the first and third time the subject rebreathed into the bag, subjects were asked to remain still. During the second and fourth time the subject rebreathed into the bag, subjects were asked to introduce motion artifacts into the measurement by shaking their right hand. Each subject wore a disposable nose clip to prevent accidental breathing of room air. The Masimo reference sensor placed in the left hand remained motionless for the entire duration of the study. Subjects had at least two minutes of rest between successive breathing maneuvers, with more time if requested. The protocol for this experiment is presented in Table 10. Worcester Polytechnic Institute IRB approved the study protocol and informed consent was required by all subjects prior to data recording.

[00181] This sequence of data recording allowed us to test the efficacy of the OxiMA method while a subject experienced different levels of short lasting hypoxia during motion artifacts. For reference, other clinical studies showed that SpO2 levels in patients suffering from mild to moderate sleep apnea can drop to about 80% for short periods of time until the patient is awakened without irreversible physiological effects (Maeda, Y., M. Sekine, and T. Tamura, Relationship between measurement site and motion artifacts in wearable reflected photoplethysmography. J Med Syst, 2011. 35(5): p. 969-76).

[00182] Methodology

[00183] The protocol for testing performance of the OxiMA method is presented in Table 10.

TABLE 10
EXPERIMENT PROTOCOL

End Time (min)	Event
2	Rest (baseline)
4	Bag breathing (motion)
5	Rest (oxygen recovery)
7	Rest
9	Bag breathing (motion)
10	Rest (oxygen recovery)
12	Rest
14	Bag breathing (no motion)
15	Rest (oxygen recovery)
17	Rest
19	Bag breathing (motion)
20	Rest (oxygen recovery)
22	Rest

[00184] Details of each stage of the OxiMA method as applied in the experiment are disclosed below.

[00185] Time-Varying Spectral Analysis of PPG and Accelerometer Data

[00186] To compute the time-frequency spectrum, a variable frequency complex demodulation technique was employed. Table 11, disclosed below, presents the OxiMA method, according to one embodiment.

[00187] The time-varying spectrum is estimated by taking a T-sec window of the PPG signal and computing the VFCDM time-frequency of the segment and then sliding the window through the whole dataset. There is no overlapping between the sliding time windows. The window segment length T was set to 8 seconds and was shifted by 8 seconds. The assumption of 8 second data length largely stems from the fact that SpO2 and heart rates do not change instantaneously; hence, an 8 second duration is a reasonable choice.

TABLE 11
OXIMA METHOD: HR AND SPO2 RECONSTRUCTION

Stage 1. VFCDM Time-Frequency Spectrum
1.1. Downsample the PPG signal to ¼ of the original sampling frequency.
1.2. Compute the VFCDM based time-frequency spectrum (TFS)

Stage 2. Signal Decomposition
2.1. Decompose the PPG signal into its frequency components according to frequency bands in the TFS

Stage 3. Spectral Filtering
3.1. Assume HR to be in the frequency range of [0.5Hz – 3Hz], to account for both low and high HR values.
3.2. The first highest two peaks and their corresponding frequencies in the PPG filtered spectrum are assumed to have HR information.

Stage 4. Heart Rate Tracking and Extraction from PPG Spectrum
Case (1): From 3.1- if the spectrum is corrupted by movement and only the first largest peak is corrupted, then the HR frequency should be the frequency of the second peak in the spectrum.
Case (2): Due to the sensor-skin interface interruption, which could be a result of gap between the pulse oximeter and a subject's skin or slight sensor alignment variations relative to skin, the HR frequency cannot be extracted from the spectrum and in this case the previous HR frequency is used or for offline implementation a cubic spline interpolation can be applied to fill in the missing HR information.

Stage 5. PPG Signal Reconstruction
5.1. The PPG signal is reconstructed by using the summation of VFCDM components with frequency close to the HR frequency at each window.

Stage 6. Oxygen Saturation Estimation
6.1. Calculate the SpO2 estimations from reconstructed infrared and red PPG signals using the following empirical calibration equation [2]

$$SpO_2(\%) = (110 - 25R)$$

where,

$$R = \frac{AC_{Red}/DC_{Red}}{AC_{IR}/DC_{IR}}$$

[00188] FIGS. 15A-B show the resultant VFCDM time-frequency spectrum of recordings from subject #5, as a representative example.

[00189] The panels in FIGS. 15A-B show infrared PPG time series data. FIG. 15B represents the time-frequency plot of the infrared PPG signal. The next section details how the PPG data is decomposed into its frequency components using VFCDM.

[00190] Signal Decomposition

[00191] The original PPG signal was decomposed into sinusoidal modulations using a VFCDM method, as disclosed in Table 12 below.

$$x(t) = \sum_{i=1}^{N} Component\{i\} = \sum_{i=1}^{N} dc_i(t)A_i(t)cos(2\pi f_i(t) + \phi_i(t)) \qquad (4)$$

[00192] By assuming N=12 fixed frequency bands each with a distinct central frequency, the PPG and accelerometer signals may be decomposed using the VFCDM method of Table 12 which yields 12 components.

TABLE 12
VFCDM METHOD

Consider a sinusoidal signal $x(t)$ to be a narrow band oscillation with a time-varying center frequency $f(\tau)$, instantaneous amplitude $A(t)$, phase $\phi(t)$, and the direct current component $dc(t)$:

$$\boldsymbol{x(t) = dc(t) + A(t)\cos\left(\int_0^t 2\pi f(\tau)d\tau + \phi(t)\right)}$$

Step (1) For a given center frequency, we can extract the instantaneous amplitude information $A(t)$ and phase information $\phi(t)$ by multiplying (1) by $e^{-j\int_0^t 2\pi f(\tau)d\tau}$ which results in the following:

$$z(t) = x(t)e^{-j\int_0^t 2\pi f(\tau)d\tau} = dc(t)e^{-j\int_0^t 2\pi f(\tau)d\tau} + \frac{A(t)}{2}e^{j\phi(t)} + \frac{A(t)}{2} e^{-j\left(\int_0^t 4\pi f(\tau)d\tau + \phi(t)\right)}$$

Step (2) From (2), if $z(t)$ is filtered with an ideal low-pass filter (LPF) with a cutoff frequency $f_c < f_0$, where f_0 is the center frequency of interest. Then the filtered signal $z_{lp}(t)$ will contain only the component of interest $z_{lp}(t) = \frac{A(t)}{2}e^{j\phi(t)}$.

Step (3) By changing the center frequency followed by using the variable frequency approach as well as the LPF, the signal, $x(t)$, will be decomposed into the sinusoid modulations, d_i, by the CDM technique as follows:

$$\boldsymbol{x(t) = \sum_i d_i = dc(t) + \sum_i A_i(t)\cos\left(\int_0^t 2\pi f_i(\tau)d\tau + \phi_i(t)\right)}$$

Step (4) The instantaneous frequency and amplitude of d_i can be calculated using the Hilbert transform

$$A(t) = 2|z_{lp}(t)| = [X^2(t) + Y^2(t)]^{1/2}$$
$$X(t) = real(z_{lp}(t))$$
$$Y(t) = image(z_{lp}(t)) = H[X(t)] = \frac{1}{\pi}\int \frac{X(t')}{t - t'}dt'$$

[00193] FIG. 16 shows the twelve components corresponding to the IR and Red signal for subject #5. Among the twelve frequency bands, bands 1 to 5 correspond to frequency range of [0.5 Hz to 3 Hz], which is typically the HR frequency range accounting for both normal and elevated heart rates. Embodiments disclosed herein select a component of these 5 components to

reconstruct the signal that preserves the HR and is less corrupted by the motion artifacts. For the selection, an accurate HR may be estimated by selecting the components that match closest to the actual HR frequency in order to reconstruct a less noisy PPG signal than the original motion corrupted data.

[00194] Spectral Filtering

[00195] After obtaining the power spectral density at each window, HR frequency may be assumed to be confined in the range [0.5 Hz – 3 Hz], which takes into account both at rest and high HR values due to either tachycardia or exercise scenarios. Next, for HR estimation, the strategy is to keep only frequencies that correspond to the first and second peak at each column of time-frequency matrix, as disclosed above, with reference to FIG. 3B.

[00196] In general, HR frequency in the VFCDM based power spectral density of the PPG at each window can have three different scenarios: (1) PPG is devoid of MA and there is no sensor-skin interface problems like a spatial gap between the sensor and the subject's skin during recording, (2) PPG is corrupted by MA and there is no spatial gap between the sensor and the subject's skin during recording and (3) There is a spatial gap between the sensor and the subject's skin during recording. For the ideal case (1), HR can be extracted and it is most likely represented as the highest peak in the PPG spectrum. For case (2), MA dynamics can result in the dominant peak and HR frequency peak's magnitude become smaller than the MA frequency peak in the spectrum. The only scenario that makes it difficult to extract HR from the spectrum is scenario (3) when there is a spatial gap between the PPG sensor and the subject's skin during recording. In this scenario, assuming that the motion artifacts are short lasting, the missing HR values can be interpolated using the cubic spline approach.

[00197] FIGS. 17A-C are plots of the above three scenarios. In FIG. 17A and FIG. 17B, the true HR frequency is close to the first and second peak respectively, while in FIG. 17C, the true HR frequency is far from the dominant peaks in the spectrum. As long as the PPG data is clean, an assumption may be made that the HR frequency belongs to the frequency component with the highest power (peak) at the each column of the TFS matrix. On the other hand, when the data becomes corrupted by MA, it might shift the HR frequency to the next highest peak in the spectrum or might lose the dominant HR frequency.

[00198] Embodiments disclosed herein employ a TFS filtering step to search for N first highest spectral peaks and their associated frequencies in each column of the TFS. Hence, the original TFS of FIG. 15B can be filtered to select only N, for example, 2, in the example embodiments, highest spectral peaks.

[00199] FIG. 18A shows a representative filtered time-frequency spectral plot of PPG recording from subject #5. This portion of the OxiMA method involves retaining only the two largest frequency peaks at each time point within the defined HR range (30-180 bpm) and they are represented as blue and green traces, respectively.

[00200] Heart Rate Tracking and Extraction

[00201] After filtering the TFS, the HR may be extracted. The HR tracking method may be summarized as: Assume there is only knowledge of the initial HR, the HR at each window is extracted by comparing the peaks to the previous HR value.

[00202] As disclosed above with reference to FIG. 3B, if the largest peak is within the 10 bpm range from the previous value of HR, it is chosen; if not, the second largest peak is checked for compliance of this scenario. If the HR value deviates by more than 10 bpm, the HR from the previous window may be adopted by the method.

[00203] FIG. 18B illustrates the tracking of HR based on OxiMA method, disclosed above.

[00204] FIGS. 19A and 19B represent comparisons, of the estimated 8 second moving averaged HR from the OxiMA method, to the reference HR, and the HR calculated from the motion-corrupted PPG signal, compared to the reference HR from the ECG, respectively. In order to calculate the performance of the OxiMA method for HR reconstruction, the error value in each time window was calculated from the estimated HR to the reference ECG-derived HR. Two measurement indices of absolute and normalized errors similar to the indices in (Wang, H., et al., A high resolution approach to estimating time-frequency spectra and their amplitudes. Ann Biomed Eng, 2006. 34(2): p. 326-3) were used.

$$Error(1) = \frac{1}{W}\Sigma_{k=1}^{W}\left|HR_{OxiMA}(k) - HR_{ref}(k)\right| \quad (5)$$

$$Error(2) = \frac{1}{W}\sum_{k=1}^{w}\frac{\left|HR_{OxiMA}(k) - HR_{ref}(k)\right|}{HR_{OxiMA}(k)} \times 100\% \quad (6)$$

where, W is the total number of windows.

[00205] PPG signal reconstruction

[00206] Now that HR values at each time window are estimated from the time-frequency spectrum, the signal reconstruction phase of the OxiMA method may be performed. An assumption may be made that the signal components corresponding to the HR frequency are more robust against motion and, thus, a less corrupted signal can be reconstructed using the summation of these components.

[00207] By calculating the components from the Signal Decomposition, using Eq (4) and the time-frequency spectrum of the PPG, at each 8-sec window a signal component may be chosen that has a frequency close to estimated HR frequency and that component may be employed to reconstruct infrared and red PPG data at each window. This yields a less motion-corrupted data that can be used for oxygen saturation estimation, as disclosed in FIG. 20A and FIG. 20B.

[00208] Oxygen Saturation Estimation

[00209] In order to calculate SpO2 from PPG signals, red and infrared PPG signals with clearly separable DC and AC components are required. Let the pulsatile components of the red and infrared PPG signals be denoted as AC_{Red} and AC_{IR}, respectively, then the "ratio-of-ratio" R is estimated (Thakor, N.V. and Y.S. Zhu, Applications of adaptive filtering to ECG analysis: noise cancellation and arrhythmia detection. IEEE Trans Biomed Eng, 1991. 38(8): p. 785-94; Diniz, P., Adaptive filtering: algorithms and practical implementation. 2008: . Springer Science, Business Media L.L.C) as

$$R = \frac{AC_{Red}/DC_{Red}}{AC_{IR}/DC_{IR}} \qquad (7)$$

[00210] Accordingly, SpO2 may be computed by substituting the R value in an empirical linear approximated relation given by $SpO_2(\%) = (110 - 25R)$.

[00211] FIG. 20C represents the reconstructed SpO2 values obtained from OxiMA in comparison to the reference SpO2 values and the estimated values before reconstruction.

[00212] OxiMA Results

[00213] Table 13 represents the average absolute error (E1) and the average absolute error percentage (E2) of HR and SpO2 estimations of the OxiMA method on the varying hypoxia level dataset.

TABLE 13
OXIMA METHOD PERFORMANCE COMPARISON (HR ESTIMATIONS)

Subject	Actual HR estimation error		OxiMA HR estimation error	
	E1	E2%	E1	E2%
1	3.84	4.83	**1.53**	**2.10**
2	6.84	9.57	**2.72**	**3.97**
3	8.15	9.59	**1.69**	**2.29**
4	4.55	5.39	**2.61**	**3.18**
5	10.53	11.96	**4.04**	**4.60**
6	4.46	5.52	**2.04**	**2.66**
7	12.41	19.65	**2.81**	**4.37**
8	3.84	4.35	**2.10**	**2.46**
9	3.80	4.13	**2.57**	**2.83**
10	3.65	4.20	**1.85**	**2.41**
mean ± std	6.20 ± 3.2	7.91 ± 5.0	2.40 ± 0.73	3.09 ± 0.90

[00214] The OxiMA method is compared to the HR and SpO2 estimations prior to the reconstruction method, where both pre- and post-reconstruction estimations are compared to the reference HR and reference SpO2 values obtained from the Masimo pulse oximeter.

[00215] The results presented in Table 13 show that OxiMA on average improves the HR and SpO2 estimations by 100% and 105%, respectively when compared to those estimations without the reconstruction method. Improvement rates are calculated as follow:

$$\boldsymbol{ImRate1}(\%) = \frac{\mathbf{1}}{\boldsymbol{W}}\sum_{\boldsymbol{k=1}}^{\boldsymbol{W}} \frac{|\boldsymbol{Error1_{OxiMA}(k) - Error1_{Act}(k)}|}{\boldsymbol{Error1_{OxiMA}(k)}} \times \mathbf{100}\% \qquad (\mathbf{8})$$

$$\boldsymbol{ImRate2}(\%) = \frac{\mathbf{1}}{\boldsymbol{W}}\sum_{\boldsymbol{k=1}}^{\boldsymbol{W}} \frac{|\boldsymbol{Error2_{OxiMA}(k) - Error2_{Act}(k)}|}{\boldsymbol{Error2_{OxiMA}(k)}} \times \mathbf{100}\% \qquad (\mathbf{9})$$

[00216] FIGS. 21A-C and FIGS. 22A-B show the reconstructed SpO2 and HR in comparison to the reference HR from ECG recordings for subject #5. The largest error among all recordings was found to be from this recording, as shown in Tables 13 and 14. The larger error could be due to rapid movements or skin-sensor gap during the recordings.

TABLE 14
OXIMA METHOD PERFORMANCE COMPARISON (SpO_2 ESTIMATIONS)

Subject	Actual SpO_2 estimation error		OxiMA SpO_2 estimation error	
	E1	E2%	E1	E2%
1	2.51	2.63	**0.86**	**0.90**
2	7.14	9.63	**2.45**	**3.10**
3	6.21	6.59	**1.61**	**1.67**
4	1.89	2.46	**0.95**	**1.16**
5	7.13	7.80	**3.25**	**3.47**
6	2.85	2.99	**1.10**	**1.14**
7	5.83	9.09	**2.57**	**4.52**
8	3.51	4.63	**1.73**	**2.22**
9	1.81	2.10	**1.50**	**1.61**
10	4.85	5.91	**1.93**	**2.07**
mean ± std	4.37 ± 2.1	5.38 ± 2.8	1.79 ± 0.8	2.19 ± 1.2

[00217] As such, the E1 (HR) for this particular subject is as low as 4.05 bpm while the E1 (SpO2) is as low as 3.25%. It can be seen from Table 15, disclosed below, that HR and SpO2 both improved by 160% and 119%, respectively, post reconstruction method.

TABLE 15
OXIMA METHOD PERFORMANCE COMPARISON (SpO_2 ESTIMATIONS)

Subject	HR Improvement Rate		SpO_2 Improvement Rate	
	ImRate1%	ImRate2%	ImRate1%	ImRate2%
1	150.90	130.00	191.86	192.22
2	151.47	141.05	191.43	210.64
3	323.08	318.78	285.71	294.61
4	74.33	69.50	98.95	112.07
5	160.17	160.66	119.38	124.78
6	118.63	107.52	159.09	162.28
7	377.22	372.54	126.85	101.10
8	82.86	76.83	102.89	108.55
9	47.86	45.94	20.67	30.43
10	97.30	74.27	151.30	185.5
mean ±	158.38 ±	149.71 ±	144.81 ±	152.2 ±

V. Conclusions

[00218] As such, the OxiMA method that may be based on time-varying spectral analysis of the PPG signal combats motion artifacts that can degrade the accuracy of SpO2 and HR estimations. According to embodiments disclosed herein, the OxiMA method may decompose

the PPG signal into many frequency bands using a VFCDM method (Chon, K.H., S. Dash, and J. Kihwan, Estimation of Respiratory Rate From Photoplethysmogram Data Using Time-Frequency Spectral Estimation. Biomedical Engineering, IEEE Transactions on, 2009. 56(8): p. 2054-2063), or any other suitable time-frequency technique, such as a wavelet analysis (Chon, K.H., S. Dash, and J. Kihwan, Estimation of Respiratory Rate From Photoplethysmogram Data Using Time-Frequency Spectral Estimation. Biomedical Engineering, IEEE Transactions on, 2009. 56(8): p. 2054-2063). According to embodiments disclosed herein, those components that are within the heart rate ranges including both extreme ranges of the low and high heart rates may be decomposed and used to reconstruct the PPG signal based on those components. As such, frequencies that are not within the prescribed HR ranges may be removed. From this reconstructed time series HR may be estimated and SpO2 may be estimated, as disclosed above.

[00219] The dataset used to verify the OxiMA method's performance was collected from 10 subjects during hypoxic experiments. The results show accurate estimation of both HR and SpO2 even during the presence of severe motion artifacts where the average error was only 2.4 bpm. More importantly, the average improvements in these estimates are astoundingly high for both HR (149%) and SpO2 (152%) when the reconstruction method applied, according to embodiments disclosed herein. Other methods for estimates of HR during severe motion artifacts for PPG signal Zhilin, Z., P. Zhouyue, and L. Benyuan, TROIKA: A General Framework for Heart Rate Monitoring Using Wrist-Type Photoplethysmographic Signals During Intensive Physical Exercise. Biomedical Engineering, IEEE Transactions on, 2015. 62(2): p. 522-531; Zhang, Z., Photoplethysmography-Based Heart Rate Monitoring in Physical Activities via Joint Sparse Spectrum Reconstruction. Biomedical Engineering, IEEE Transactions on, 2015. PP(99): p. 1-1; Salehizadeh, S., et al., A Novel Time-Varying Spectral Filtering Algorithm for Reconstruction of Motion Artifact Corrupted Heart Rate Signals During Intense Physical Activities Using a Wearable Photoplethysmogram Sensor. Sensors, 2015. 16(1): p. 10) produced good results (Kalman, R.E., A New Approach to Linear Filtering and Prediction Problems Transactions of the ASME – Journal of Basic Engineering, 1960. Series D (82)). However, these methods are only confined to HR estimation and not SpO2. Specifically, previous PPG reconstruction methods, such as (Salehizadeh, S.M.A., et al., Photoplethysmograph Signal Reconstruction based on a Novel Motion Artifact Detection-Reduction Approach. Part II:

Motion and Noise Artifact Removal. Annals of Biomedical Engineering, 2014. 42(11): p. 2251-2263; Kim, B.S. and S.K. Yoo, Motion artifact reduction in photoplethysmography using independent component analysis. IEEE Trans Biomed Eng, 2006. 53(3): p. 566-8), have been tested under MA conditions but not with concomitant hypoxia. The results, disclosed abele, illustrate the efficacy of a method which provides accurate estimates of both SpO2 and HR even when there are significant MA and concomitant low oxygen saturation values.

[00220] Observations were made while analyzing the OxiMA data. The tracking ability of the OxiMA method decreased as the frequency changes during recordings increased. This is mostly likely because OxiMA tracks a dominant frequency through an 8-second window. Since each subjects' motion varied throughout each hypoxic maneuver, the dominant frequency can change within the observed window. The strength of the PPG's LED is one of the most important factors determining the performance. A reduction in the strength of the PPG signal can be caused by ambient light leaking into the gap between a PPG sensor and the skin surface (Zhang, Z., Photoplethysmography-Based Heart Rate Monitoring in Physical Activities via Joint Sparse Spectrum Reconstruction. Biomedical Engineering, IEEE Transactions on, 2015. PP(99): p. 1-1). This is because the power of the signal is dependent on the depth and reflection of the light from the pulse oximeter sensor to the subject's skin. This gap between the skin and the sensor may be the result of movement during physical activities or the shape of tissue that the sensors touch. In the datasets that have been analyzed, recordings #5 and #7 are examples of the above two scenarios.

[00221] Additionally, the local blood perfusion of the monitored region affects the signal-to-noise ratio of the PPG signal. When performing the hypoxic maneuvers, subjects' HR and breathing rate normally increase as oxygen saturation decreases. These physiologic changes cause more distinct pulsations in the digits, which increase the signal-to-noise ratio.

[00222] The OxiMA method can be easily implemented in real-time. Execution time of the method has been found to be only 180 msec on data divided into 8 second segments using Matlab® R2014a and CPU 3.6GHz. Therefore, given the high accuracy of the OxiMA method in estimating HR and SpO2 despite severe motion artifacts, this method has the potential to be applicable for implementation on wearable devices such as smart watches and PPG-based fitness sensors.

[00223] FIG. 23 is a block diagram of an example of the internal structure of a computer 2300 in which various embodiments of the present disclosure may be implemented. The computer 2300 contains a system bus 2302, where a bus is a set of hardware lines used for data transfer among the components of a computer or processing system. The system bus 2302 is essentially a shared conduit that connects different elements of a computer system (*e.g.*, processor, disk storage, memory, input/output ports, network ports, *etc.*) that enables the transfer of information between the elements. Coupled to the system bus 2302 is an I/O device interface 2404 for connecting various input and output devices (*e.g.*, keyboard, mouse, displays, printers, speakers, *etc.*) to the computer 2300. A network interface 2306 allows the computer 2300 to connect to various other devices attached to a network. Memory 2308 provides volatile storage for computer software instructions 2310 and data 2312 that may be used to implement embodiments of the present disclosure. Disk storage 2314 provides non-volatile storage for computer software instructions 2310 and data 2312 that may be used to implement embodiments of the present disclosure. A central processor unit 2318 is also coupled to the system bus 2302 and provides for the execution of computer instructions.

[00224] Further example embodiments disclosed herein may be configured using a computer program product; for example, controls may be programmed in software for implementing example embodiments. Further example embodiments may include a non-transitory computer-readable medium containing instructions that may be executed by a processor, and, when loaded and executed, cause the processor to complete methods described herein. It should be understood that elements of the block and flow diagrams, such as the reconstruction unit 416, output unit 418, reconstruction unit 516, output unit 518, heart rate unit, arterial oxygen saturation (SpO2) unit, and ailment unit, disclosed above, may be implemented in software, hardware, such as via one or more arrangements of circuitry of FIG. 23, disclosed above, or equivalents thereof, firmware, a combination thereof, or other similar implementation determined in the future. In addition, the elements of the block and flow diagrams described herein may be combined or divided in any manner in software, hardware, or firmware. If implemented in software, the software may be written in any language that can support the example embodiments disclosed herein. The software may be stored in any form of computer readable medium, such as random access memory (RAM), read only memory (ROM), compact

disk read-only memory (CD-ROM), and so forth. In operation, a general purpose or application-specific processor or processing core loads and executes software in a manner well understood in the art. It should be understood further that the block and flow diagrams may include more or fewer elements, be arranged or oriented differently, or be represented differently. It should be understood that implementation may dictate the block, flow, and/or network diagrams and the number of block and flow diagrams illustrating the execution of embodiments disclosed herein.

[00225] The teachings of all patents, published applications and references cited herein are incorporated by reference in their entirety.

[00226] While this invention has been particularly shown and described with references to example embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the invention encompassed by the appended claims.

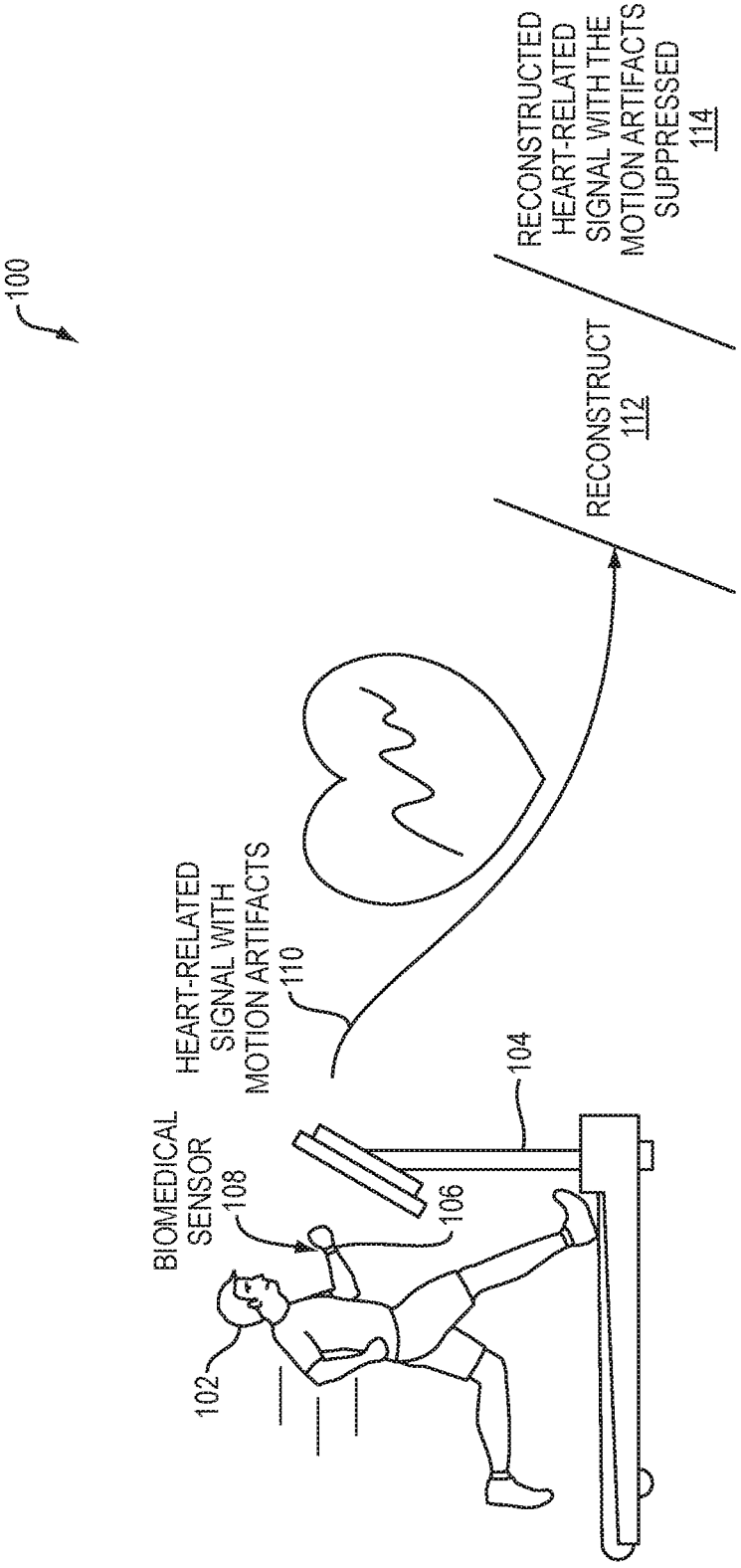


FIG. 1

Petitioner Ex-1004, 1187

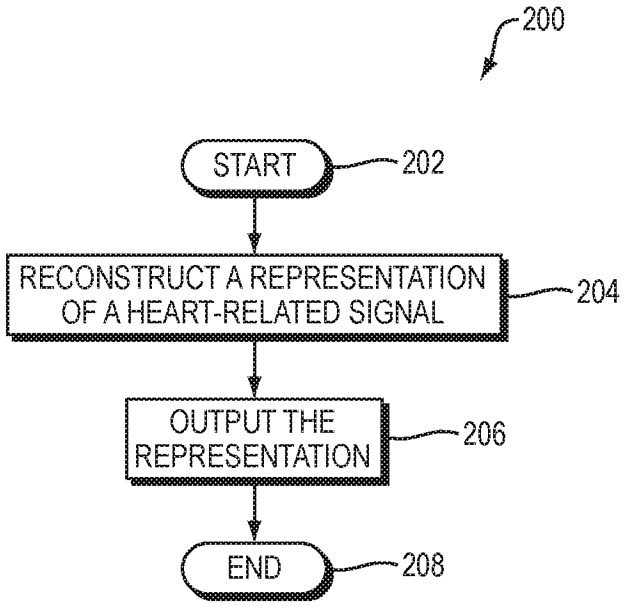

200
START
202
RECONSTRUCT A REPRESENTATION OF A HEART-RELATED SIGNAL
204
OUTPUT THE REPRESENTATION
206
END
208

FIG. 2

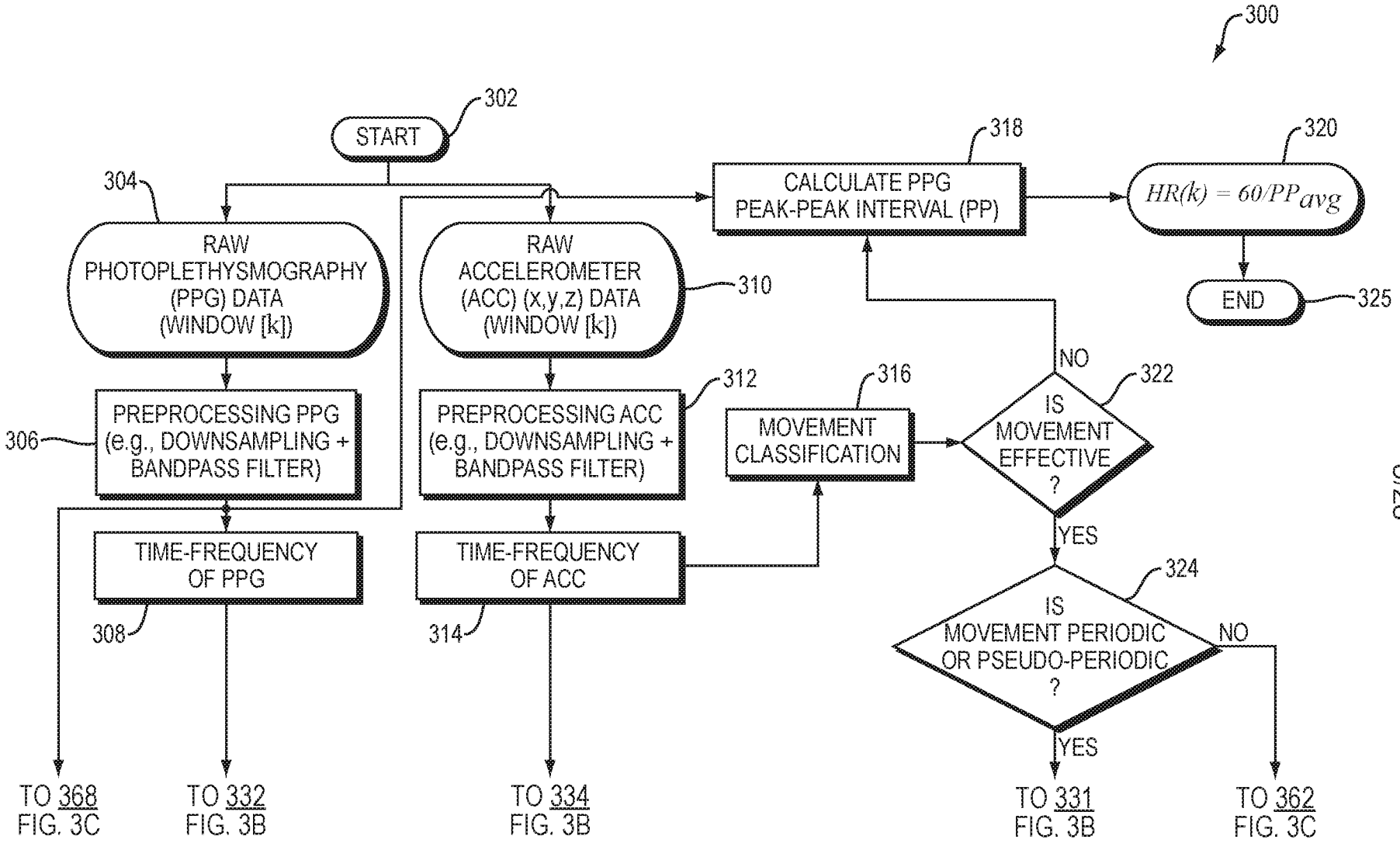

300
START
302
304
RAW PHOTOPLETHYSMOGRAPHY (PPG) DATA (WINDOW [k])
RAW ACCELEROMETER (ACC) (x,y,z) DATA (WINDOW [k])
310
CALCULATE PPG PEAK-PEAK INTERVAL (PP)
318
HR(k) = 60/PPavg
320
END
325
306
PREPROCESSING PPG (e.g., DOWNSAMPLING + BANDPASS FILTER)
312
PREPROCESSING ACC (e.g., DOWNSAMPLING + BANDPASS FILTER)
316
MOVEMENT CLASSIFICATION
NO
322
IS MOVEMENT EFFECTIVE ?
YES
TIME-FREQUENCY OF PPG
308
TIME-FREQUENCY OF ACC
314
324
IS MOVEMENT PERIODIC OR PSEUDO-PERIODIC ?
NO
YES
TO 368 FIG. 3C
TO 332 FIG. 3B
TO 334 FIG. 3B
TO 331 FIG. 3B
TO 362 FIG. 3C

FIG. 3A

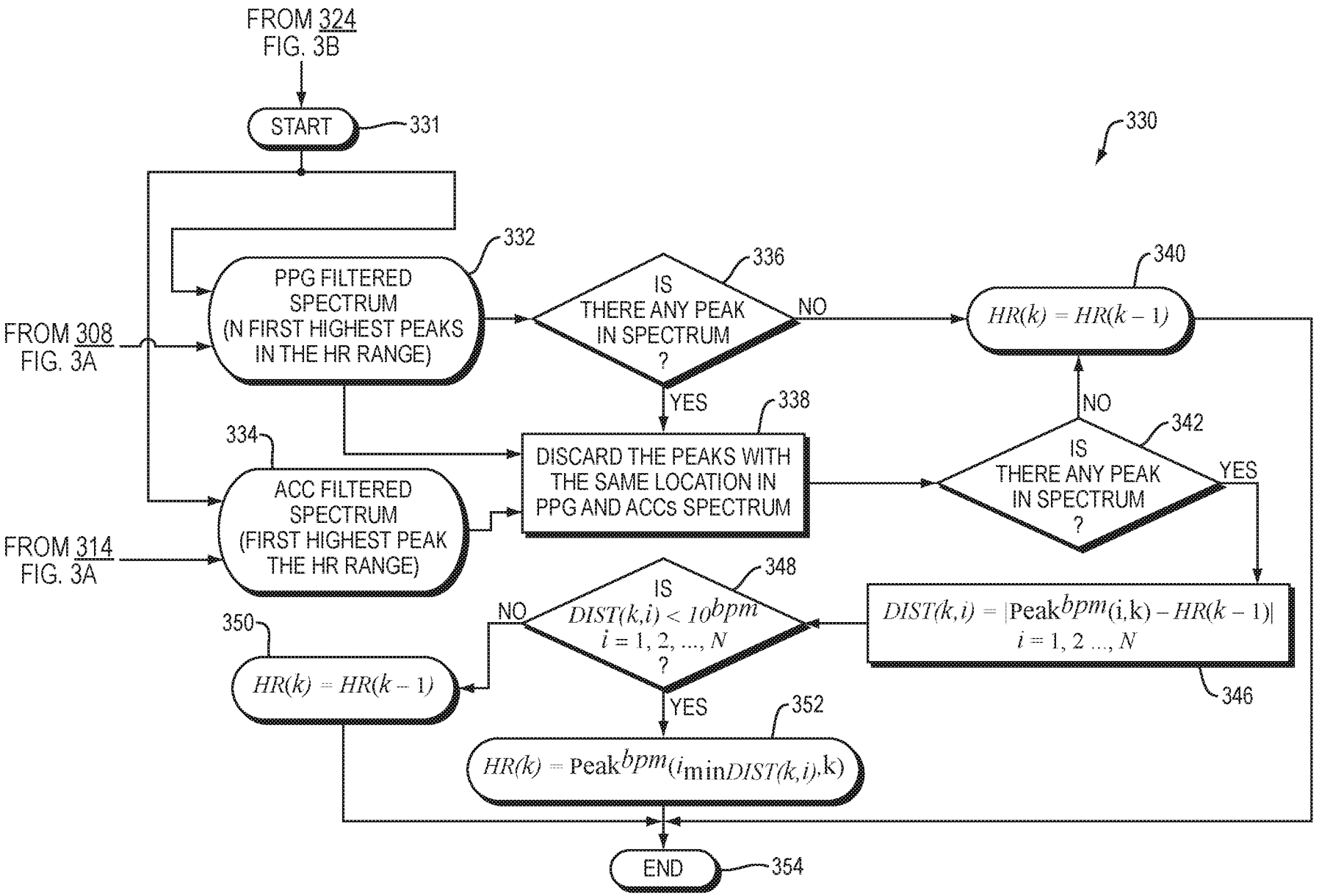


FIG. 3B

Docket No.: 4147.1020-002
Title: Method and Apparatus For Removing...
Inventors: Salehizadeh et al.
REPLACEMENT SHEET

Petitioner Ex-1004, 1191

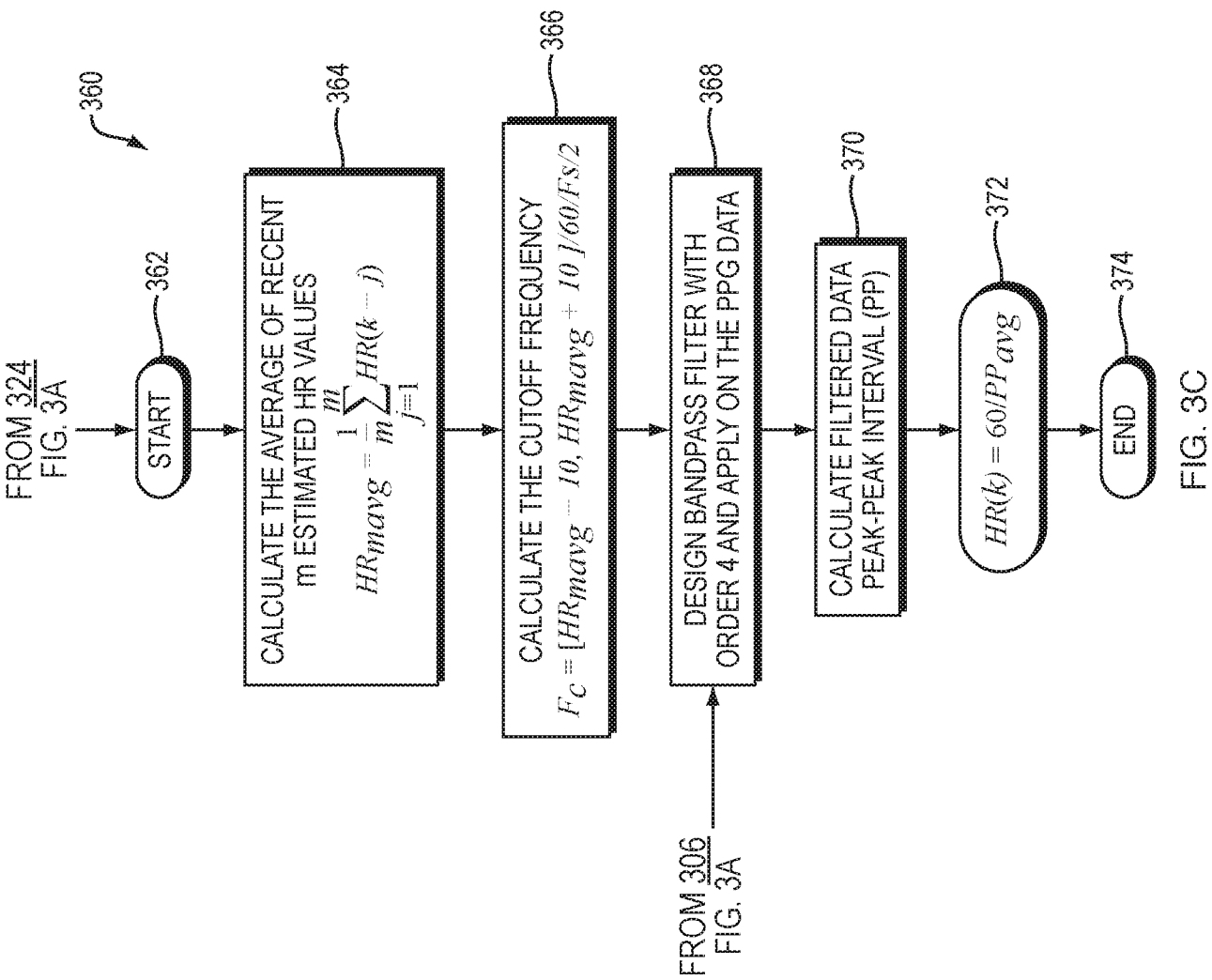


FIG. 3C

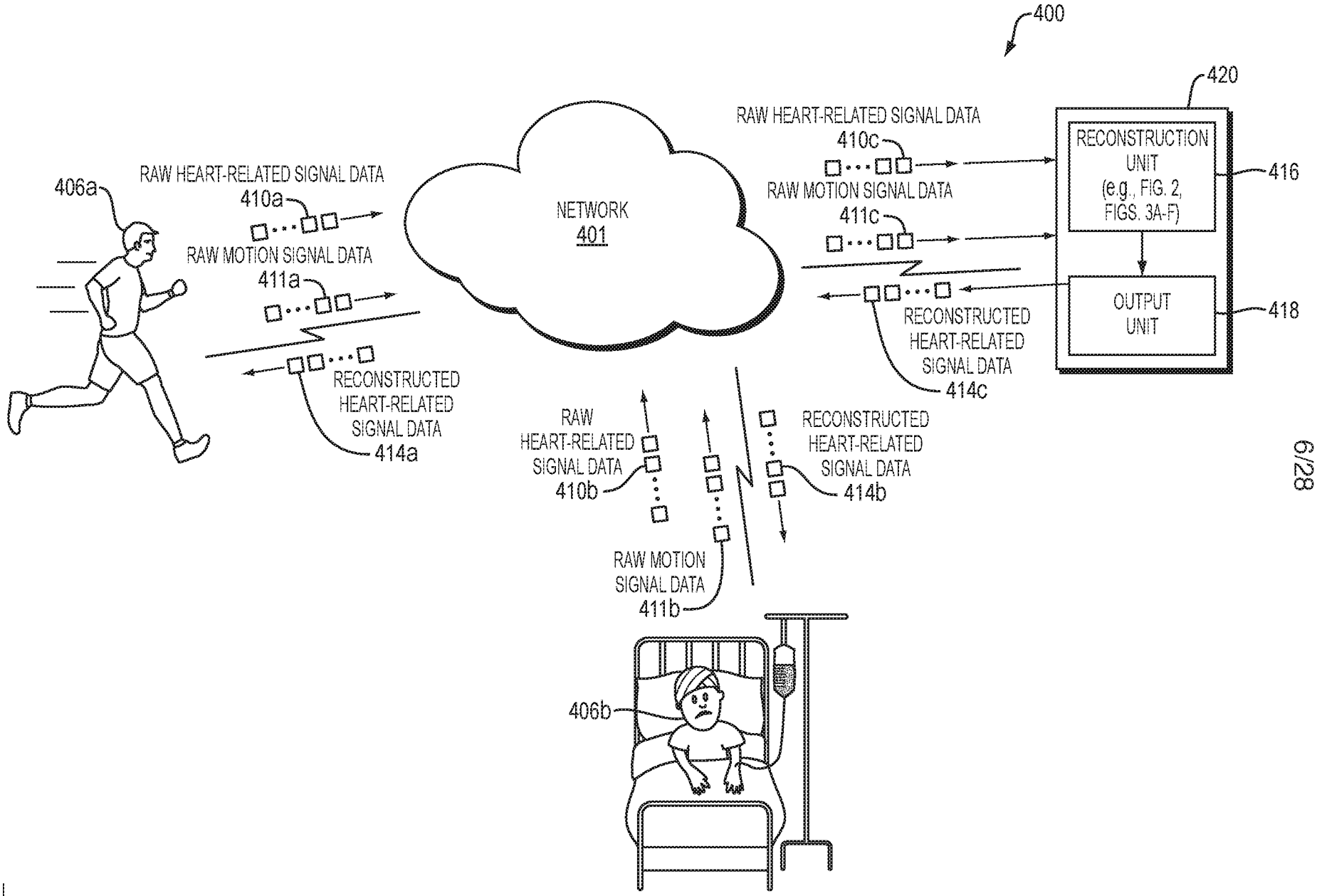

400
420
RECONSTRUCTION UNIT (e.g., FIG. 2, FIGS. 3A-F)
416
OUTPUT UNIT
418
NETWORK 401
406a
406b
RAW HEART-RELATED SIGNAL DATA
410a
RAW MOTION SIGNAL DATA
411a
RECONSTRUCTED HEART-RELATED SIGNAL DATA
414a
RAW HEART-RELATED SIGNAL DATA
410c
RAW MOTION SIGNAL DATA
411c
RECONSTRUCTED HEART-RELATED SIGNAL DATA
414c
RAW HEART-RELATED SIGNAL DATA
410b
RAW MOTION SIGNAL DATA
411b
RECONSTRUCTED HEART-RELATED SIGNAL DATA
414b

FIG. 4

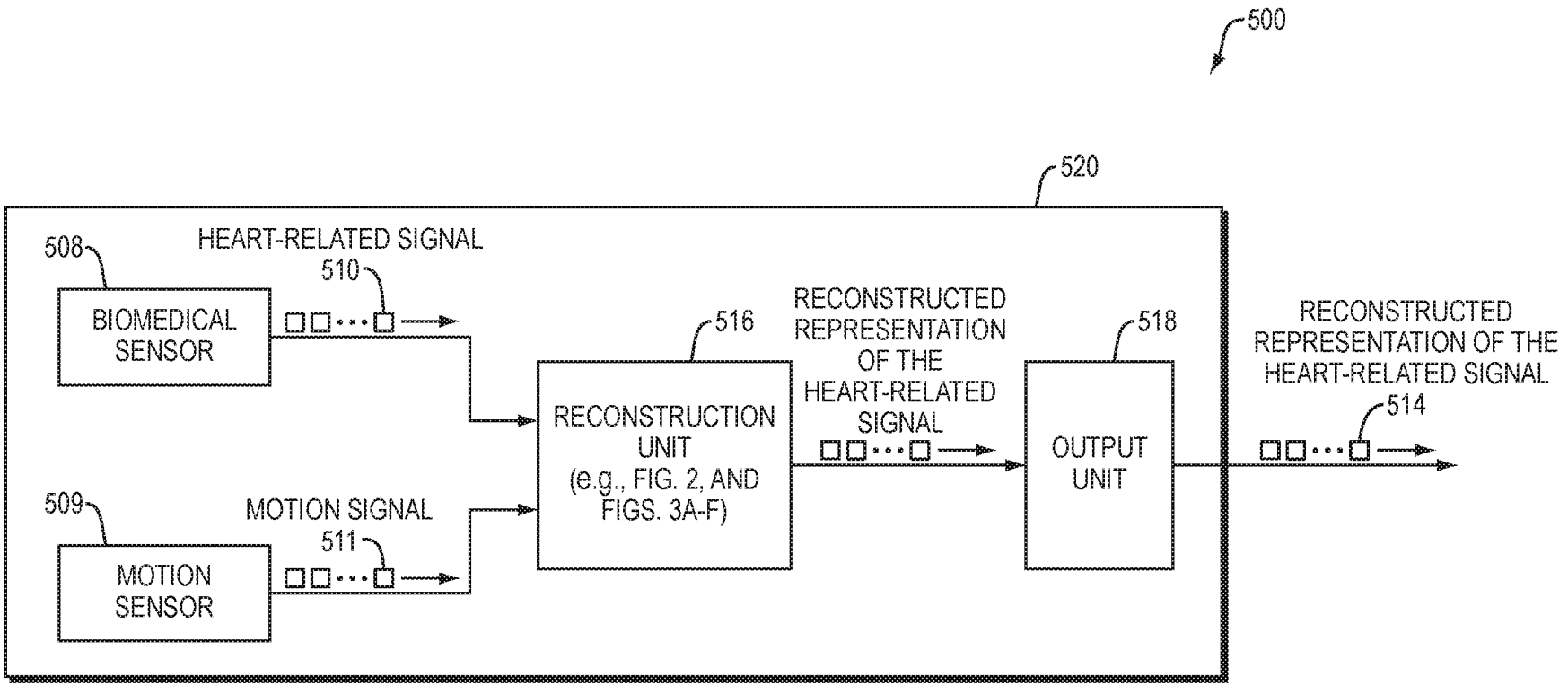

500
520
508
HEART-RELATED SIGNAL
510
BIOMEDICAL SENSOR
516
RECONSTRUCTED REPRESENTATION OF THE HEART-RELATED SIGNAL
518
RECONSTRUCTED REPRESENTATION OF THE HEART-RELATED SIGNAL
514
RECONSTRUCTION UNIT (e.g., FIG. 2, AND FIGS. 3A-F)
OUTPUT UNIT
509
MOTION SIGNAL
511
MOTION SENSOR

FIG. 5

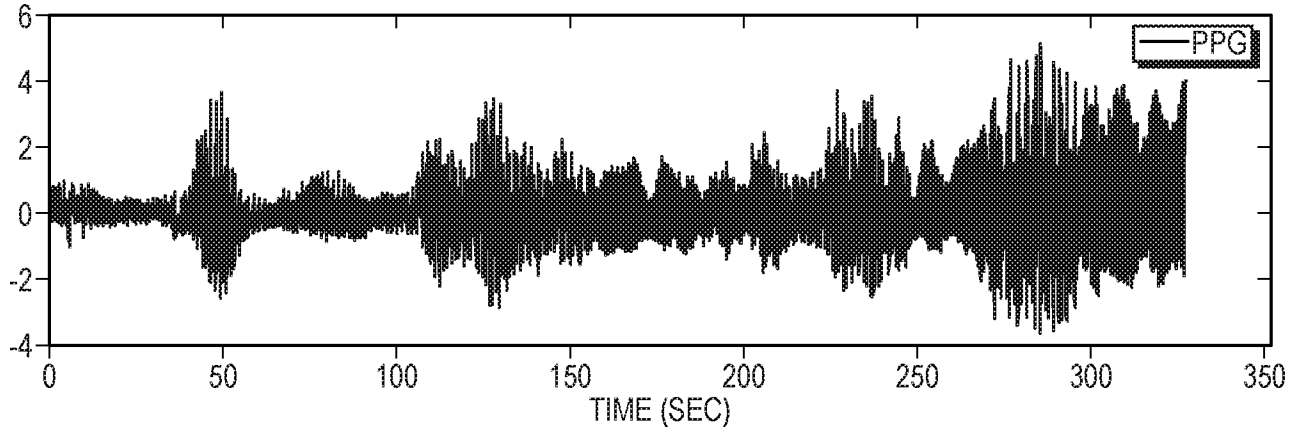

PPG
6
4
2
0
-2
-4
0
50
100
150
200
250
300
350
TIME (SEC)

FIG. 6A

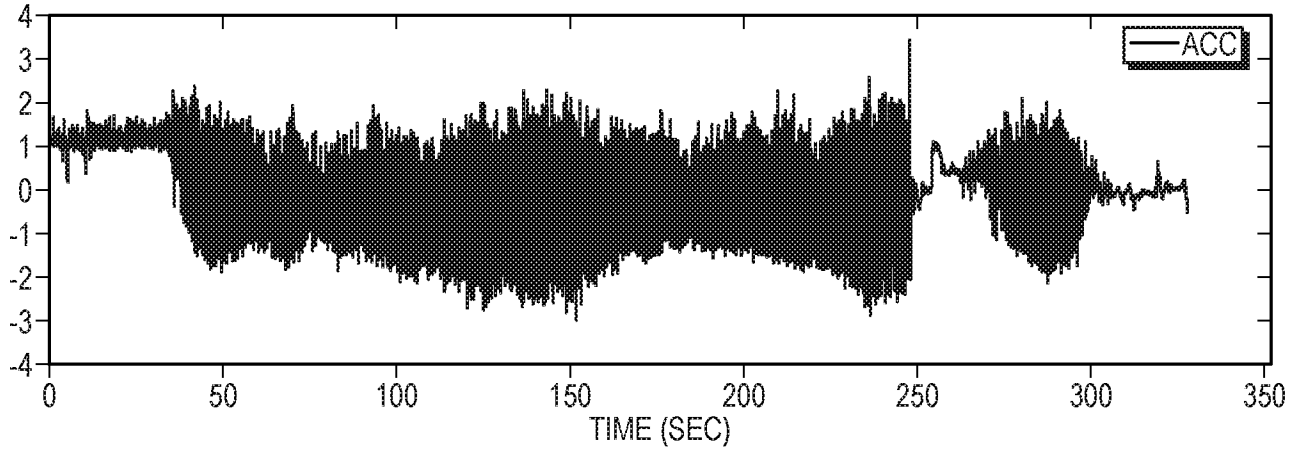

ACC
4
3
2
1
0
-1
-2
-3
-4
0
50
100
150
200
250
300
350
TIME (SEC)

FIG. 6B

Petitioner Ex-1004, 1195

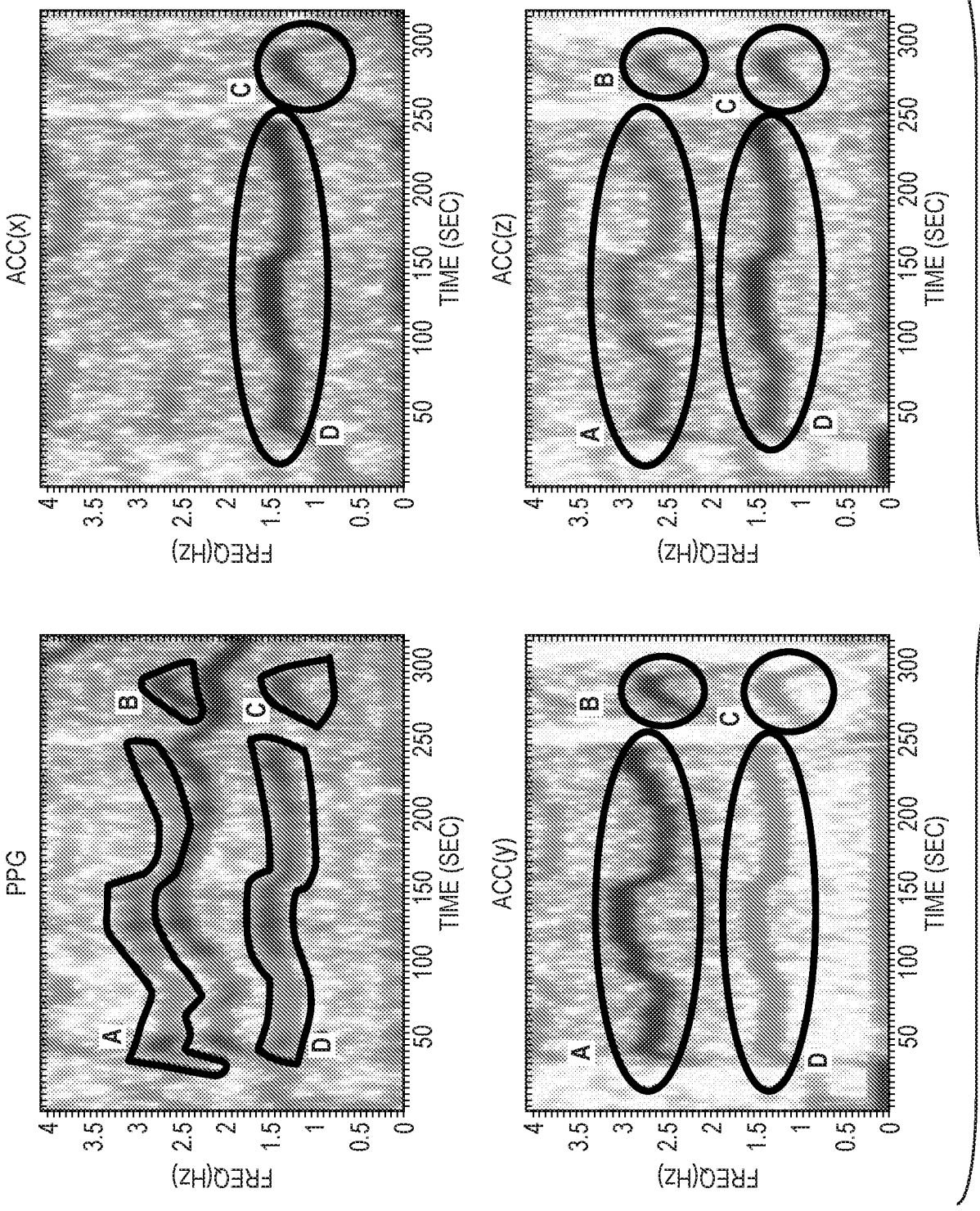


FIG. 6C

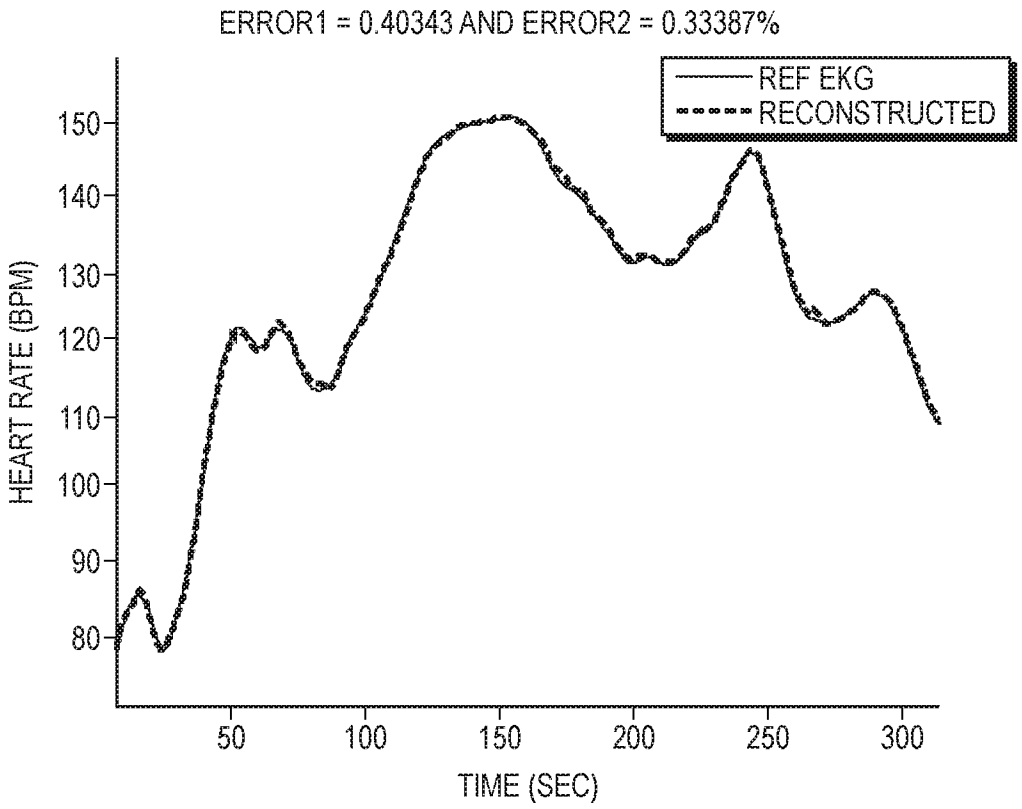

ERROR1 = 0.40343 AND ERROR2 = 0.33387%
REF EKG
RECONSTRUCTED
HEART RATE (BPM)
150
140
130
120
110
100
90
80
50
100
150
200
250
300
TIME (SEC)

FIG. 9

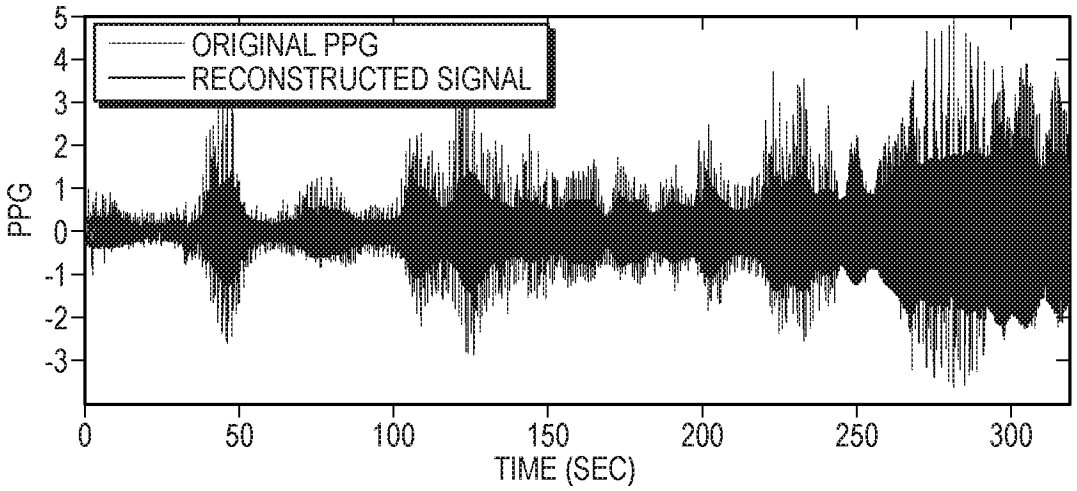


FIG. 10A

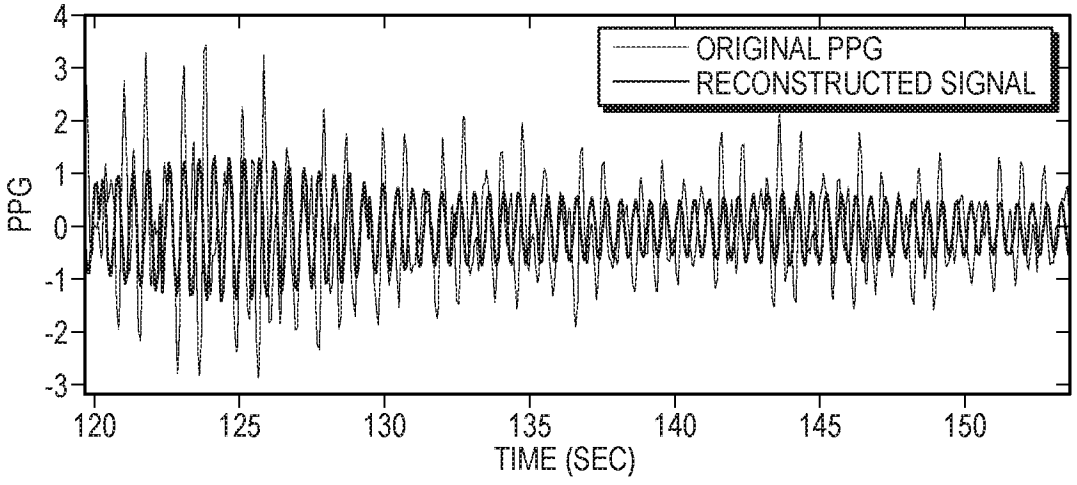


FIG. 10B

6

Subject	Dataset	Activity Type	TROIKA		JOSS		WFPV		SpaMA	
			E1	E2%	E1	E2%	E1	E2%	E1	E2%
1	1 (IEEE Cup)	Type (1)	2.87	2.18	1.33	1.19	1.23	-	1.23	1.14
2			2.75	2.37	1.75	1.66	1.26	-	1.59	1.30
3			1.91	1.50	1.47	1.27	0.72	-	0.57	0.45
4			2.25	2.00	1.48	1.41	0.98	-	0.44	0.31
5			1.69	1.22	0.69	0.51	0.75	-	0.47	0.31
6			3.16	2.51	1.32	1.09	0.91	-	0.61	0.45
7			1.72	1.27	0.71	0.54	0.67	-	0.54	0.40
8			1.83	1.47	0.56	0.47	0.91	-	0.40	0.33
9			1.58	1.28	0.49	0.41	0.54	-	0.40	0.32
10			4.00	2.49	3.81	2.43	2.61	-	2.63	1.59
11			1.96	1.29	0.78	0.51	0.94	-	0.64	0.42
12			3.33	2.30	1.04	0.81	0.98	-	1.20	0.86
mean±std			2.42±0.8	1.82±0.5	1.28±0.9	1.02±0.6	1.04±0.5	-	0.89±0.6	0.65±0.4
13	2 (IEEE Cup)	Type (2)					3.58	-	3.41	4.25
14							9.66	-	7.29	9.80
15							2.31	-	2.73	2.21
16		Type (3)					4.93	-	3.18	2.11
17							3.07	-	3.01	2.52
18							2.67	-	4.46	3.23
19							3.11	-	3.58	3.98
20		Type (2)					2.10	-	1.94	1.66
21		Type (3)					3.22	-	2.56	2.02
22							4.35	-	3.12	3.28
23		Type (2)					0.75	-	1.72	1.97
mean±std							3.61±2.2	-	3.36±1.5	3.33±2.2
Type (1,2) mean±std							2.27±2.0	-	1.93±2.0	2.07±1.7
24	3 (Chon Lab)	Type (4)							0.88	0.91
25									1.03	0.83
26									1.10	0.90
27									1.64	1.54
28									1.41	1.12
29									0.82	0.70
30									0.63	0.58
31									4.78	3.87
32									0.95	0.79
33									0.62	0.52
mean±std									1.38±1.2	1.17±1.0
Total mean±std									1.86±1.6	1.70±1.8

FIG. 11C

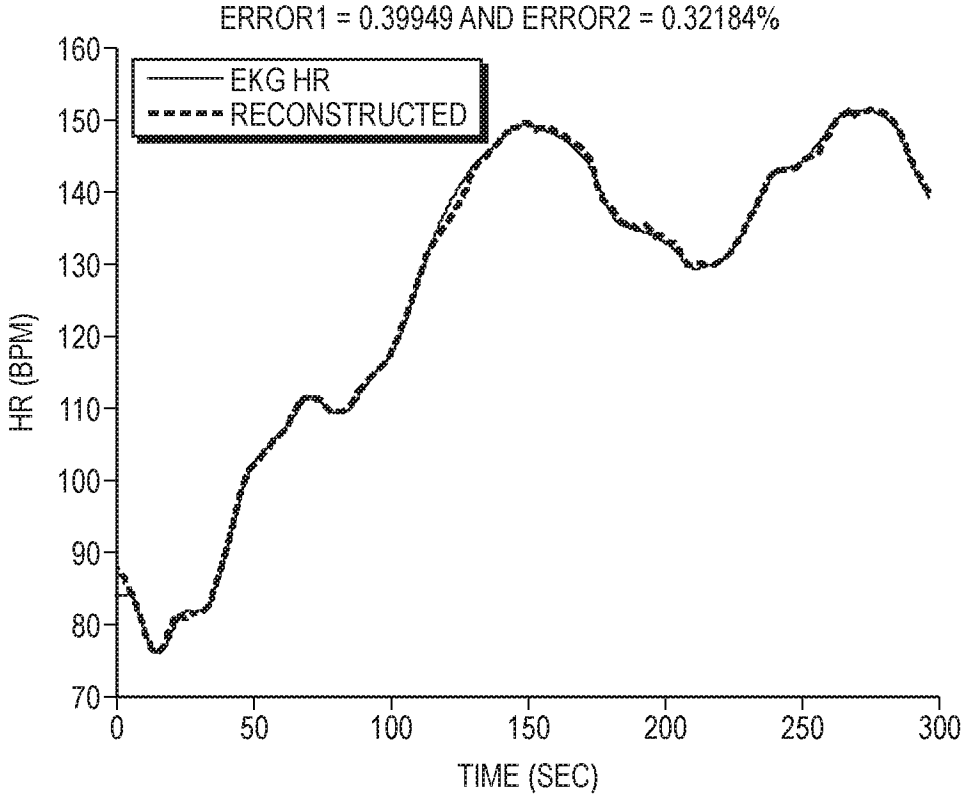


FIG. 12A

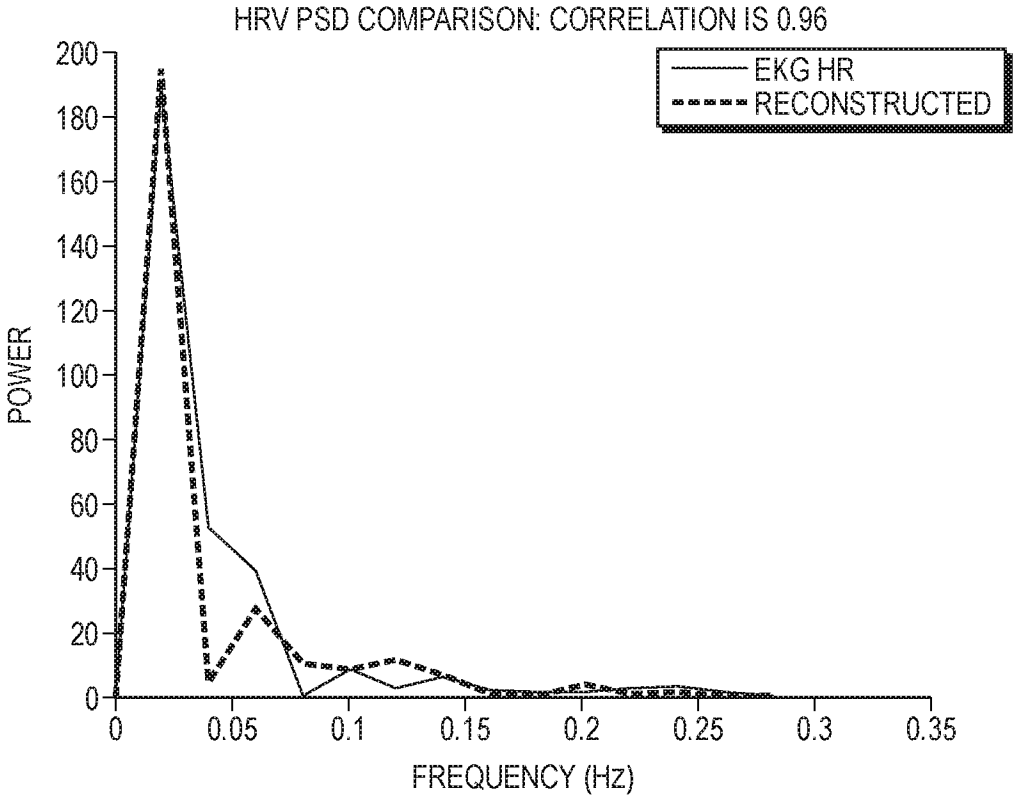


FIG. 12B

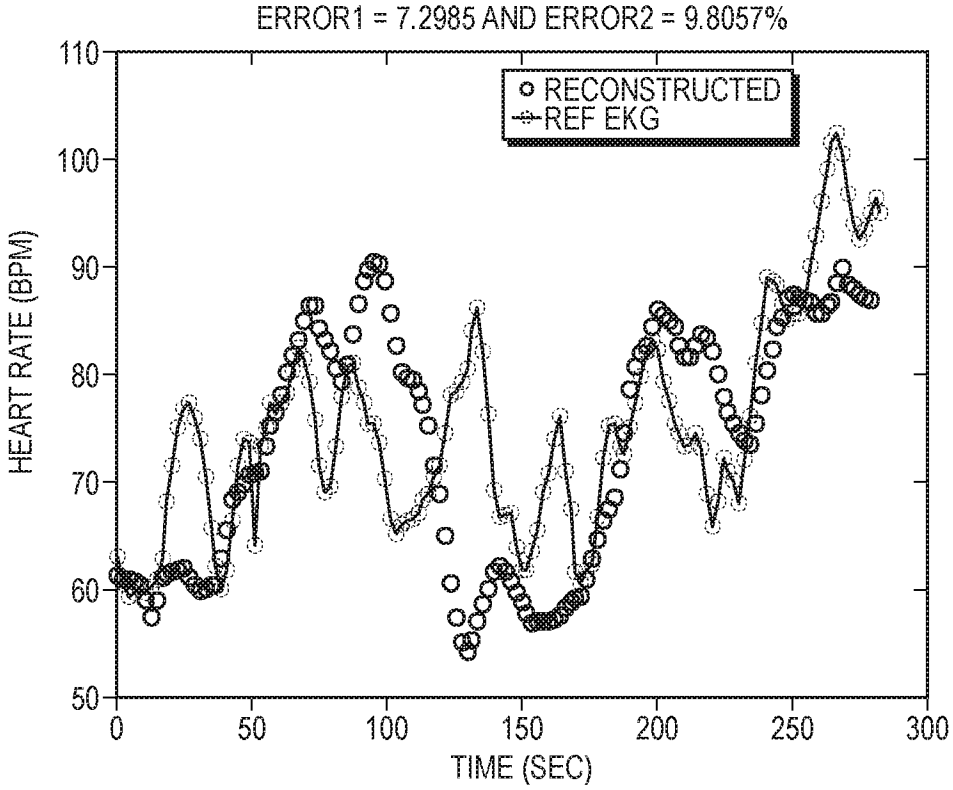


FIG. 13A

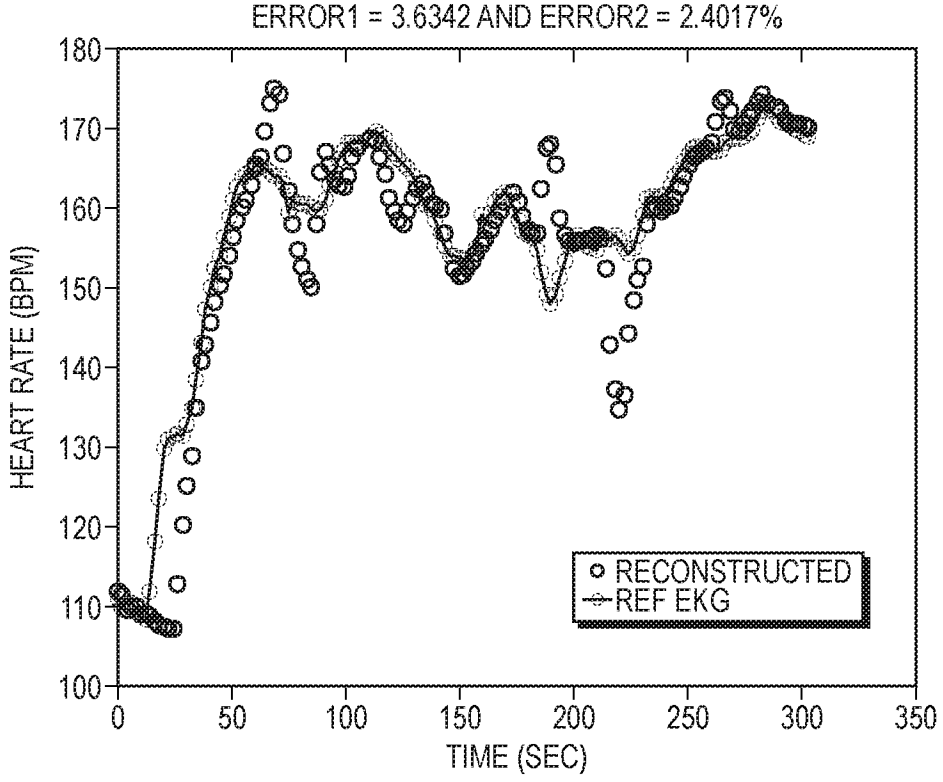


FIG. 13B

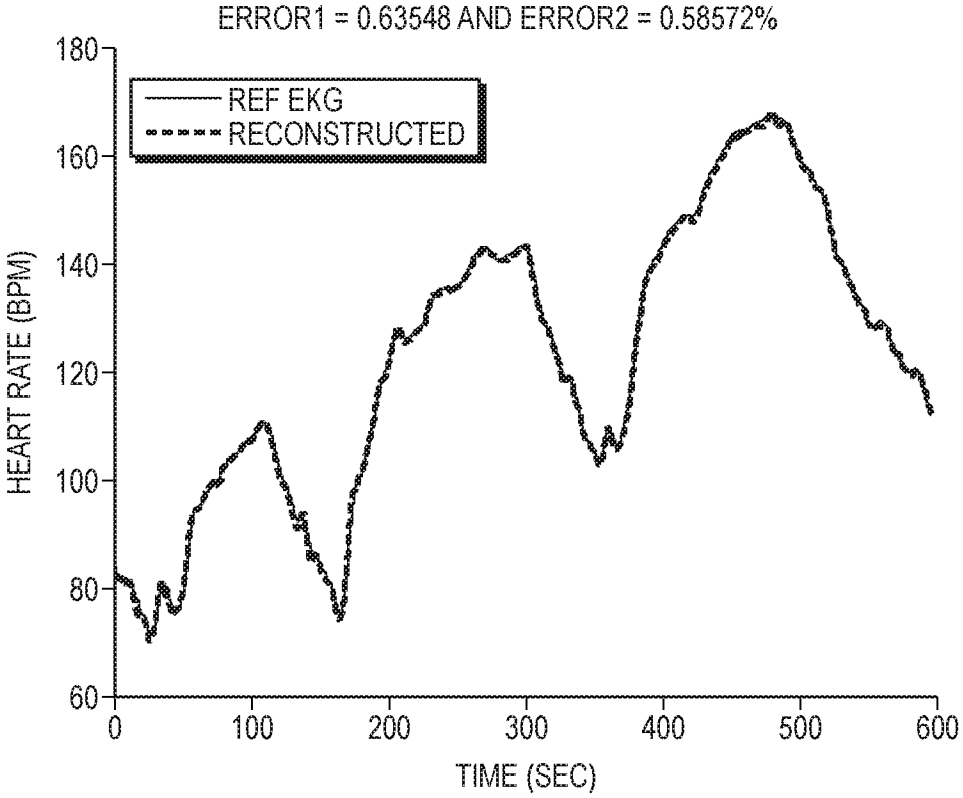


FIG. 14A

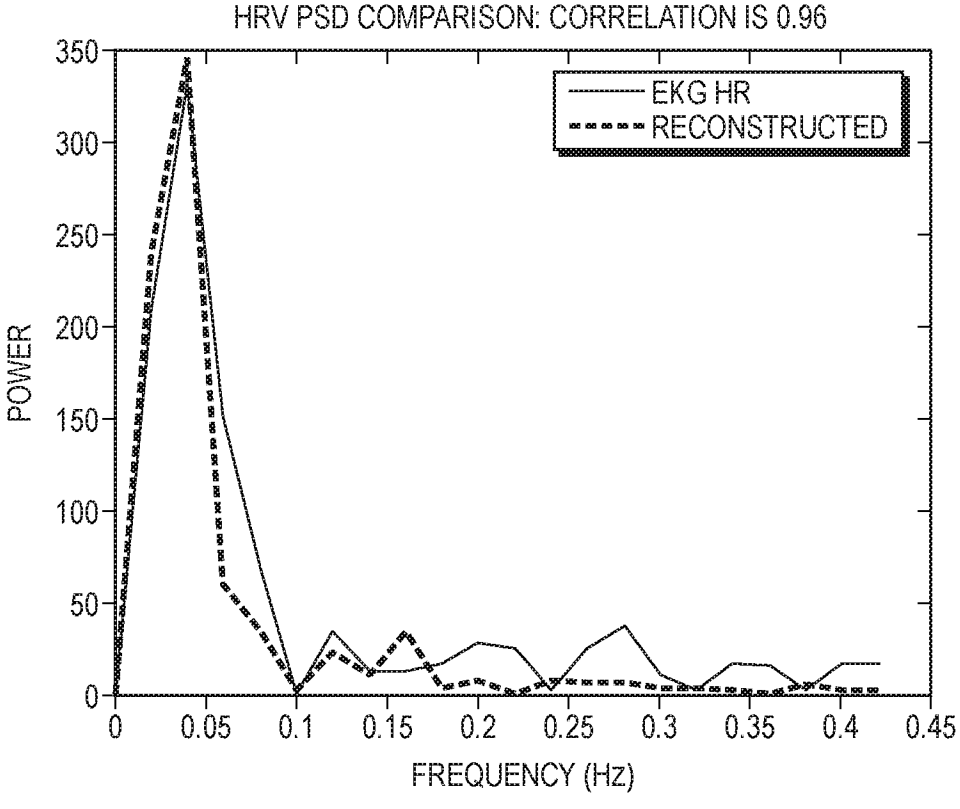


FIG. 14B

9

PPG DATASETS AND EXPERIMENTS SETTINGS

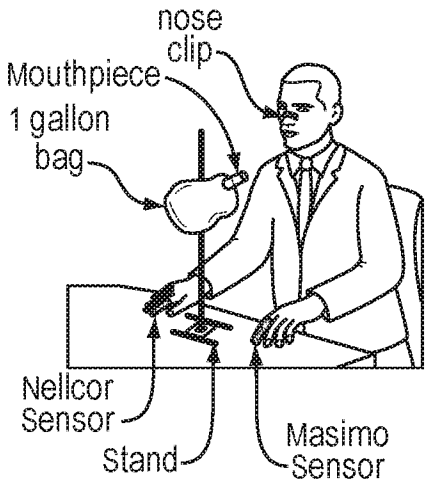
Scenario	Sensor Type	Age/Sex Ethnicity
Oxygen Saturation Variations 	[Actual PPG] Finger Pulse Oximeter Nellcor [Ref SpO_2] Finger Pulse Oximeter [Ref HR] SilverRest ECG Electrode	23-58 yr (10 Males) 3 Asian 2 Hispanic 3 American 2 White

FIG. 14C

Petitioner Ex-1004, 1203

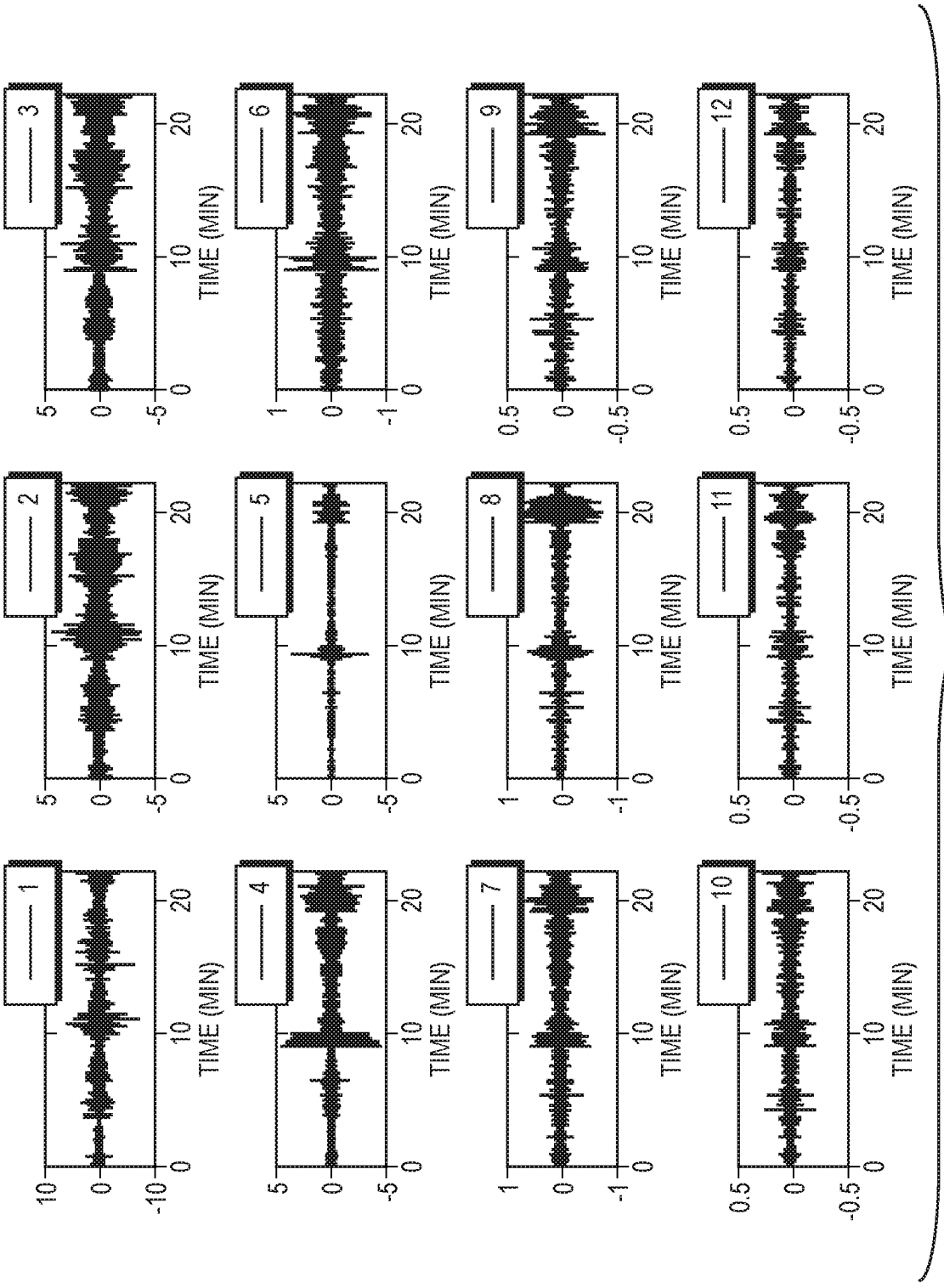


FIG. 16

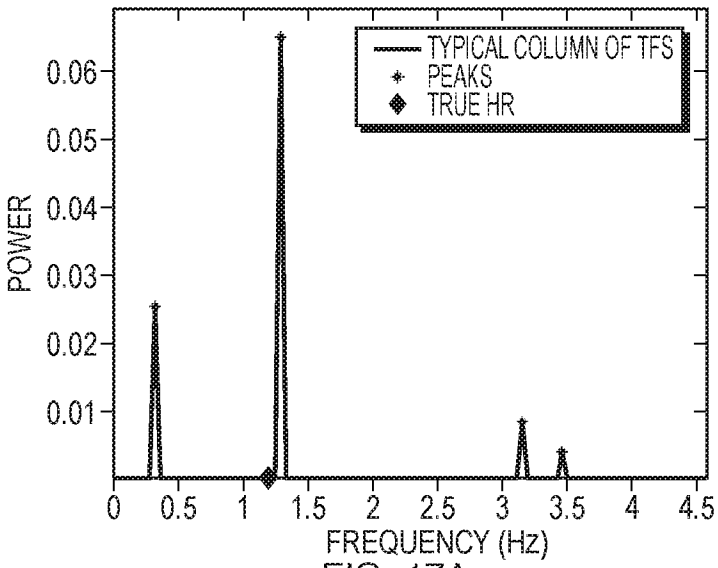


FIG. 17A

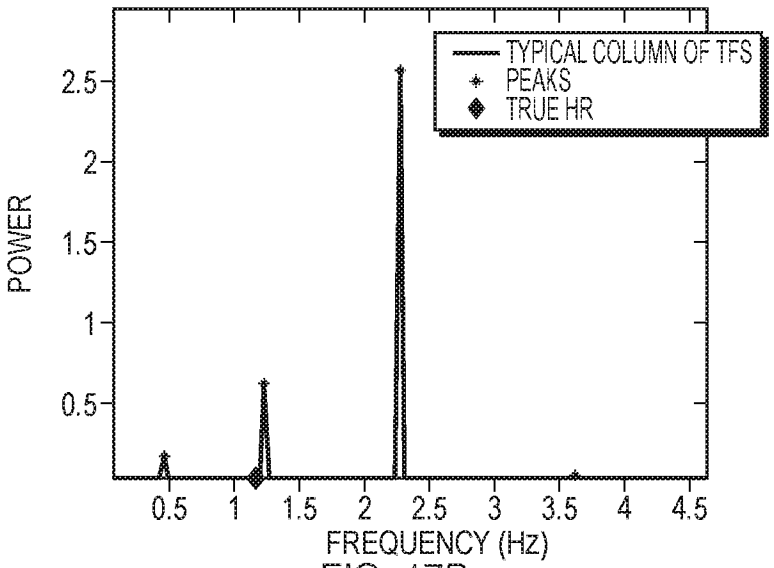


FIG. 17B

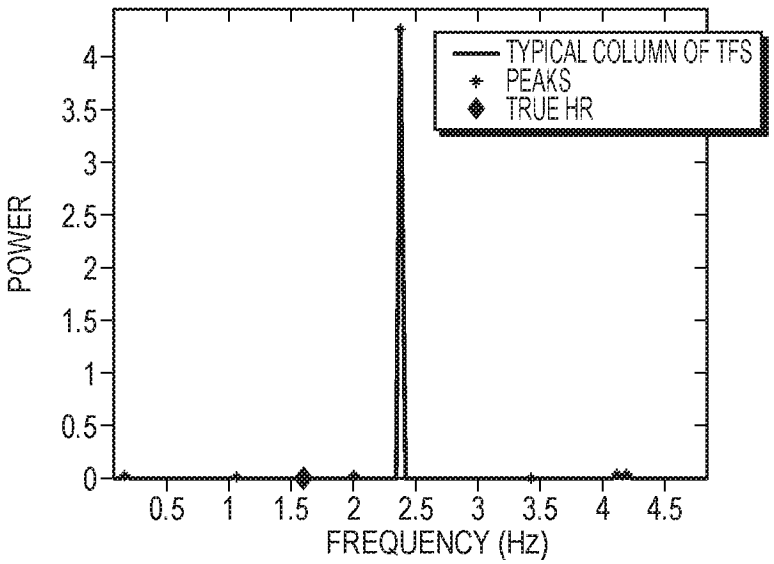


FIG. 17C

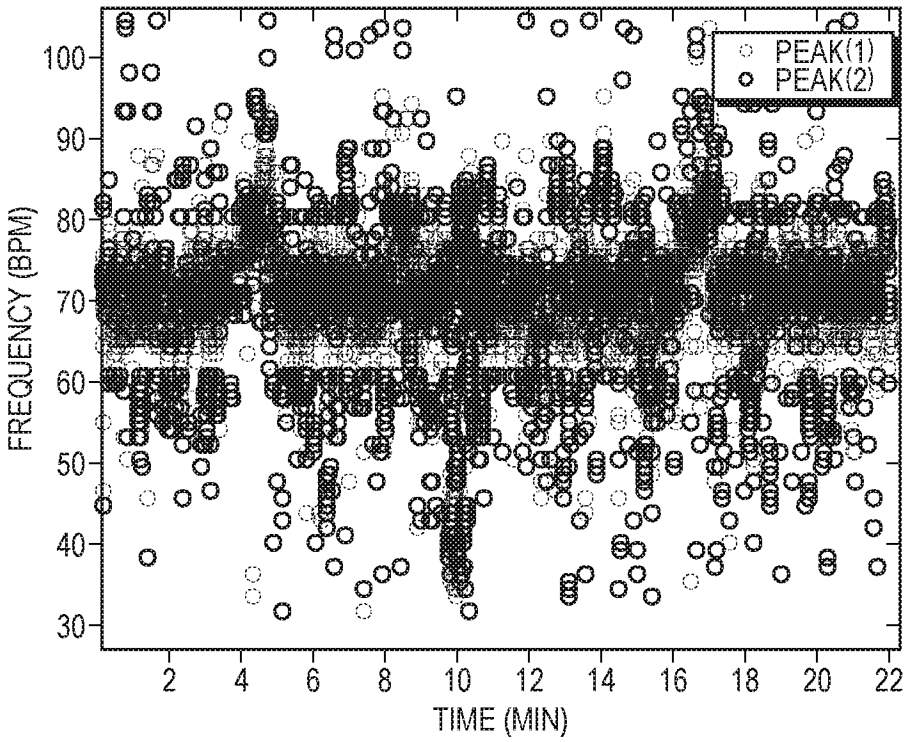


FIG. 18A

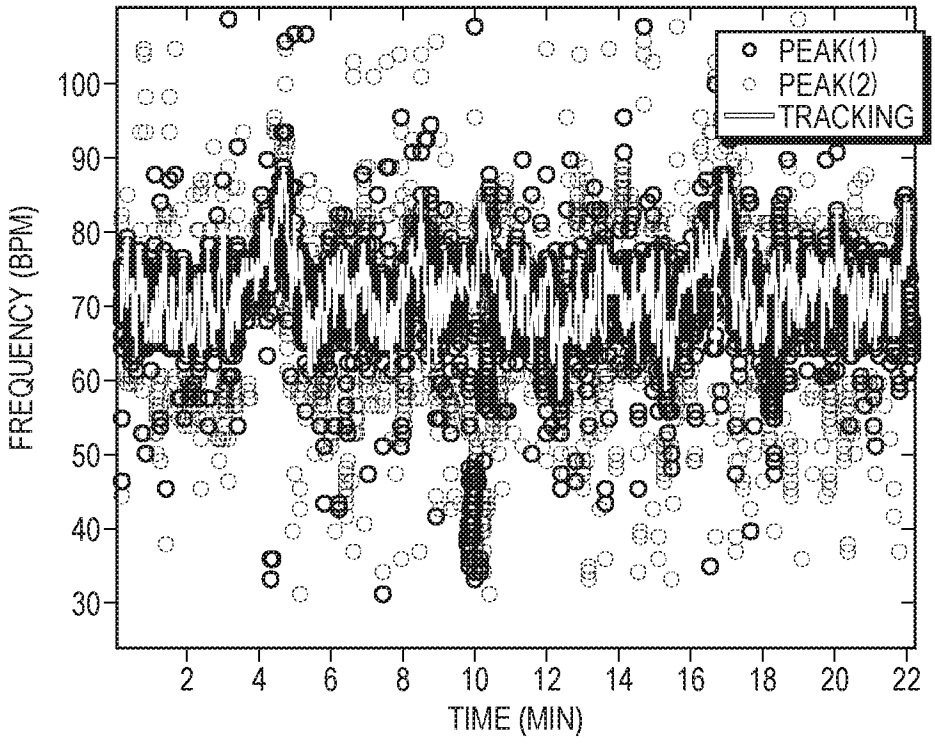


FIG. 18B

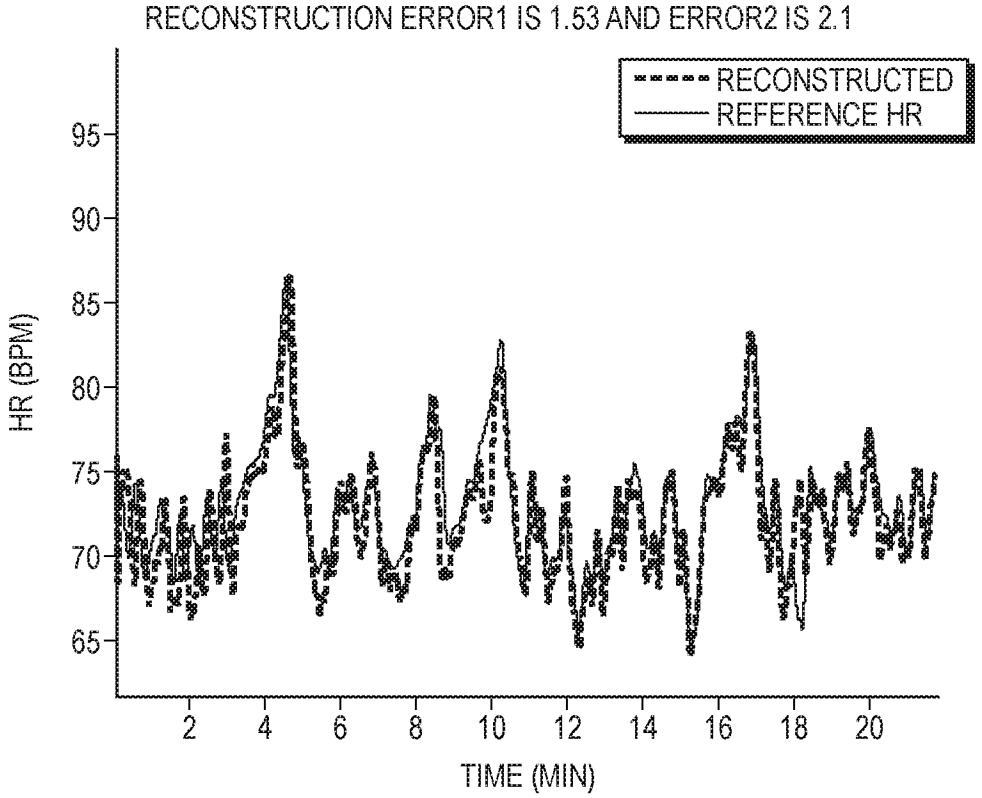


FIG. 19A

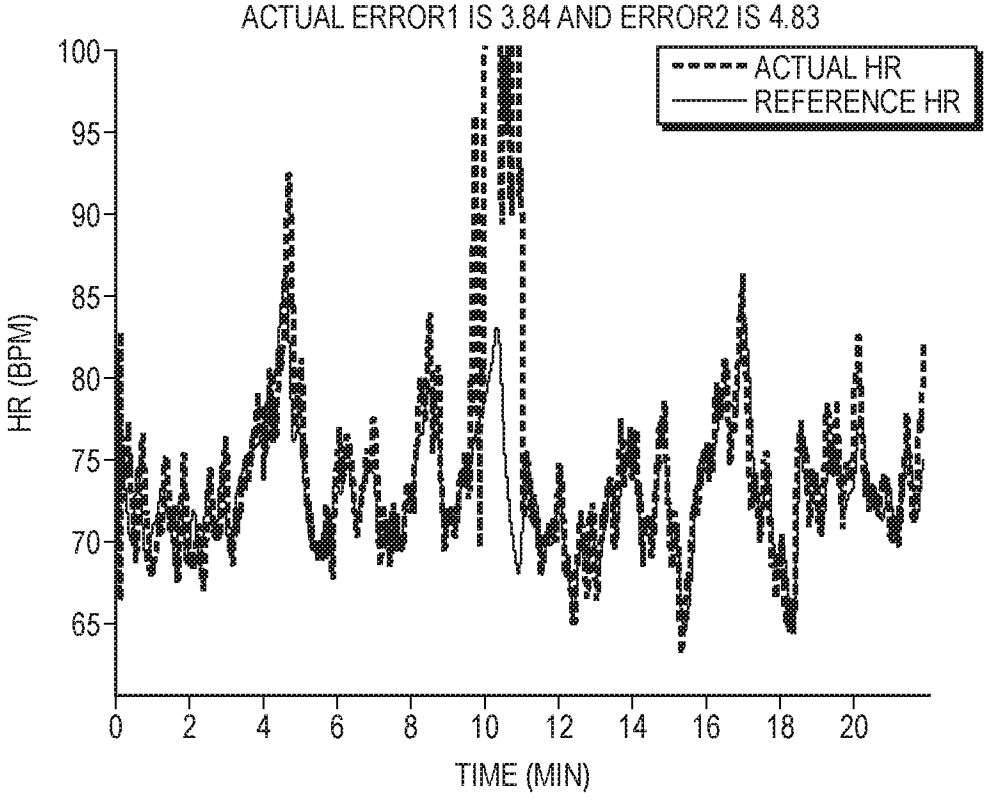


FIG. 19B

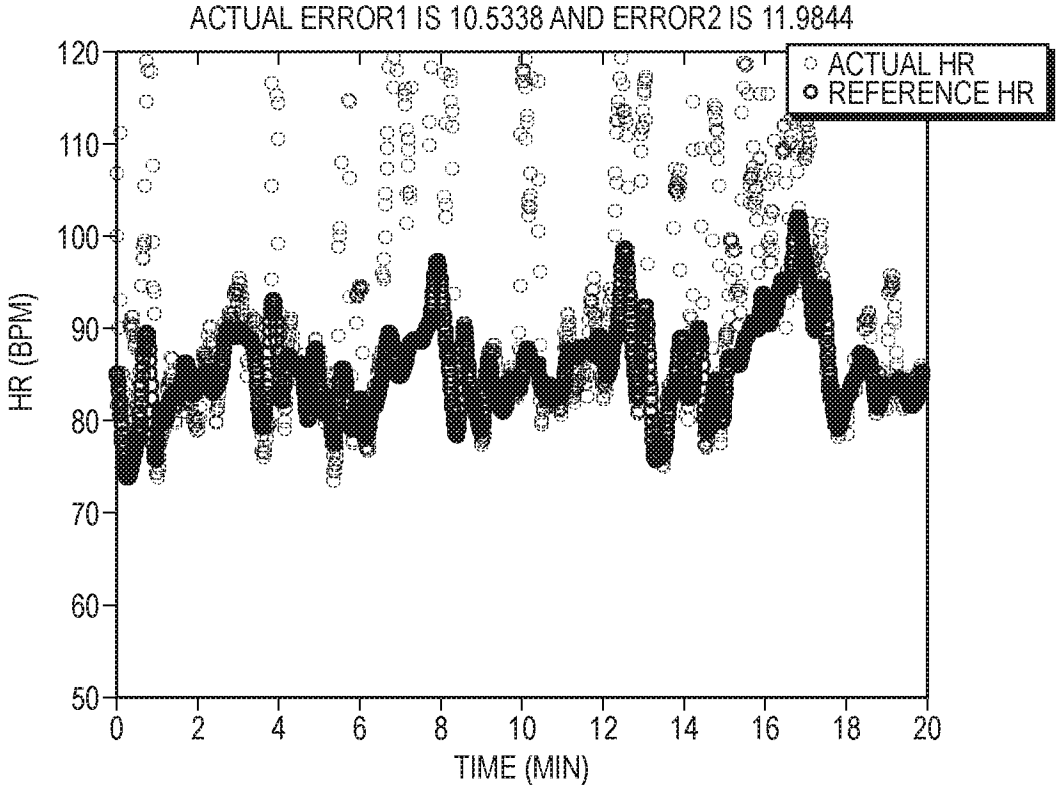


FIG. 22A

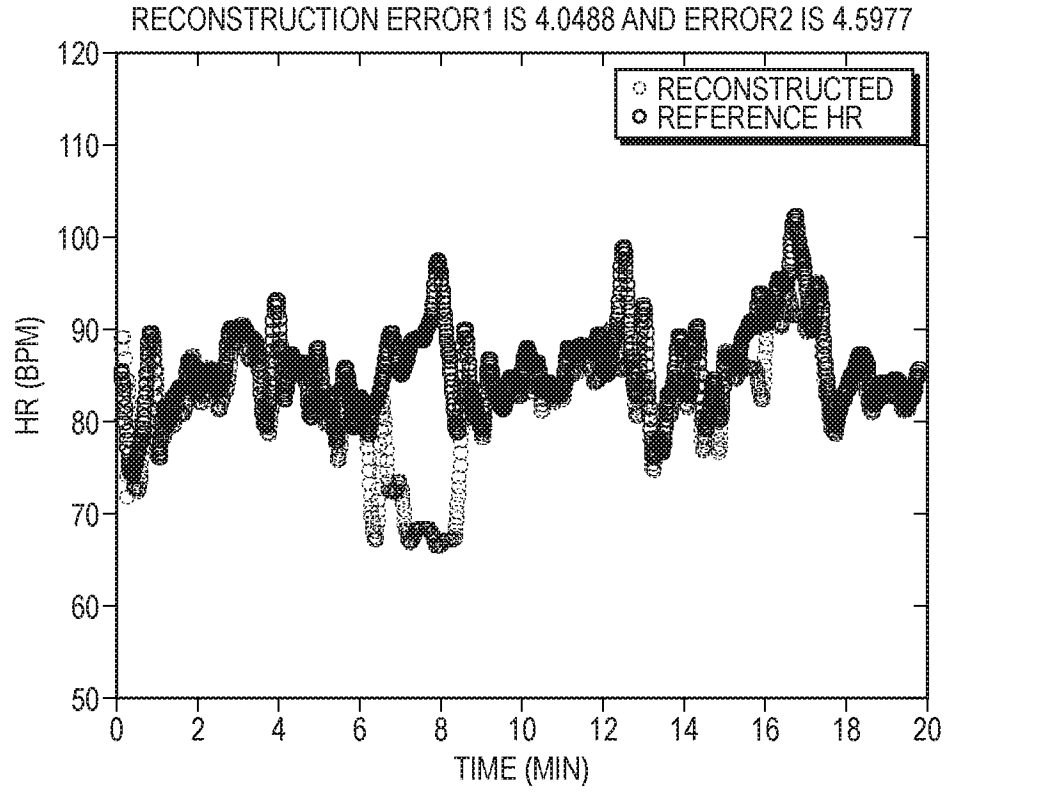


FIG. 22B

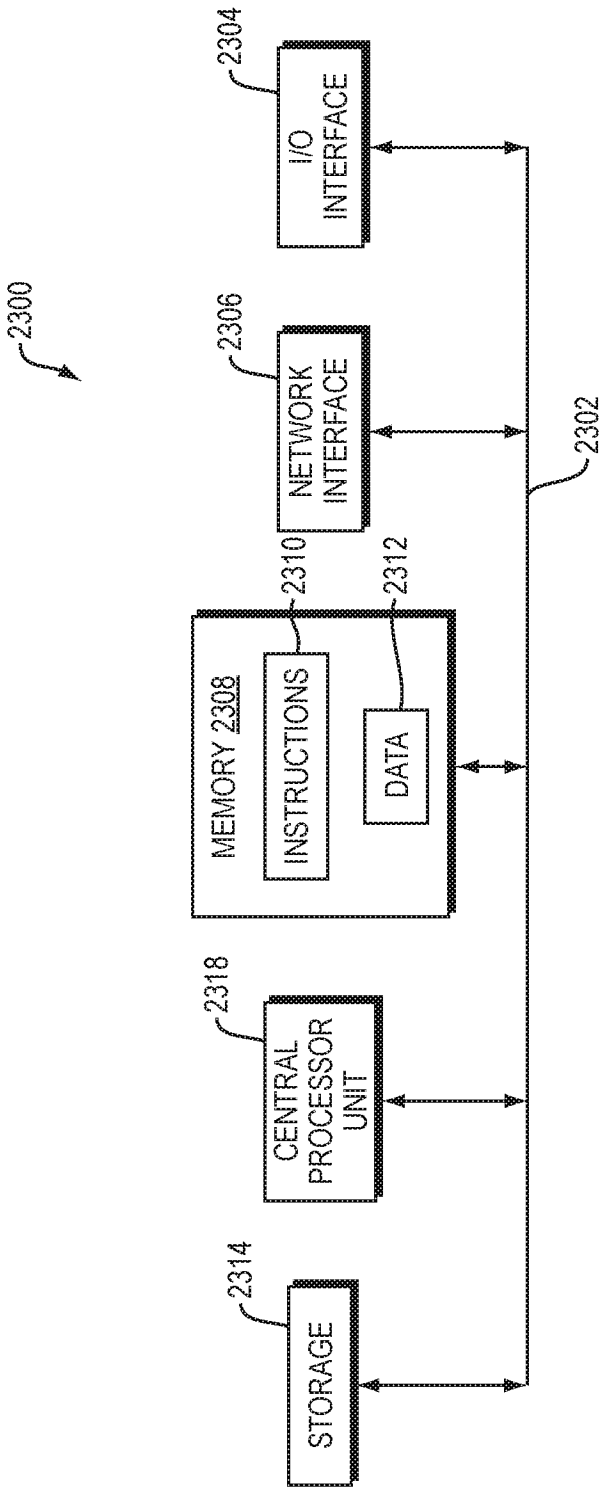

2300
2304
I/O INTERFACE
2306
NETWORK INTERFACE
2302
2310
2312
MEMORY 2308
INSTRUCTIONS
DATA
2318
CENTRAL PROCESSOR UNIT
2314
STORAGE

FIG. 23

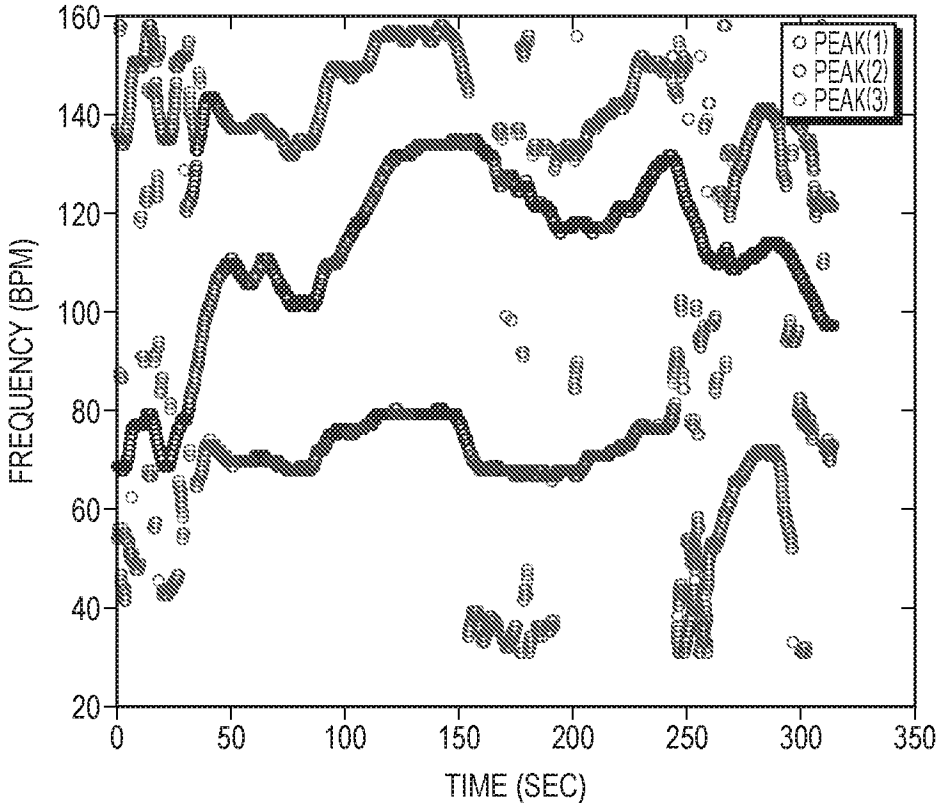

160
140
120
100
80
60
40
20
FREQUENCY (BPM)
0
50
100
150
200
250
300
350
TIME (SEC)
PEAK(1)
PEAK(2)
PEAK(3)

FIG. 7

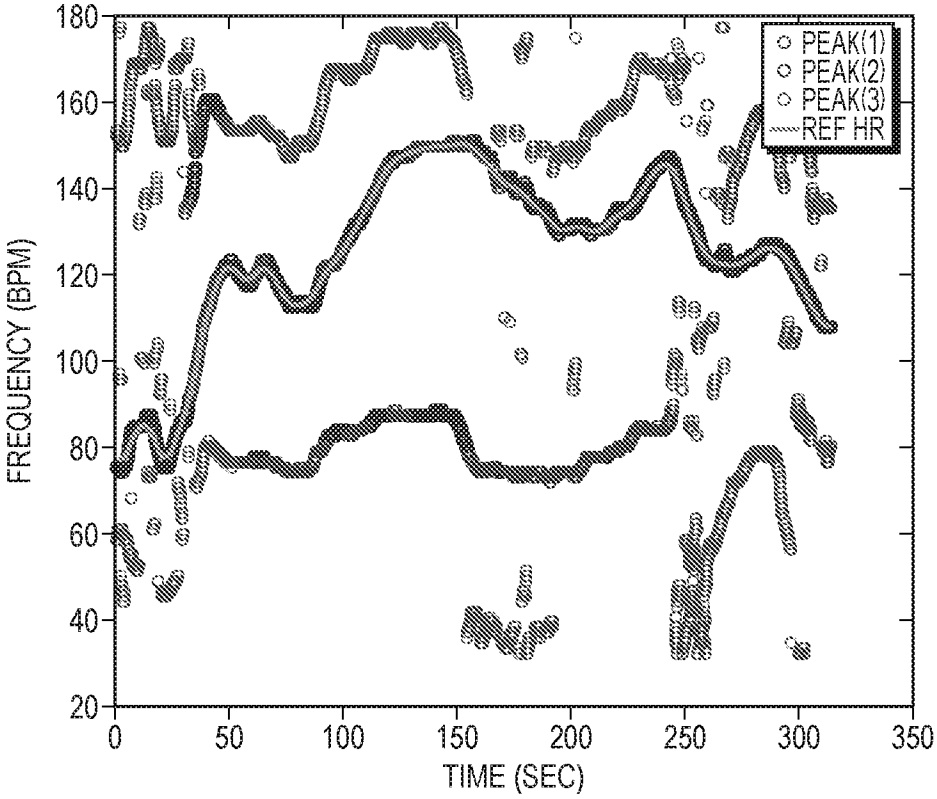

PEAK(1)
PEAK(2)
PEAK(3)
REF HR
FREQUENCY (BPM)
TIME (SEC)
180
160
140
120
100
80
60
40
20
0
50
100
150
200
250
300
350

FIG. 8A

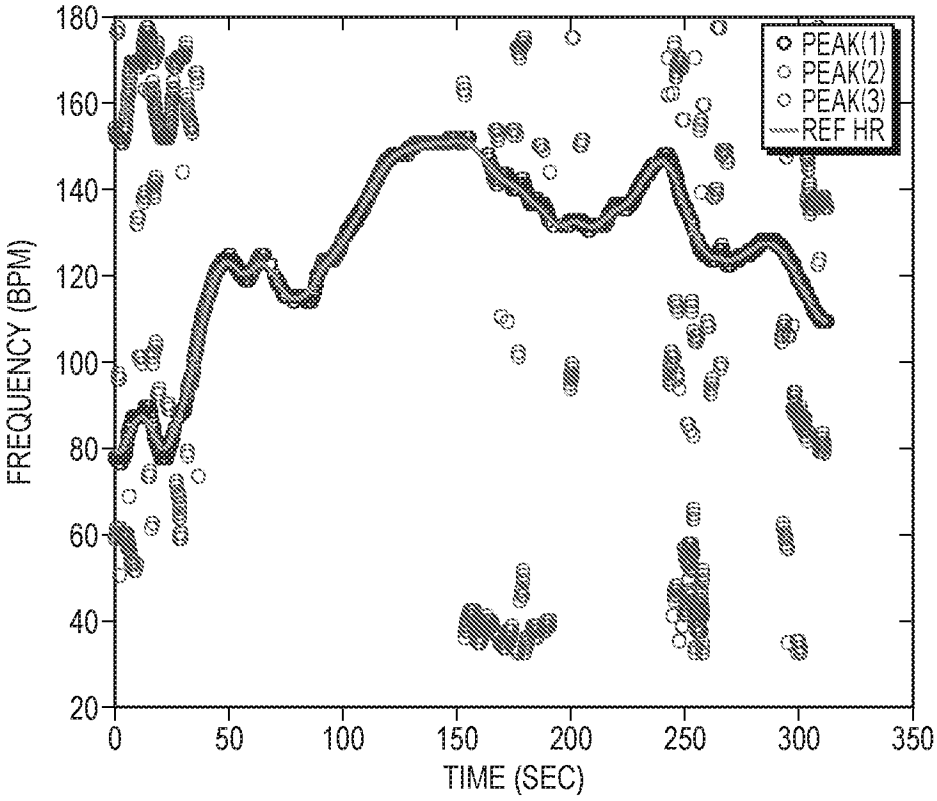

PEAK(1)
PEAK(2)
PEAK(3)
REF HR
FREQUENCY (BPM)
TIME (SEC)
180
160
140
120
100
80
60
40
20
0
50
100
150
200
250
300
350

FIG. 8B

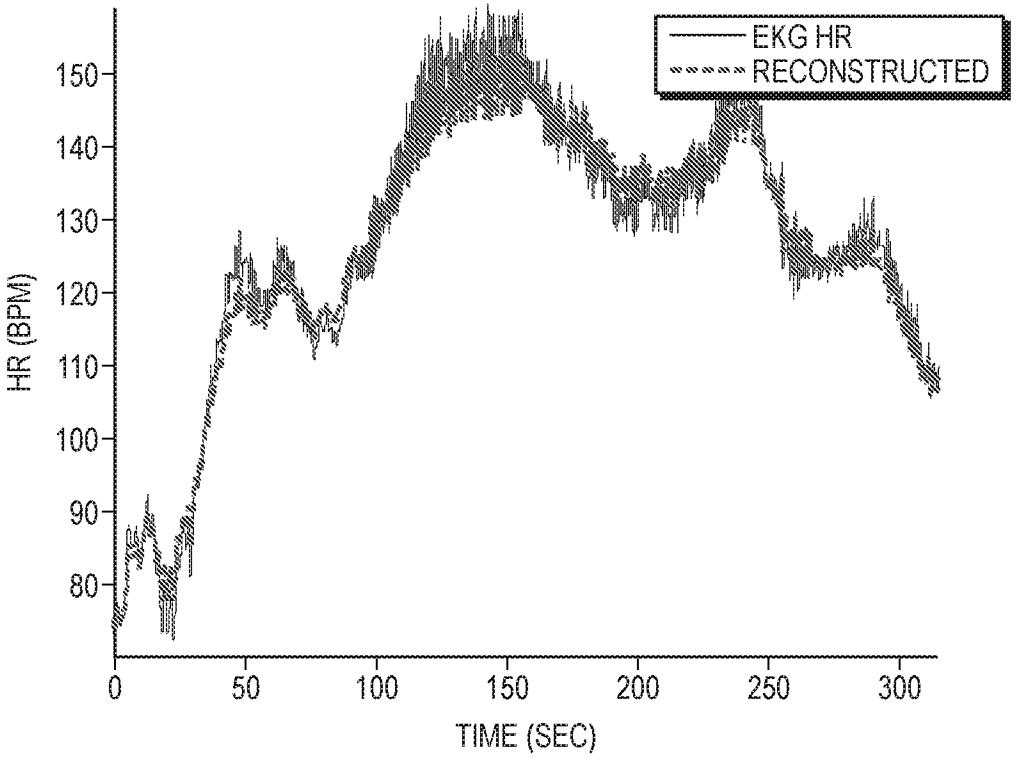


FIG. 11A

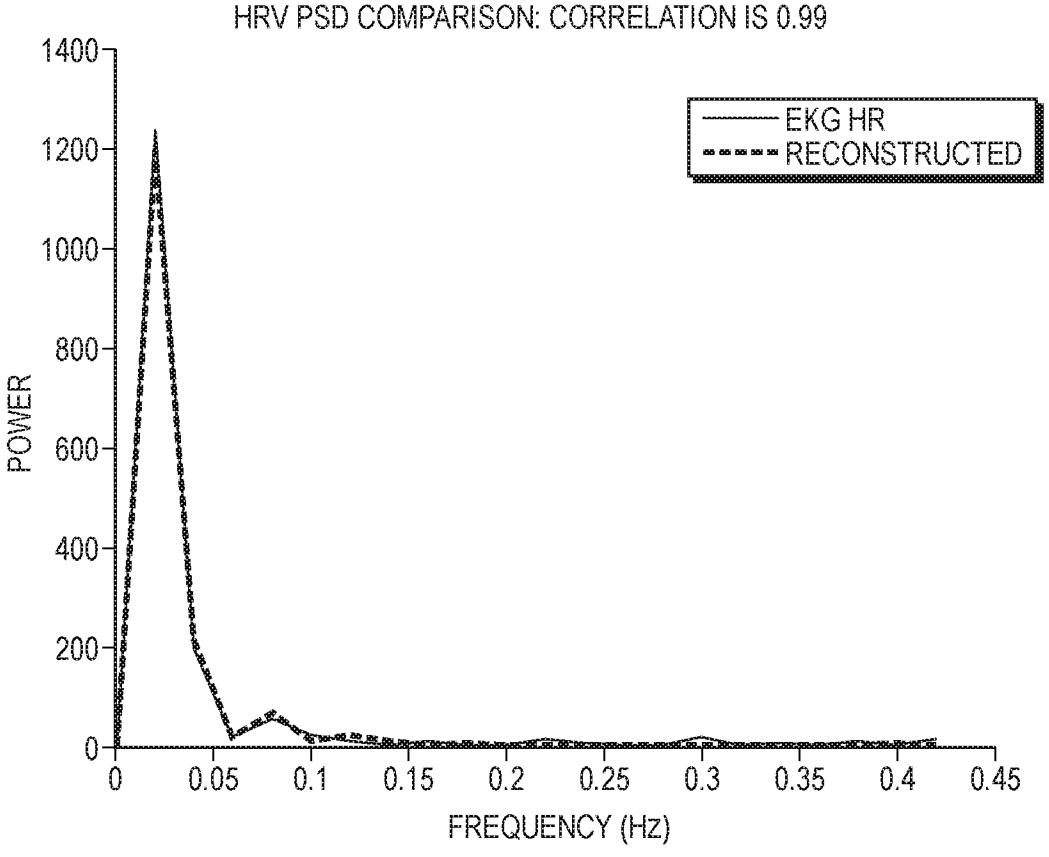


FIG. 11B

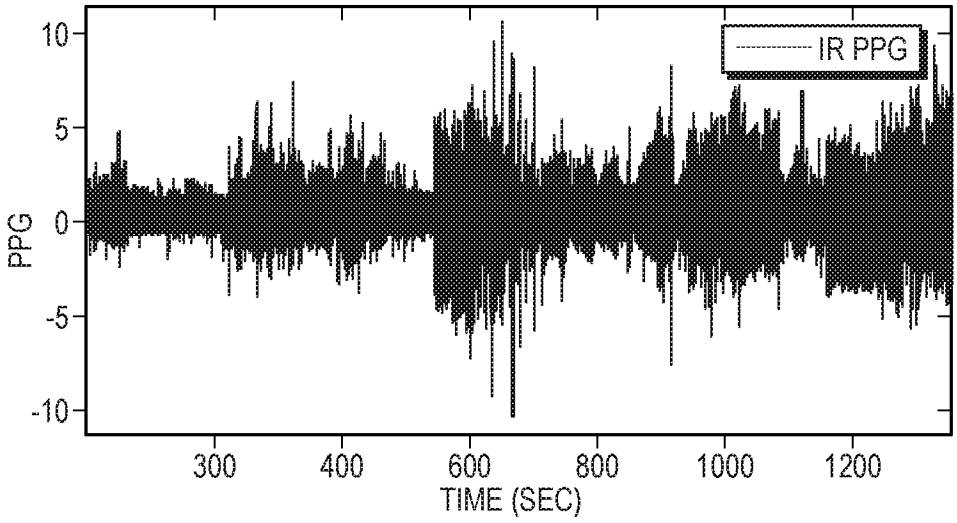


FIG. 15A

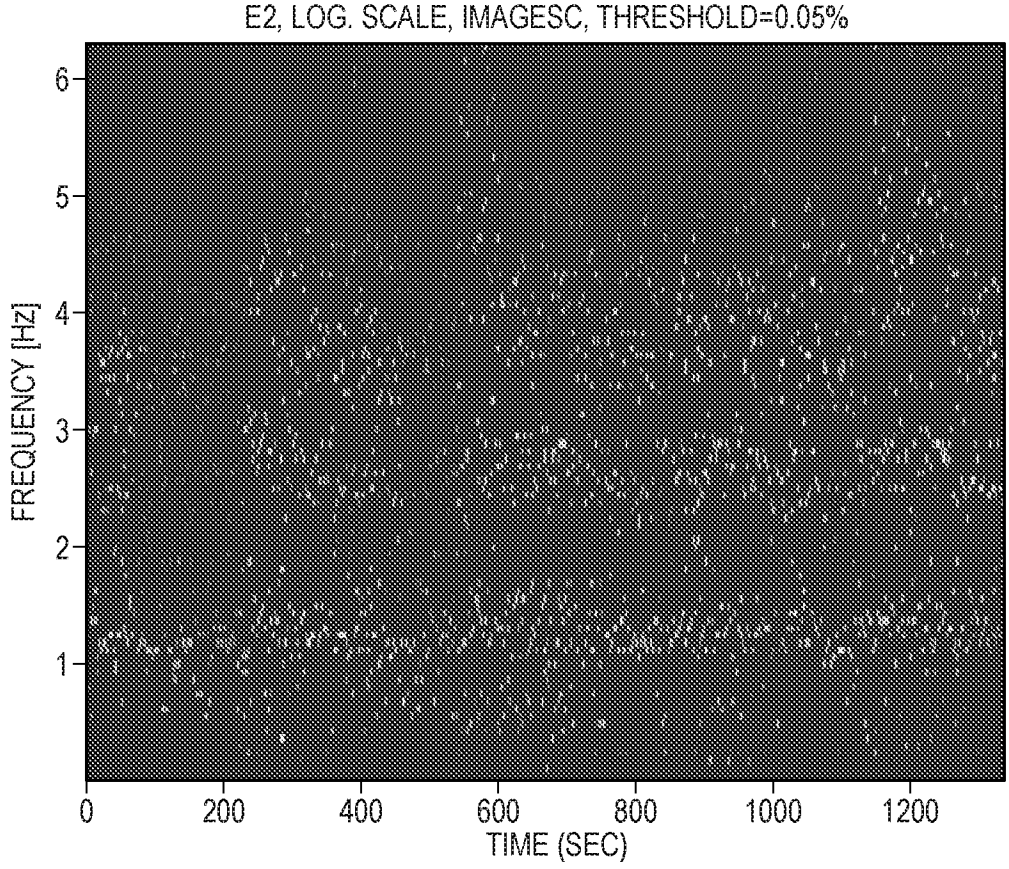


FIG. 15B

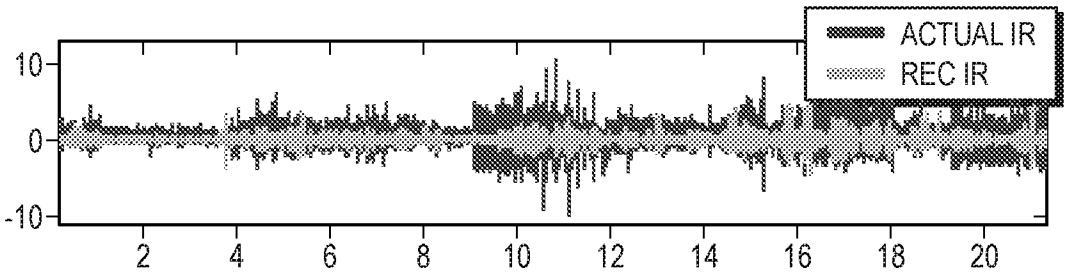


FIG. 20A

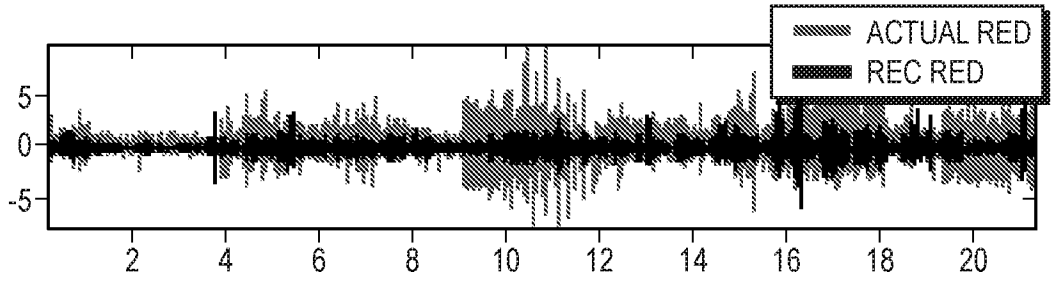


FIG. 20B

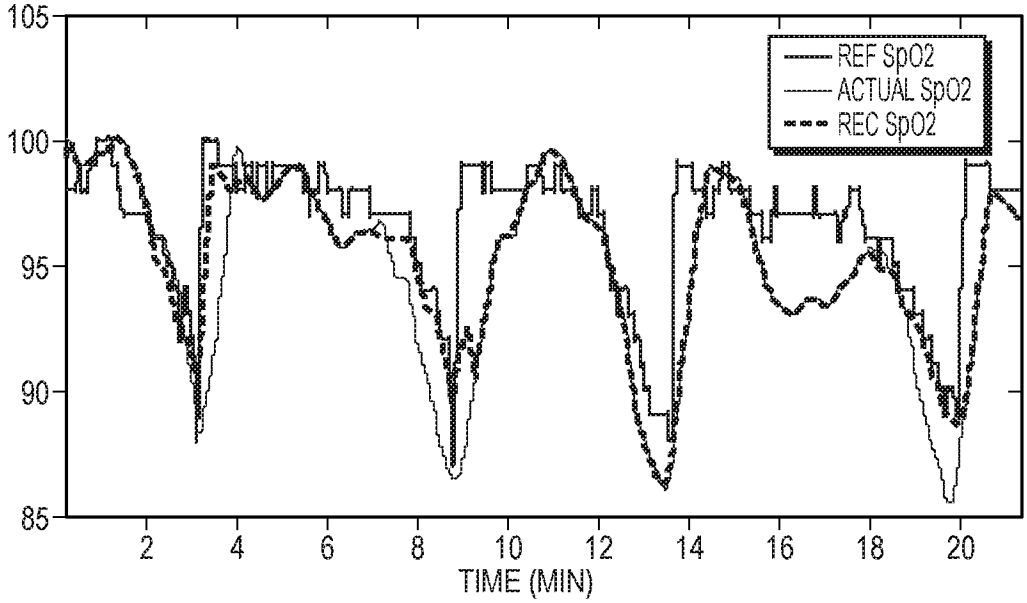


FIG. 20C

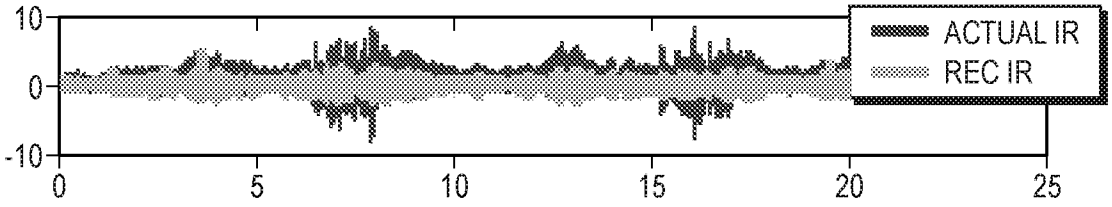


FIG. 21A

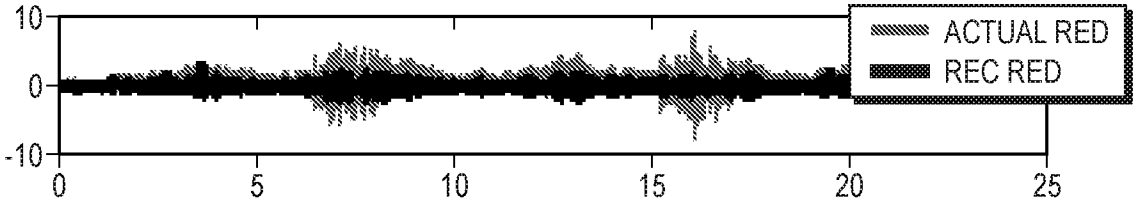


FIG. 21B

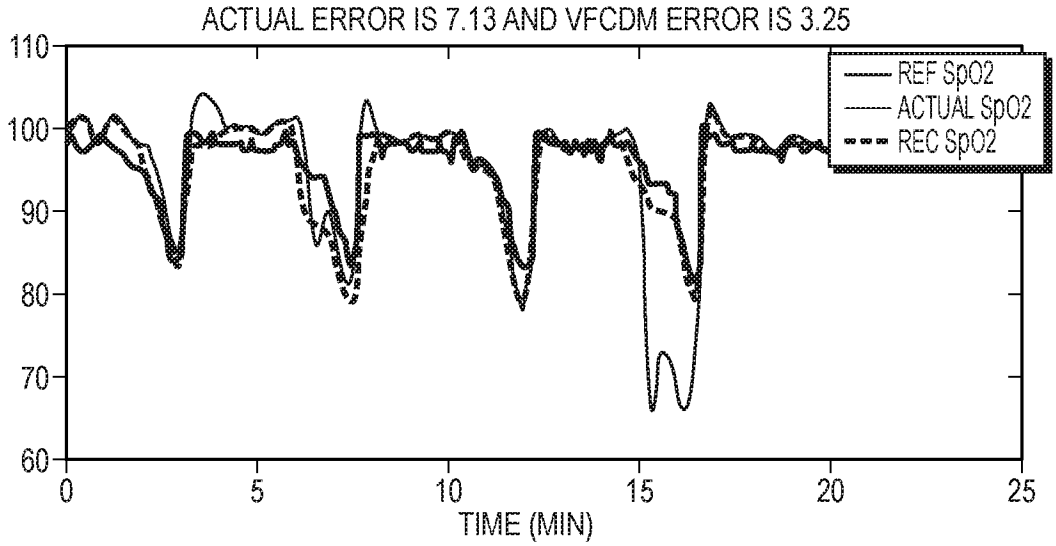


FIG. 21C

Electronic Acknowledgement Receipt

EFS ID:	35146637
Application Number:	15178089
International Application Number:	
Confirmation Number:	7605
Title of Invention:	METHOD AND APPARATUS FOR REMOVING MOTION ARTIFACTS FROM BIOMEDICAL SIGNALS
First Named Inventor/Applicant Name:	Seyed M. A. Salehizadeh
Customer Number:	21005
Filer:	Mark B Solomon/Kristina Fay
Filer Authorized By:	Mark B Solomon
Attorney Docket Number:	4147.1020-002 (15-089)
Receipt Date:	14-FEB-2019
Filing Date:	09-JUN-2016
Time Stamp:	15:40:47
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	no

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Miscellaneous Incoming Letter	41471020002_NoticeToFileCorrected.pdf	725095 e8828eba91f9e39395505eacfa8c80e0bf7a3a32	no	3

Warnings:

Information:					
2	Transmittal Letter accompanying New/ Add'l Drawings	41471020002_TransmittalReplacementDrwgs.pdf	72757 5e65464dc101904317b37e8e12041d27e49d5a6b	no	1
Warnings:					
Information:					
3	Transmittal Letter	41471020002_StatementUnder1125b.pdf	82819 44aeb047da5a0e5e7a6995691a779bb391e22c4b	no	3
Warnings:					
Information:					
4	Specification	41471020002_SubstituteSpec_MarkedUp.pdf	486568 36271d8be2c1b32c4c986f7d03233232c8e60657	no	62
Warnings:					
Information:					
5	Specification	41471020002_SubstituteSpec_Clean.pdf	418825 46fd29ea800eeb547bb71c260770513a72f697f7	no	59
Warnings:					
Information:					
6	Drawings-only black and white line drawings	41471020002_ReplacementDrawingsBW.pdf	8871687 8495e1fe522ed04d3ddd8c769be3cfe955a77fc1	no	22
Warnings:					
The page size in the PDF is too large. The pages should be 8.5 x 11 or A4. If this PDF is submitted, the pages will be resized upon entry into the Image File Wrapper and may affect subsequent processing					
Information:					
7	Drawings-other than black and white line drawings	41471020002_ReplacementDrawingsColor.pdf	2407414 2b09941d869220dc531c26d1eca041819f10c8c7	no	6
Warnings:					
Information:					
			Total Files Size (in bytes):	13065165	

This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

New Applications Under 35 U.S.C. 111

If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371

If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office

If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
15/178,089	06/09/2016	Seyed M. A. Salehizadeh	4147.1020-002 (15-089)	7605

21005 7590 03/08/2019

HAMILTON, BROOK, SMITH & REYNOLDS, P.C.
530 VIRGINIA ROAD
P.O. BOX 9133
CONCORD, MA 01742-9133

EXAMINER	
GEDEON, BRIAN T	

ART UNIT	PAPER NUMBER
3792	

NOTIFICATION DATE	DELIVERY MODE
03/08/2019	ELECTRONIC

Please find below and/or attached an Office communication concerning this application or proceeding.

The time period for reply, if any, is set in the attached communication.

Notice of the Office communication was sent electronically on above-indicated "Notification Date" to the following e-mail address(es):

docketing.department@hbsr.com
helpdesk@hbsr.com

Response to Rule 312 Communication	Application No.	Applicant(s)	
	15/178,089	Salehizadeh et al.	
	Examiner	Art Unit	AIA Status
	BRIAN T GEDEON	3792	Yes

-- The MAILING DATE of this communication appears on the cover sheet with the correspondence address --

1. ☑ The amendment filed on 14 February 2019 under 37 CFR 1.312 has been considered, and has been:

a) ☑ entered.

b) ☐ entered as directed to matters of form not affecting the scope of the invention.

c) ☐ disapproved because the amendment was filed after the payment of the issue fee.

Any amendment filed after the date the issue fee is paid must be accompanied by a petition under 37 CFR 1.313(c)(1) and the required fee to withdraw the application from issue.

d) ☐ disapproved. See explanation below.

e) ☐ entered in part. See explanation below.

/BRIAN T GEDEON/
Primary Examiner, Art Unit 3792

OK TO ENTER: /B.T.G/

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Inventors:	Seyed M.A. Salehizadeh, Ki H. Chon, Yeonsik Noh		
Application No.:	15/178,089	Group:	3792
Filed:	June 9, 2016	Examiner:	Brian T. Gedeon
Confirmation No.:	7605		
For:	Method And Apparatus For Removing Motion Artifacts From Biomedical Signals		

REPLY AFTER FINAL REJECTION UNDER 37 CFR § 1.116

Mail Stop AF
Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Sir:

This Reply After Final Rejection is being filed in response to the Final Office Action mailed from the U.S. Patent and Trademark Office on October 22, 2018 in the above-identified application. Reconsideration and further examination are requested.

Because this Reply after Final Rejection (37 C.F.R. § 1.116) is being filed within two months of the mailing date of the Final Office Action, Applicant respectfully requests an Advisory Action under MPEP 706.07(f)(I)(C).

Petitioner Ex-1004, 1220

MBS/hrp
February 14, 2019

PATENT APPLICATION
Docket No.: 4147.1020-002 (15-089)

OK TO ENTER: /B.T.G/

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Inventors: Seyed M. A. Salehizadeh, Ki H. Chon, Yeonsik Noh

Application No.: 15/178,089 Group: 3792

Filed: Jun 9, 2016 Examiner: Gedeon Brian T.

Confirmation No.: 7605

For: Method And Apparatus For Removing Motion Artifacts From Biomedical Signals

STATEMENT UNDER 37 CFR § 1.125(b)

Mail Stop ISSUE FEE
Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Commissioner:

This Statement is being filed in response to the Notice to File Corrected Application Papers mailed from the U.S. Patent and Trademark Office on January 8, 2019 (hereinafter, "Notice to File Corrected Application Papers"), after mailing of the Notice of Allowance on December 20, 2018, in the above-identified application.

Applicant submits concurrently herewith a substitute specification in compliance with 37 CFR § 1.52, § 1.121(b)(3) and § 1.125 for replacement in the subject application filed on June 9, 2016 along with a copy of the Notice to File Corrected Application Papers. Pursuant to 37 CFR § 1.125(c), submitted concurrently herewith is a copy of the substitute specification marked-up relative to the original specification filed on June 9, 2016.

Further, Applicant submits concurrently herewith 28 sheets of Replacement Drawings consisting of FIGS. 1–23. The Replacement Drawings are identical to the Replacement Drawings filed August 30, 2016; however, sheets have been added for new FIGS. 11C and 14C, and sheet numbers have been applied to all sheets.

The specification is amended to remove Table 6, found at page 40 through 41 of the original specification, and to remove Table 9, found at page 48 of the original specification. Tables 6 and 9 have been added as new FIGS. 11C and 14C, respectively. The specification is amended to include brief descriptions of new FIGS. 11C and 14C. Support for the amendments can be found at least at pages 40, 41, and 48 of the original specification.

The specification is also amended to remove shading from Tables 7, 8, 13, 14, and 15, located at pages 42; 42 and 43; 55; 56; and again on 56 of the original specification, respectively, and to add lines to delineate rows and columns of Table 15. In addition, the specification is amended to correct a typographical error by replacing "comparted" with "compared," found at paragraph [00154] on page 39 of the original specification. Further, the specification is amended to change formatting from bold to normal for equations 7, 8, and 9, located at pages 54, 55, and 55, respectively, of the original specification.

Applicant respectfully submits that the above-noted amendments address each of the Office's non-compliant illustration objections raised in the Notice to File Corrected Application Papers for pages 40–42, 48, 55, and 56. Applicant respectfully submits that while the Notice to File Corrected Application Papers also listed page 57 as having a non-compliant illustration, no illustration at page 57 of the original specification could be located. As such, no amendment to page 57 was made to correct a non-compliant illustration. Page 57 is amended, however, to correct typographical errors. Specifically, page 57 is amended to replace "Time–Frequency" with "Time-Frequency." Page 10 is also amended to replace "Time–Frequency" with "Time-Frequency."

No new matter has been added.

PATENT APPLICATION
Docket No.: 4147.1020-002 (15-089)

MBS/hrp
February 14, 2019

Please charge any deficiency, including any application size fee that may be due with this submission, or credit any overpayment in the fees that may be due in this matter to Deposit Account No. 08-0380.

Respectfully submitted,

HAMILTON, BROOK, SMITH & REYNOLDS, P.C.

By /Mark B. Solomon, Reg. No. 44348/
Mark B. Solomon
Registration No.: 44,348
Telephone: (978) 341-0036
Facsimile: (978) 341-0136

Concord, MA 01742-9133
Dated: 2/14/2019

PART B - FEE(S) TRANSMITTAL

Complete and send this form, together with applicable fee(s), by mail or fax, or via EFS-Web.

By mail, send to: Mail Stop ISSUE FEE
Commissioner for Patents
P.O. Box 1450
Alexandria, Virginia 22313-1450

By fax, send to: (571)-273-2885

INSTRUCTIONS: This form should be used for transmitting the ISSUE FEE and PUBLICATION FEE (if required). Blocks 1 through 5 should be completed where appropriate. All further correspondence including the Patent, advance orders and notification of maintenance fees will be mailed to the current correspondence address as indicated unless corrected below or directed otherwise in Block 1, by (a) specifying a new correspondence address; and/or (b) indicating a separate "FEE ADDRESS" for maintenance fee notifications.

CURRENT CORRESPONDENCE ADDRESS (Note: Use Block 1 for any change of address)

21005 7590 12/20/2018
HAMILTON, BROOK, SMITH & REYNOLDS, P.C.
530 VIRGINIA ROAD
P.O. BOX 9133
CONCORD, MA 01742-9133

Note: A certificate of mailing can only be used for domestic mailings of the Fee(s) Transmittal. This certificate cannot be used for any other accompanying papers. Each additional paper, such as an assignment or formal drawing, must have its own certificate of mailing or transmission.

Certificate of Mailing or Transmission

I hereby certify that this Fee(s) Transmittal is being deposited with the United States Postal Service with sufficient postage for first class mail in an envelope addressed to the Mail Stop ISSUE FEE address above, or being transmitted to the USPTO via EFS-Web or by facsimile to (571) 273-2885, on the date below.

(Typed or printed name)
(Signature)
(Date)

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
15/178,089	06/09/2016	Seyed M. A. Salehizadeh	4147.1020-002 (15-089)	7605

TITLE OF INVENTION: METHOD AND APPARATUS FOR REMOVING MOTION ARTIFACTS FROM BIOMEDICAL SIGNALS

APPLN. TYPE	ENTITY STATUS	ISSUE FEE DUE	PUBLICATION FEE DUE	PREV. PAID ISSUE FEE	TOTAL FEE(S) DUE	DATE DUE
nonprovisional	SMALL	$500	$0.00	$0.00	$500	03/20/2019

EXAMINER	ART UNIT	CLASS-SUBCLASS
GEDEON, BRIAN T	3792	600-301000

1. Change of correspondence address or indication of "Fee Address" (37 CFR 1.363).

☐ Change of correspondence address (or Change of Correspondence Address form PTO/SB/122) attached.

☐ "Fee Address" indication (or "Fee Address" Indication form PTO/SB/47; Rev 03-09 or more recent) attached. **Use of a Customer Number is required.**

2. For printing on the patent front page, list
(1) The names of up to 3 registered patent attorneys or agents OR, alternatively,
(2) The name of a single firm (having as a member a registered attorney or agent) and the names of up to 2 registered patent attorneys or agents. If no name is listed, no name will be printed.

1 Hamilton, Brook, Smith & Reynolds, P.C.
2
3

3. ASSIGNEE NAME AND RESIDENCE DATA TO BE PRINTED ON THE PATENT (print or type)

PLEASE NOTE: Unless an assignee is identified below, no assignee data will appear on the patent. If an assignee is identified below, the document must have been previously recorded, or filed for recordation, as set forth in 37 CFR 3.11 and 37 CFR 3.81(a). Completion of this form is NOT a substitute for filing an assignment.

(A) NAME OF ASSIGNEE: University of Connecticut

(B) RESIDENCE: (CITY and STATE OR COUNTRY): Farmington, CT

Please check the appropriate assignee category or categories (will not be printed on the patent) : ☐ Individual ☒ Corporation or other private group entity ☐ Government

4a. Fees submitted: ☒ Issue Fee ☐ Publication Fee (if required) ☐ Advance Order - # of Copies

4b. Method of Payment: *(Please first reapply any previously paid fee shown above)*

☒ Electronic Payment via EFS-Web ☐ Enclosed check ☐ Non-electronic payment by credit card (Attach form PTO-2038)

☒ The Director is hereby authorized to charge the required fee(s), any deficiency, or credit any overpayment to Deposit Account No. 08-0380

5. **Change in Entity Status** (from status indicated above)

☐ Applicant certifying micro entity status. See 37 CFR 1.29

☐ Applicant asserting small entity status. See 37 CFR 1.27

☐ Applicant changing to regular undiscounted fee status.

NOTE: Absent a valid certification of Micro Entity Status (see forms PTO/SB/15A and 15B), issue fee payment in the micro entity amount will not be accepted at the risk of application abandonment.
NOTE: If the application was previously under micro entity status, checking this box will be taken to be a notification of loss of entitlement to micro entity status.
NOTE: Checking this box will be taken to be a notification of loss of entitlement to small or micro entity status, as applicable.

NOTE: This form must be signed in accordance with 37 CFR 1.31 and 1.33. See 37 CFR 1.4 for signature requirements and certifications.

Authorized Signature /Mark B. Solomon, Reg. No. 44348/ Date 3/12/2019

Typed or printed name Mark B. Solomon Registration No. 44,348

Electronic Patent Application Fee Transmittal

Application Number:	15178089
Filing Date:	09-Jun-2016
Title of Invention:	METHOD AND APPARATUS FOR REMOVING MOTION ARTIFACTS FROM BIOMEDICAL SIGNALS
First Named Inventor/Applicant Name:	Seyed M. A. Salehizadeh
Filer:	Mark B Solomon/Kristina Fay
Attorney Docket Number:	4147.1020-002 (15-089)

Filed as Small Entity

Filing Fees for Utility under 35 USC 111(a)

Description	Fee Code	Quantity	Amount	Sub-Total in USD($)
Basic Filing:				
Pages:				
Claims:				
Miscellaneous-Filing:				
Petition:				
Patent-Appeals-and-Interference:				
Post-Allowance-and-Post-Issuance:				
UTILITY APPL ISSUE FEE	2501	1	500	500

Description	Fee Code	Quantity	Amount	Sub-Total in USD($)
Extension-of-Time:				
Miscellaneous:				
			Total in USD ($)	**500**

Electronic Acknowledgement Receipt

EFS ID:	35393836
Application Number:	15178089
International Application Number:	
Confirmation Number:	7605
Title of Invention:	METHOD AND APPARATUS FOR REMOVING MOTION ARTIFACTS FROM BIOMEDICAL SIGNALS
First Named Inventor/Applicant Name:	Seyed M. A. Salehizadeh
Customer Number:	21005
Filer:	Mark B Solomon/Kristina Fay
Filer Authorized By:	Mark B Solomon
Attorney Docket Number:	4147.1020-002 (15-089)
Receipt Date:	12-MAR-2019
Filing Date:	09-JUN-2016
Time Stamp:	12:20:52
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	yes
Payment Type	DA
Payment was successfully received in RAM	$500
RAM confirmation Number	031219INTEFSW00012356080380
Deposit Account	
Authorized User	

The Director of the USPTO is hereby authorized to charge indicated fees and credit any overpayment as follows:

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Issue Fee Payment (PTO-85B)	41471020002_IssueFee.pdf	672098 d98ccf9203a5c90aceb34305889d5640c3add087	no	1
Warnings:					
Information:					
2	Fee Worksheet (SB06)	fee-info.pdf	30501 03631ffe66e07658e3d18dc763f323e19c79bc7d	no	2
Warnings:					
Information:					
		Total Files Size (in bytes):	702599		

This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

New Applications Under 35 U.S.C. 111

If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371

If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office

If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

APPLICATION NO.	ISSUE DATE	PATENT NO.	ATTORNEY DOCKET NO.	CONFIRMATION NO.
15/178,089	05/07/2019	10278647	4147.1020-002 (15-089)	7605

21005 7590 04/17/2019

HAMILTON, BROOK, SMITH & REYNOLDS, P.C.
530 VIRGINIA ROAD
P.O. BOX 9133
CONCORD, MA 01742-9133

ISSUE NOTIFICATION

The projected patent number and issue date are specified above.

Determination of Patent Term Adjustment under 35 U.S.C. 154 (b)
(application filed on or after May 29, 2000)

The Patent Term Adjustment is 229 day(s). Any patent to issue from the above-identified application will include an indication of the adjustment on the front page.

If a Continued Prosecution Application (CPA) was filed in the above-identified application, the filing date that determines Patent Term Adjustment is the filing date of the most recent CPA.

Applicant will be able to obtain more detailed information by accessing the Patent Application Information Retrieval (PAIR) WEB site (http://pair.uspto.gov).

Any questions regarding the Patent Term Extension or Adjustment determination should be directed to the Office of Patent Legal Administration at (571)-272-7702. Questions relating to issue and publication fee payments should be directed to the Application Assistance Unit (AAU) of the Office of Data Management (ODM) at (571)-272-4200.

APPLICANT(s) (Please see PAIR WEB site http://pair.uspto.gov for additional applicants):

Seyed M. A. Salehizadeh, Coventry, CT;
University of Connecticut, Farmington, CT;
Ki H. Chon, Mansfield Center, CT;
Yeonsik Noh, Willington, CT;

The United States represents the largest, most dynamic marketplace in the world and is an unparalleled location for business investment, innovation, and commercialization of new technologies. The USA offers tremendous resources and advantages for those who invest and manufacture goods here. Through SelectUSA, our nation works to encourage and facilitate business investment. To learn more about why the USA is the best country in the world to develop technology, manufacture products, and grow your business, visit SelectUSA.gov.

Doc Code: PA..
Document Description: Power of Attorney

PTO/AIA/82A (07-13)
Approved for use through 03/31/2021. OMB 0651-0035
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it displays a valid OMB control number.

TRANSMITTAL FOR POWER OF ATTORNEY TO ONE OR MORE REGISTERED PRACTITIONERS

NOTE: This form is to be submitted with the Power of Attorney by Applicant form (PTO/AIA/82B) to identify the application to which the Power of Attorney is directed, in accordance with 37 CFR 1.5, unless the application number and filing date are identified in the Power of Attorney by Applicant form. If neither form PTO/AIA/82A nor form PTO/AIA82B identifies the application to which the Power of Attorney is directed, the Power of Attorney will not be recognized in the application.

Application Number	15/178,089
Filing Date	June 9, 2016
First Named Inventor	Seyed M. A. Salehizadeh
Title	METHOD AND APPARATUS FOR REMOVING MOTION ARTIFACTS FROM BIOMEDICAL SIGNALS
Art Unit	3792
Examiner Name	Brian T. Gedeon
Attorney Docket Number	38100.0002U1

SIGNATURE of Applicant or Patent Practitioner

Signature	/Charley F. Brown #52,658/	Date (Optional)	December 18, 2020
Name	Charley F. Brown	Registration Number	52,658
Title (if Applicant is a juristic entity)	Patent Counsel		
Applicant Name (if Applicant is a juristic entity)	University of Connecticut		

NOTE: This form must be signed in accordance with 37 CFR 1.33. See 37 CFR 1.4(d) for signature requirements and certifications. If more than one applicant, use multiple forms.

☑ *Total of 1 forms are submitted.

This collection of information is required by 37 CFR 1.131, 1.32, and 1.33. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.11 and 1.14. This collection is estimated to take 3 minutes to complete, including gathering, preparing, and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

If you need assistance in completing the form, call 1-800-PTO-9199 and select option 2.

Doc Code: PA..
Document Description: Power of Attorney

PTO/AIA/82B (07-13)
Approved for use through 03/31/2021. OMB 0651-0035
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it displays a valid OMB control number

POWER OF ATTORNEY BY APPLICANT

I hereby revoke all previous powers of attorney given in the application identified in either the attached transmittal letter or the boxes below.

Application Number	Filing Date

(Note: The boxes above may be left blank if information is provided on form PTO/AIA/82A.)

☑ I hereby appoint the Patent Practitioner(s) associated with the following Customer Number as my/our attorney(s) or agent(s), and to transact all business in the United States Patent and Trademark Office connected therewith for the application referenced in the attached transmittal letter (form PTO/AIA/82A) or identified above: 23859

OR

☐ I hereby appoint Practitioner(s) named in the attached list (form PTO/AIA/82C) as my/our attorney(s) or agent(s), and to transact all business in the United States Patent and Trademark Office connected therewith for the patent application referenced in the attached transmittal letter (form PTO/AIA/82A) or identified above. (Note: Complete form PTO/AIA/82C.)

Please recognize or change the correspondence address for the application identified in the attached transmittal letter or the boxes above to:

☑ The address associated with the above-mentioned Customer Number

OR

☐ The address associated with Customer Number:

OR

☐ Firm or Individual Name					
Address					
City		State		Zip	
Country					
Telephone		Email			

I am the Applicant (if the Applicant is a juristic entity, list the Applicant name in the box):

University of Connecticut

☐ Inventor or Joint Inventor (title not required below)

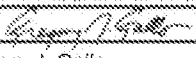
☐ Legal Representative of a Deceased or Legally Incapacitated Inventor (title not required below)

☑ Assignee or Person to Whom the Inventor is Under an Obligation to Assign (provide signer's title if applicant is a juristic entity)

☐ Person Who Otherwise Shows Sufficient Proprietary Interest (e.g., a petition under 37 CFR 1.46(b)(2) was granted in the application or is concurrently being filed with this document) (provide signer's title if applicant is a juristic entity)

SIGNATURE of Applicant for Patent

The undersigned (whose title is supplied below) is authorized to act on behalf of the applicant (e.g., where the applicant is a juristic entity).

Signature		Date (Optional)	December 16, 2020
Name	Gregory J. Gallo		
Title	Director of Technology Transfer		

NOTE: Signature - This form must be signed by the applicant in accordance with 37 CFR 1.33. See 37 CFR 1.4 for signature requirements and certifications. If more than one applicant, use multiple forms.

☐ Total of forms are submitted.

This collection of information is required by 37 CFR 1.131, 1.32, and 1.33. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.11 and 1.14. This collection is estimated to take 3 minutes to complete, including gathering, preparing, and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

If you need assistance in completing the form, call 1-800-PTO-9199 and select option 2.