thereto. Central server 312 may be any suitable processor-based device for receiving and processing the sensed data including without limitation a personal computer (PC) or mainframe computer. Furthermore, it should be understood that central server 312 may actually comprise a plurality of processor-based devices communicatively coupled together; and gateway may be communicated from wireless gateway 310 to all of such plurality of processor-based devices simultaneously, and/or such data may be communicated from one of such processor-based devices to the next of such devices. Additionally, while only one platform 302 is shown in Fig. 3, it should be understood that in a preferred embodiment, many such platforms may be implemented, and central server 312 may receive data sensed by all of such platforms. Further, each platform may have associated therewith its own transceiver 306, as well as its own wireless gateway 310 in order to communicate sensed data to central server 312. Alternatively, multiple platforms may share a single transceiver 306 and/or a single wireless gateway 310. Thus, in some embodiments, wireless gateway 310 may be utilized to communicate sensed data from a plurality of platforms, each having one or more sensors, to central server 312. Furthermore, each platform may include one or more various sensors 304.

Because a preferred embodiment enables sensed data to be communicated from various different sensors 304 to a central server 312, rather than each sensor communicating data to a separate, dedicated monitoring device, the quality, efficiency and cost effectiveness of processing such data can be improved at central server 312 to improve the overall processing (e.g., monitoring/analysis) of the sensed data. Thus, for example, in a most preferred embodiment the functionality of the monitoring devices of the prior art (e.g., monitoring devices 104_A, 104_B, and 104_B of Figs. 1 and 2) may be provided by central server 312, thereby eliminating the requirement of providing monitoring devices that are dedicated solely to a particular sensor or platform (e.g., dedicated to a particular patient). As will be discussed in greater detail hereafter, in some implementations transceiver 306 and/or wireless gateway 310 may include data processing (e.g., monitoring/analysis) functionality. However, in a most preferred embodiment, central server 312 provides the primary processing functionality.

In a preferred embodiment, a user can select the most desirable software program(s) to be utilized at central server 312 for processing (e.g., monitoring/analyzing) the sensed data. Thus, for example, a user is not limited specifically to software provided by the

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manufacturer of a monitoring device, but may instead choose one or more of various different software program(s) to be utilized at central server 312 for processing the sensed data. Additionally, software programs may be utilized to process data received from multiple sensors on platform 302 in order to more fully monitor/analyze the overall condition of platform 302 or some entity (e.g., a patient) associated with platform 302. Using a software program to monitor data collected from various different sensors is typically not available in the prior art. For example, in the prior art the output of a heart sensor is generally monitored by a heart rate monitoring device, and the output of a blood pressure sensor is generally monitored by a blood pressure device. However, a system that allows for data from a heart sensor, data from a blood pressure sensor, as well as data from various other sensors, to be collectively processed by such system to monitor/analyze the overall condition of a patient is typically not available. Thus, a preferred embodiment is advantageous in that it enables data from various different sensors to be collectively processed to evaluate the condition of platform 302 or an entity (e.g., a patient) associated with platform 302.

As further shown in Fig. 3, in a preferred embodiment a user, such as a care giver (e.g., a physician or nurse), may access data from central server 312 via a suitable processor-based device, such as devices 316, 318 and 308. For example, processor-based device 316, which may be any suitable processor-based device including without limitation a personal PC or laptop computer, may be communicatively coupled to central server 312 to enable a user to access data from central server 312. Similarly, processor-based device 318, which may also be any suitable processor-based device including without limitation a PC or laptop computer, may be communicatively coupled to central server 312 via communication network 314 to enable a user to access data from central server 312. Communication network 314 may be any suitable communication network, including without limitation a public switched telephone network (PSTN), wireless communication network, a general purpose processor-based information network, dedicated communication lines, a cable system, digital subscriber line (DSL), direct PC to PC connection, a local area network (LAN), a wide area network (WAN), modem to modem connection, the Internet, an Intranet, an Extranet, or any combination thereof suitable for providing information communication between processor-based device 318 and central server 312.

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Additionally, a handheld device 308, such as a personal digital assistant (PDA), pager, or 3G cellular telephone, may be capable of communicating with one or more of central server 312, wireless gateway 310, and transceiver 306. Handheld device 308 may be referred to herein as a "personal status monitor" ("PSM"), and may enable an entity associated with platform 302 (e.g., a patient) to monitor sensed data and/or receive warnings/instructions. For example, a warning (e.g., an audible alarm) may be provided by PSM 308 upon detection by PSM 308 or central server 312 of a dangerous condition based on the sensed data, and/or instructions may be provided from central server 312 to PSM 308 to educate the entity associated with platform 302 as to appropriate actions to take. Additionally, PSM 308 may be a device used by an entity not associated with platform 302, such as a care giver responsible for a patient being monitored by platform 302. In this manner, for example, a nurse, physician, or other care giver may use PSM 308 to monitor the status of one or more patients. Preferably, PSM 308 is a wireless device capable of receiving data via a wireless protocol, such as Bluetooth.

A most preferred embodiment of the present invention has particularly desired application within the health care arena to communicate sensed personal data (e.g., vital sign data) from one or more patients to a central server. However, as will be recognized by one of ordinary skill in the art, various embodiments of the present invention may be implemented within many other arenas. Thus, the present invention, therefore, is not intended to be limited solely to application within the health care arena or solely to the communication of personal data of patients to a central server, but instead may be implemented within various other arenas (some of which are briefly mentioned herein) and may be implemented to communicate various other types of sensed data to a central server.

Turning to Fig. 4, an exemplary environment 400 in which a most preferred embodiment may be implemented is shown. As shown, a platform 402 is provided, which includes one or more sensors 403. As illustrated in Fig. 4, in a most preferred embodiment, platform 402 is implemented as fabric that includes an integrated infrastructure in which sensors 403 may be implemented. Most preferably, such fabric is fashioned into a wearable garment such that sensors 403 may detect physical characteristics (e.g., personal data) from the person wearing the garment and/or about the physical characteristics of the environmental surroundings of such person. Such a fabric platform may be implemented in the manner described in greater detail in co-pending U.S. Patent Application Serial

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Numbers 09/157,607, filed September 21, 1998, entitled "Full-Fashioned Weaving Process for Production of a Woven Garment with Intelligence Capability," and 09/273,175, filed March 19, 1999, entitled "Fabric or Garment with Integrated Flexible Information Infrastructure;" and also as in co-pending U.S. Provisional Application Serial Number 60/142,360, filed July 6, 2000, entitled "Fabric or Garment with Integrated Flexible Information Infrastructure for Monitoring Vital Signs of Infants," the disclosures all of which are hereby incorporated herein by reference. Thus, for instance, as shown in the example of Fig. 4, platform 402 may be a wearable fabric garment (e.g., a shirt, a vest, pants, shorts, a cap, etcetera). In alternative embodiments, platform 402 may be implemented as fabric having an integrated infrastructure that is fashioned into something other than a wearable garment (e.g., fabric for a chair or other furnishing, fabric for curtains, fabric for carpeting, etcetera). In still other alternatives, platform 402 may be implemented as a non-fabric platform that includes an infrastructure in which one or more sensors 403 may be implemented.

Transceiver 306 is communicatively coupled to the infrastructure of platform 402 to receive sensed data from the one or more sensors 403. Thus, transceiver 306 may be integrated within the infrastructure of platform 402, or otherwise communicatively coupled to such infrastructure. Wireless gateway 310_A is included within environment 400 to receive the sensed data from transceiver 306 and communicate such data, either directly or indirectly, to a central server, which in this exemplary implementation is a web-based server 406. More specifically, in this exemplary implementation, wireless gateway 310_A communicates the sensed data to a base unit 404, which in turn communicates the sensed data to web-based server 406 via fixed transmission facility (e.g., the Internet, PSTN, private data network, or other suitable communication network). Transceiver 306 may communicate the sensed data to wireless gateway 310_A via a first wireless protocol (e.g., via short-range radio protocol, such as Bluetooth), and wireless gateway 310_A translates the data to a second wireless protocol (e.g., WLAN, infrared, PAN, cellular, or other wireless protocol) that is suitable for communicating with base unit 404. Base unit 404 communicates the sensed data in a suitable protocol (e.g., Internet Protocol) to web-based server 406.

Web-based server 406 may include one or more software application programs 408 executing thereon to process the received sensed data. Additionally, a processor-based

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device 316 (e.g., workstation, PC, or laptop) may be communicatively coupled to web-based server 406 to enable a user to input information to web-based server 406 and/or to receive output of information from web-based server 406. For example, a user may utilize processor-based device 316 to monitor and/or analyze the received sensed data. For instance, a user may interact with application programs 408 to monitor/analyze the physical characteristics represented by the sensed data (e.g., a patient's vital signs). As further shown in Fig. 4, a data storage device 407 may be communicatively coupled to central server 406 to enable central server 406 to store the sensed data thereto. Such data storage device 407 may be implemented as any suitable data storage device, including without limitation RAM, a hard drive, floppy disk, or writeable CD-ROM. Furthermore, sensed data and/or data output by application programs 408 may be stored to data storage device 407 as one or more databases. Accordingly, in a preferred embodiment, a user may utilize processor-based device 316, for example, to query the data collected by the central server 406 in data storage device 407. For instance, a user may utilize Standard Query Language (SQL) or may otherwise interact with an application program 408 to query data for one or more patients collected in data storage device 407. As a result, reports including data from data storage device 407 may be generated, for instance, in hypertext markup language (HTML), Dynamic hypertext markup language (DHTML), extensible markup language (XML), extensible hypertext markup language (XHTML), standard generalized markup language (SGML), or other appropriate format for displaying to the user on processor-based device 316.

Furthermore, a processor-based handheld device 308 (e.g., PDA or PSM) may be communicatively coupled to transceiver 306 and/or wireless gateway 310_A. Thus, a user may receive sensed data from transceiver 306 and/or wireless gateway 310_A, and the user may then analyze/monitor the sensed data using handheld device 308. Handheld device 308 may execute one or more application programs, such as application programs 408, to aid a user in evaluating the received sensed data information. Most preferably, handheld device 308 communicates in the same protocol in which transceiver 306 communicates to enable handheld device 308 to receive information directly from such transceiver 306. Of course, wireless gateway 310_A may be utilized to forward sensed data to handheld device 308 if, for example, handheld device 308 is not within communication range of transceiver 306.

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Additionally, handheld device 308 may provide redundancy or backup in the event of communication failure with web-based server 406. For instance, within the health care arena, a patient may have personal data (e.g., vital sign data) communicated from transceiver 306 to wireless gateway 310_A, which communicates the data to base unit 404, which communicates the data to web-based server 406. A physician, nurse, or other care giver may utilize handheld device 308 to receive sensed data for one or more patients for which such care giver is responsible in order to monitor the patients. More specifically, wireless gateway 310_A may communicate sensed data to handheld device 308 in substantially real-time. However, handheld device 308 is most preferably implemented to enable communication directly with transceiver 306, such that if a failure occurs, for example, with wireless gateway 310_A, a care giver has the ability to monitor a patient with handheld device 308. Furthermore, such a handheld device 308 may be utilized by a patient being monitored to provide information (e.g., monitoring information and/or instructions) to the patient. For example, software may execute on handheld device 308 to analyze the patient's sensed data, and provide information/instructions to the patient based on the sensed data. Additionally, a patient may receive via handheld device 308 instructions from a care giver, which the care giver may communicate, for example, from another handheld device 308 and/or via web-based server 406 using workstation 316.

Fig. 5 shows an exemplary implementation of a preferred embodiment within a hospital environment 500 for communication of sensed data within the hospital environment. As shown, platform 402 is again provided, which includes one or more sensors 403. As described in conjunction with Fig. 4, in a most preferred embodiment, platform 402 may be implemented as fabric that includes an integrated infrastructure in which sensors 403 may be implemented, and such fabric may be fashioned into a wearable garment, which may be worn by a patient to enable sensors 403 to sense personal data (e.g., vital sign data) for such patient. Also shown is transceiver 306, which is communicatively coupled to the infrastructure of platform 402 to receive sensed data from the one or more sensors 403. Thus, transceiver 306 may be integrated within the infrastructure of platform 402, or otherwise communicatively coupled to such infrastructure.

Wireless gateway 310_B is included within environment 500 to receive the sensed data from transceiver 306 and communicate such data, either directly or indirectly, to a central server, which in this exemplary implementation is again shown as web-based server

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406. More specifically, in this exemplary implementation, wireless gateway 310_B communicates the sensed data to base unit 404_A, which in turn communicates the sensed data to web-based server 406. Transceiver 306 may communicate the sensed data to wireless gateway 310_B via a first wireless protocol, and wireless gateway 310_B translates the data to a second wireless protocol that is suitable for communicating with base unit 404_A within the hospital environment 500. For instance, transceiver 306 may communicate the sensed data to wireless gateway 310_B via Bluetooth protocol, and wireless gateway 310_B may translate the data to WMTS, which is a suitable protocol for transmission within hospital environment 500. Thus, wireless gateway 310_B may communicate the sensed data to base unit 404_A using WMTS protocol, and base unit 404_A may then communicate the sensed data in a suitable protocol (e.g., Internet Protocol) to web-based server 406 via the hospital's Intranet 502 or other communication network.

In this exemplary implementation, a patient may have data sensed by sensors 403, which may, for instance, be communicatively coupled to an infrastructure of a wearable garment, and the sensed data is received from the sensors 403 at transceiver 306, which in turn transmits the sensed data using Bluetooth protocol to wireless gateway 310_B. It should be recognized that transceiver 306 may be capable of communicating the data only a limited distance, shown as D_1. For example, to save on power consumption, transceiver 306 may be capable of communicating at only a relatively short distance. Thus, for instance the distance D_1 within which transceiver 306 is capable of communicating the sensed data may be approximately 30 feet. Accordingly, wireless gateway 310_B is preferably maintained within relative close proximity of transceiver 306 to enable wireless gateway 310_B to receive the sensed data from transceiver 306. For instance, wireless gateway 310_B may be placed beside the bed of a patient within hospital 500, or the wireless gateway 310_B may be clipped to the clothing of such patient, as examples.

Wireless gateway 310_B is preferably capable of communicating at a further distance than transceiver 306, shown as distance D_2. Thus, for instance, distance D_2 within which wireless gateway transceiver is capable of communicating the sensed data may be approximately 300 feet. Accordingly, base unit 404_A is preferably maintained within range of wireless gateway 310_B (e.g., within distance D_2) to enable base unit 404_A to receive the sensed data from wireless gateway 310_B. For instance, base unit 404_A may be placed at a

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nurses station on the floor of hospital 500 on which a patient being monitored is located, as an example.

In a most preferred embodiment, wireless gateway 310_B includes the capability of communicating via a wireline protocol. For example, wireless gateway 310_B preferably includes a connector for being communicatively coupled to communication network 502 via a wireline connection 503. For example, wireless gateway 310_B may include a telephone jack connection (e.g., an RJ-11 connector) or an RJ-45 connector with a standard modem for communicating with network 502. Accordingly, wireless gateway 310_B may provide further flexibility by enabling not only wireless communication, but also wireline communication. Thus, for example, if wireless communication with base unit 404_A is interrupted (e.g., base unit 404_A fails), wireless gateway 310_B may utilize wireline connection 503 to maintain communication with central server 406.

Fig. 6 shows an exemplary implementation that enables communication of sensed data from a particular base location 600, such as a patient's home, to a central server. As shown, platform 402 including one or more sensors 403, transceiver 306, wireless gateway 310_C, and base unit 404_B may be implemented within a base location (e.g., a patient's home) 600. In this exemplary implementation, wireless gateway 310_C receives sensed data from transceiver 306 and communicates the sensed data to base unit 404_B, which in turn communicates the sensed data to web-based server 406. Thus, for example, transceiver 306 may communicate the sensed data to wireless gateway 310_C via a first wireless protocol, and wireless gateway 310_C translates the data to a second wireless protocol that is suitable for communicating with base unit 404_B within the base location (e.g., patient's home) 600. For instance, transceiver 306 may communicate the sensed data to wireless gateway 310_C via Bluetooth protocol, and wireless gateway 310_C may translate the data to 802.11, which is a suitable protocol for communication with base unit 404_B. Thus, wireless gateway 310_C may communicate the sensed data to base unit 404_B using 802.11 protocol, and base unit 404_B may then communicate the sensed data in a suitable protocol (e.g., Internet Protocol) to web-based server 406 via the Internet 602 or other communication network. As examples, base unit 404_B may access Internet 602 via a cable modem or DSL connection, or base unit 404_B may access an Internet Service Provider (ISP) 604 via an analog or ISDN dial-up modem in order to communicate the sensed data over Internet 602.

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In this exemplary implementation, a patient may have physical characteristics sensed by sensors 403, which may, for instance, be communicatively coupled to an infrastructure of a wearable garment, and the sensed data is received from the sensors 403 at transceiver 306, which in turn transmits the sensed data using Bluetooth protocol to wireless gateway 310_C. As described above, transceiver 306 may be capable of communicating the data only a limited distance D_1 (e.g., 30 feet). Accordingly, wireless gateway 310_C is preferably maintained within relative close proximity of transceiver 306 to enable wireless gateway 310_C to receive the sensed data from transceiver 306. For instance, wireless gateway 310_C may be clipped to the clothing of such patient, carried in a purse (or other handbag, such as a diaper bag), arranged within room(s) of the patient's house, or may actually be implemented within (or coupled to) handheld device 308, which the patient keeps with him/her, as examples.

Wireless gateway 310_C is preferably capable of communicating at a further distance than transceiver 306, shown as distance D_2 (e.g., 300 feet). Accordingly, base unit 404_B is preferably maintained within range of wireless gateway 310_C (e.g., within distance D_2) to enable base unit 404_B to receive the sensed data from wireless gateway 310_C. For instance, one or more base unit(s) 404_B may be strategically placed within the base location 600 to enable such one or more base unit(s) 404_B to be within communication range of wireless gateway 310_C within base location 600. For example, one or more base units 404_B may be strategically placed within a patient's home (base location 600) to enable communication between wireless gateway 310_C and base unit(s) 404_B within the patient's home. Accordingly, this exemplary implementation enables a patient to be monitored by central server 406 from the patient's home. Again, wireless gateway 310_C most preferably includes the capability of communicating via a wireline protocol. For example, wireless gateway 310_C most preferably includes a connector for being communicatively coupled to Internet 602 (or ISP 604) via a wireline connection 603 (e.g., a telephone jack connection with a standard modem for communicating with Internet 602).

Fig. 7 shows an exemplary implementation that further enables communication of sensed data from a wide area to a central server. That is, Fig. 7 shows an exemplary implementation that enables communication of sensed data from areas outside of the base location 600 (e.g., outside the patient's home). As shown, platform 402 including one or more sensors 403, transceiver 306, wireless gateway 310_D, and base unit 404_B may be

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implemented within a base location (e.g., a patient's home) 600. In this exemplary implementation, wireless gateway 310_D receives sensed data from transceiver 306 and communicates the sensed data to base unit 404_B, which in turn communicates the sensed data to web-based server 406, in the manner described above in conjunction with Fig. 6. However, in this exemplary implementation, wireless gateway 310_D is further capable of communicating sensed data to web-based server 406 from within base location 600 or outside of base location 600. More specifically, in this exemplary implementation, wireless gateway 310_D is capable of communicating via one or more cellular protocols, such as CDPD, EDGE, HDR, CDMA, or WCDMA. Thus, for example, transceiver 306 may communicate the sensed data to wireless gateway 310_D via a first wireless protocol, and wireless gateway 310_D may translate the data to a second wireless protocol that is suitable for communicating via cellular network 702, which may in turn be communicatively coupled to Internet 602 for communicating data to web-based server 406. For instance, transceiver 306 may communicate the sensed data to wireless gateway 310_D via Bluetooth protocol, and wireless gateway 310_D may translate the data to a cellular protocol for communication central server 406 via cellular network 702 (which may be communicatively coupled to Internet 602). Thus, wireless gateway 310_D may communicate the sensed data to cellular network 702 using an appropriate cellular protocol, and the cellular network may then communicate the sensed data in a suitable protocol (e.g., Internet Protocol) to web-based server 406 via the Internet 602 or other communication network. As an example, as is well-known in the art, a packet data gateway within the cellular network may be utilized to communicate the sensed data in a suitable protocol to web-based server 406.

In this exemplary implementation, a patient may have data sensed by sensors 403, which may, for instance, be communicatively coupled to an infrastructure of a wearable garment, and the sensed data is received from the sensors 403 at transceiver 306, which in turn transmits the sensed data using Bluetooth protocol to wireless gateway 310_D. As described above, transceiver 306 may be capable of communicating the data only a limited distance D_1 (e.g., 30 feet). Accordingly, wireless gateway 310_D is preferably maintained within relative close proximity of transceiver 306 to enable wireless gateway 310_D to receive the sensed data from transceiver 306. For instance, wireless gateway 310_D clipped to the clothing of such patient, carried in a purse (or other handbag, such as a diaper bag),

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or may actually be implemented within (or coupled to) handheld device 308, which the patient keeps with him/her, as examples

Because wireless gateway 310_D is capable of communicating via cellular communication in this exemplary implementation, such wireless gateway 310_D is capable of communicating at a much further distance than transceiver 306. In this implementation, if wireless gateway 310_D is within range of base unit 404_B, then base unit 404_B is preferably used to communicate with central server 406. However, if communication between base unit 404_B and wireless gateway 310_D is interrupted (e.g., wireless gateway 310_D is not within range for communication with base unit 404_B, or the communication there between is otherwise interrupted), wireless gateway 310_D may utilize cellular network 702 to communicate with central server 406, as well as other suitable third parties 703, such as a 911 operator. As will be described in greater detail hereafter, in a most preferred embodiment, wireless gateway 310_D may be implemented with an amount of intelligence for analyzing sensed data received from transceiver 306. For example, wireless gateway 310_D may be capable of recognizing critical conditions indicated by the sensed data, and may utilize cellular network 702 to contact 911, central server 406, or otherwise make an emergency call to notify appropriate personnel of the critical condition.

Turning to Fig. 8, an exemplary implementation that enables communication of sensed data within a wide area of communication is shown. In this exemplary implementation, a particular base area (e.g., a patient's home) may not be defined for a user, and a base unit is not included for use within such a particular base area, but instead a wide area communication, such as cellular communication, may be utilized for communicating sensed data to central server 406. That is, Fig. 8 shows an exemplary implementation that enables communication of sensed data within a wide area utilizing wide area communication, such as cellular communication. In this exemplary implementation, wireless gateway 310_E receives sensed data from transceiver 306 and communicates the sensed data to central server 406 via cellular network 702. More specifically, in this exemplary implementation, wireless gateway 310_E is capable of communicating via one or more cellular protocols, such as CDPD, EDGE, HDR, CDMA, or WCDMA. Thus, for example, transceiver 306 may communicate the sensed data to wireless gateway 310_E via a first wireless protocol, and wireless gateway 310_E may translate the data to a second wireless protocol that is suitable for communicating via

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cellular network 702, which may in turn be communicatively coupled to Internet 602 for communicating data to web-based server 406. For instance, transceiver 306 may communicate the sensed data to wireless gateway 310_E via Bluetooth protocol, and wireless gateway 310_E may translate the data to a cellular protocol for communication to central server 406 via cellular network 702 (which may be communicatively coupled to Internet 602). Thus, wireless gateway 310_E may communicate the sensed data to cellular network 702 using an appropriate cellular protocol, and the cellular network may then communicate the sensed data in a suitable protocol (e.g., Internet Protocol) to web-based server 406 via the Internet 602 or other communication network.

In this exemplary implementation, a patient may have physical characteristics sensed by sensors 403, which may, for instance, be communicatively coupled to an infrastructure of a wearable garment, and the sensed data is received from the sensors 403 at transceiver 306, which in turn transmits the sensed data using Bluetooth protocol to wireless gateway 310_E. As described above, transceiver 306 may be capable of communicating the data only a limited distance D_1 (e.g., 30 feet). Accordingly, wireless gateway 310_E is preferably maintained within relative close proximity of transceiver 306 to enable wireless gateway 310_E to receive the sensed data from transceiver 306. For instance, wireless gateway 310_E may be clipped to the clothing of such patient, carried in a purse (or other handbag, such as a diaper bag), or may actually be implemented within (or coupled to) handheld device 308, which the patient keeps with him/her, as examples.

Because wireless gateway 310_E is capable of communicating via cellular communication in this exemplary implementation, such wireless gateway 310_E is capable of communicating at a much further distance than transceiver 306. In this implementation, wireless gateway 310_E utilizes cellular network 702 to communicate with central server 406, as well as other suitable third parties 703, such as a 911 operator. Wireless gateway 310_E may only periodically communicate data to central server 406 via cellular network 702. For example, wireless gateway 310_E may only access central server 406 via cellular network 702 periodically or upon detection of particular conditions of the sensed data. For instance, wireless gateway 310_E may store an hour's worth of sensed data, and only access central server 406 via cellular network 702 once an hour for transmission of the data. As will be described in greater detail hereafter, in a most preferred embodiment, wireless gateway 310_E may be implemented with an amount of intelligence for analyzing sensed

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data received from transceiver 306. Accordingly, wireless gateway 310_E may be capable of recognizing critical conditions indicated by the sensed data, and may utilize cellular network 702 to contact 911, central server 406, or otherwise make an emergency call to notify appropriate personnel of the critical condition.

An exemplary implementation of transceiver 306 that may be utilized in a preferred embodiment is shown in Fig. 9. Of course, it should be recognized that any other suitable implementation of such transceiver 306 now known or later developed may be utilized, and any such implementation is intended to be within the scope of the present invention.

In a most preferred embodiment, sensed data communicated to wireless gateway 310 includes information in addition to the actual sensed data. For example, in a most preferred embodiment, the sensed data includes physical characteristic type, source identification, time stamp, and location information. Of course, additional information may also be included. The physical characteristic type information identifies the type of physical characteristic that the sensed data represents. For instance, the physical characteristic type information may identify certain sensed data as representing heart rate data and other sensed data as representing body temperature information. Source identification information identifies the source of the physical characteristic, such as a particular patient or a particular platform from which the physical characteristic was obtained. For instance, source identification information may identify a particular patient from which the sensed data was obtained, such as the patient's name, social security number, or other identifier. Such source identification may further include contact information for quickly reaching the source, such as a patient's room number within a hospital, a patient's address, and the patient's telephone number. Time stamp information identifies the specific date and time at which the sensed data was actually obtained. Location information identifies the location of the source of such sensed data. For instance, location information may identify the exact location (e.g., address) at which a patient is located at the time of obtaining the sensed data (e.g., such information may be acquired using a global positioning system for instance).

In a preferred embodiment, data may be temporarily stored in any suitable data storage device, such as a hard drive, floppy disk, or writeable CD-ROM, that is communicatively coupled to wireless gateway 310, and wireless gateway 310 may periodically communicate such data to the central server. Thus, wireless gateway 310 may

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not be required to maintain a constant communication connection with the central server, but may instead only periodically establish such a connection to communicate the data. Furthermore, as described in greater detail in concurrently filed and commonly assigned U.S. Patent Application Serial Number 09/676,382 entitled "WIRELESS GATEWAY CAPABLE OF COMMUNICATING ACCORDING TO A PLURALITY OF PROTOCOLS," the disclosure of which is hereby incorporated herein by reference, wireless gateway 310 of a most preferred embodiment may be capable of performing at least a limited amount of analysis of the sensed data. Accordingly, wireless gateway 310 may, based on the sensed data, determine that communication with the central server (or an appropriate third party) should be initiated. For example, wireless gateway 310 may determine that heart rate data it receives is at a critical (or dangerous) level or is otherwise abnormal, and may in response to receiving such data initiate communication with the central server to immediately communicate the data to such central server in order to alert a monitoring care giver. Alternatively (or in addition thereto), wireless gateway 310 may initiate a call to 911 (or other emergency personnel) to request immediate medical attention for the monitored patient. As described above, the data most preferably includes information identifying the monitored patients name, location (e.g., address), and other information, which wireless gateway 310 may use to properly notify emergency personnel of the situation.

Furthermore, in a preferred embodiment, wireless gateway 310 may determine an appropriate communication method or protocol to use based on the sensed data. For example, in the exemplary implementation of Fig. 7, wireless gateway 310_D may based upon the sensed data determine to use either protocol 802.11 (or other suitable protocol) to communicate to central server 406 via base unit 404_B or cellular network 702 to communicate to central server 406 or a suitable third party 703. For instance, wireless gateway 310_D may receive heart rate data, and upon determining that the heart rate data is not at a critical or otherwise abnormal level, wireless gateway 310_D may communicate the sensed data to central server 406 via base unit 404_B. On the other hand, wireless gateway 310_D may determine that heart rate data it receives is at a critical (or dangerous) level or is otherwise abnormal, and may in response to receiving such data initiate communication with central server 406 or a third party 703 via cellular network 702 (or via a wireline network, such as PSTN). Additionally, if no communication path is available, wireless

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gateway 310 may be implemented to sound an audible alarm and/or present a visual alarm (e.g., on a display that may be implemented within such wireless gateway 310).

While the various embodiments have been described above as being implemented within the health care arena (e.g., for communicating vital sign data from a patient to a central server), it should be understood that the present invention may be implemented in various other arenas. As one example, a preferred embodiment may be implemented to enable communication of sensed data (e.g., temperature data) to a temperature control system or air conditioning system (central server) responsible for controlling the temperature of a particular facility. As another example, a preferred embodiment may be implemented within a robot to detect hazardous conditions in an environment and communicate the sensed data acquired in such an environment to a central server.

Although the present invention and its advantages have been described in detail, it should be understood that various changes, substitutions and alterations can be made herein without departing from the spirit and scope of the invention as defined by the appended claims. Moreover, the scope of the present application is not intended to be limited to the particular embodiments of the process, machine, manufacture, composition of matter, means, methods and steps described in the specification. As one of ordinary skill in the art will readily appreciate from the disclosure of the present invention, processes, machines, manufacture, compositions of matter, means, methods, or steps, presently existing or later to be developed that perform substantially the same function or achieve substantially the same result as the corresponding embodiments described herein may be utilized according to the present invention. Accordingly, the appended claims are intended to include within their scope such processes, machines, manufacture, compositions of matter, means, methods, or steps.

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WHAT IS CLAIMED IS:

1. A system for communicating data to a central server for processing thereon, said system comprising:

at least one sensor, each of said at least one sensor for sensing a physical characteristic and outputting data representing said physical characteristic to a transmitter;

said transmitter for communicating said data via a first wireless protocol to a wireless gateway;

said wireless gateway for translating said data from said first wireless protocol to at least a second wireless protocol and for communicating said data either directly or indirectly to a central server via said at least a second wireless protocol; and

said central server for receiving said data and processing said data.

2. The system of claim 1 further comprising:

at least one platform on which one or more of said at least one sensor is coupled.

3. The system of claim 2 wherein said at least one platform comprises fabric having an information infrastructure integrated therein.

4. The system of claim 3 wherein said fabric is fashioned into a wearable garment.

5. The system of claim 2 wherein said at least one platform provides an information infrastructure to which said at least one sensor can be removably coupled.

6. The system of claim 2 wherein said at least one platform provides an information infrastructure to which said at least one sensor is permanently coupled.

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7. The system of claim 1 wherein said transmitter is a transceiver that is further capable of receiving data.

8. The system of claim 1 wherein said central server comprises a plurality of processor-based devices communicatively coupled together.

9. The system of claim 1 wherein said central server is a web-based server.

10. The system of claim 1 further comprising:

at least one intermediary for receiving data from said wireless gateway and communicating said data to said central server.

11. The system of claim 10 wherein said at least one intermediary receives said data from said wireless gateway in said at least a second wireless protocol, and wherein said at least one intermediary communicates said data to said central server in a protocol different from said at least a second wireless protocol.

12. The system of claim 11 wherein said at least a second wireless protocol is selected from the group consisting of WLAN, infrared, PAN, and cellular protocol.

13. The system of claim 11 wherein said WLAN protocol includes 802.11 and WMTS protocol.

14. The system of claim 11 wherein said at least one intermediary communicates said data to said central server using a wireline protocol.

15. The system of claim 11 wherein said at least one intermediary communicates said data to said central server using Internet Protocol.

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16. The system of claim 10 herein said at least one intermediary communicates said data to said central server via a communication network.

17. The system of claim 16 wherein said communication network is selected from the group consisting of:

public switched telephone network (PSTN), wireless communication network, general purpose processor-based information network, dedicated communication lines, cable system, digital subscriber line (DSL), direct PC to PC connection, local area network (LAN), wide area network (WAN), modem to modem connection, the Internet, an Intranet, an Extranet, or any combination thereof suitable for providing information communication between said at least one intermediary and said central server.

18. The system of claim 10 wherein said intermediary comprises a processor-based device.

19. The system of claim 10 wherein said intermediary comprises a device selected from the group consisting of:

base unit and a packet data gateway within a cellular network.

20. The system of claim 1 wherein said physical characteristic is selected from the group consisting of vital sign characteristic and environmental characteristic.

21. The system of claim 20 wherein said vital sign characteristic includes heart rate, breathing rate, blood pressure, pulse, body temperature, and blood oxygen level.

22. The system of claim 20 wherein said environmental characteristic includes temperature, audio, atmospheric smoke and oxygen levels, gas level, light level, air flow, and radiation level.

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23. The system of claim 1 wherein said data includes information selected from the group consisting of:

physical characteristic type, source identification, time stamp, and location information.

24. The system of claim 1 further comprising:

at least one handheld device arranged to receive said data from at least one of said transmitter, said wireless gateway, and said central server.

25. The system of claim 1 further comprising:

at least one software program executing on said central server for interpreting said data to enable a user to monitor said physical characteristic.

26. The system of claim 1 wherein said first wireless protocol and said at least a second wireless protocol are selected from the group consisting of: short-range radio protocols, WLAN protocols, infrared, PAN protocols, and cellular protocols.

27. The system of claim 26 wherein said short-range radio protocols include Bluetooth protocol, said WLAN protocols include 802.11 and wireless medical transmission standard (WMTS) protocols, and said cellular protocols include CDPD, EDGE, HDR, CDMA, and WCDMA protocols.

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28. A method for communicating data to a central server for processing thereon, said method comprising:

sensing at least one physical characteristic;

generating data representing said at least one physical characteristic;

communicating said data in a first wireless protocol to a wireless gateway;

translating by said wireless gateway from said first wireless protocol to at least a second wireless protocol; and

communicating said data from said wireless gateway to a central server via a communication path, wherein at least a portion of said communication path is in said at least a second wireless protocol.

29. The method of claim 28 further comprising:

using at least one sensor to perform said sensing and said generating steps.

30. The method of claim 29 further comprising:

communicatively coupling said at least one sensor to at least one platform.

31. The method of claim 30 wherein said at least one platform comprises fabric having an information infrastructure integrated therein.

32. The method of claim 31 wherein said fabric is fashioned into a wearable garment.

33. The method of claim 30 wherein said communicatively coupling includes removably coupling said at least one sensor to said at least one platform.

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34. The method of claim 28 further comprising:

using a transmitter to perform said communicating said data to said wireless gateway.

35. The method of claim 28 further comprising:

using a transceiver to perform said communicating said data to said wireless gateway.

36. The method of claim 35 further comprising:

receiving data from said wireless gateway at said transceiver.

37. The method of claim 28 wherein said central server comprises a plurality of processor-based devices communicatively coupled together.

38. The method of claim 28 wherein said central server is a web-based server.

39. The method of claim 28 wherein said communicating said data from said wireless gateway to said central server via a communication path further comprises:

communicating said data from said wireless gateway to at least one intermediary; and

communicating said data from said at least one intermediary to said central server.

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40. The method of claim 39 further comprising:

communicating said data from said wireless gateway to said at least one intermediary in said at least a second wireless protocol; and

communicating said data from said at least one intermediary to said central server in a protocol different from said at least a second wireless protocol.

41. The method of claim 40 wherein said at least a second wireless protocol is selected from the group consisting of WLAN, infrared, PAN, WLAN, and cellular protocol.

42. The method of claim 40 wherein said protocol different from said at least a second wireless protocol is a wireline protocol.

43. The method of claim 40 wherein said protocol different from said at least a second wireless protocol is Internet Protocol.

44. The method of claim 39 further comprising:

said at least one intermediary communicating said data to said central server via a communication network.

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45. The method of claim 44 wherein said communication network is selected from the group consisting of:

public switched telephone network (PSTN), wireless communication network, general purpose processor-based information network, dedicated communication lines, cable system, digital subscriber line (DSL), direct PC to PC connection, local area network (LAN), wide area network (WAN), modem to modem connection, the Internet, an Intranet, an Extranet, or any combination thereof suitable for providing information communication between said at least one intermediary and said central server.

46. The system of claim 39 wherein said at least one intermediary comprises a processor-based device.

47. The method of claim 39 wherein said at least one intermediary comprises a device selected from the group consisting of:

base unit and a packet data gateway within a cellular network.

48. The method of claim 28 wherein said at least one physical characteristic is a characteristic selected from the group consisting of vital sign characteristic and environmental characteristic.

49. The method of claim 48 wherein said vital sign characteristic includes heart rate, breathing rate, blood pressure, pulse, body temperature, and blood oxygen level.

50. The method of claim 48 wherein said environmental characteristic includes temperature, audio, atmospheric smoke and oxygen levels, gas level, light level, air flow, and radiation level.

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51. The method of claim 28 wherein said communicating said data from said wireless gateway to said central server via a communication path comprises:

periodically communicating said data from said wireless gateway to said central server.

52. The method of claim 51 further comprising:

storing said data to a data storage device communicatively coupled to said wireless gateway until said data is communicated from said wireless gateway to said central server.

53. The method of claim 28 further comprising:

determining from said data whether to immediately communicate said data to said central server; and

upon determining to immediately communicate said data, performing said step of communicating said data from said wireless gateway to said central server.

54. The method of claim 53 wherein said determining step comprises:

determining that said data represents a critical physical characteristic.

55. The method of claim 53 wherein said determining step comprises:

determining an abnormality in said data.

56. The method of claim 53 further comprising:

performing said determining step by said wireless gateway.

57. The method of claim 28 further comprising:

selecting said at least a second wireless protocol from a plurality of wireless protocols.

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58. The method of claim 57 further comprising:

performing said selecting step by said wireless gateway.

59. The method of claim 57 wherein said selecting step further comprises:

selecting a wireless protocol that is available for communicating with said central server.

60. The method of claim 57 wherein said selecting step further comprises:

selecting a wireless protocol based on said data.

61. The method of claim 60 wherein said selecting step further comprises:

selecting one wireless protocol if determined that said data represents a critical physical characteristic, and selecting a different wireless protocol if determined that said data represents a non-critical physical characteristic.

62. The method of claim 28 wherein said first wireless protocol and said at least a second wireless protocol are selected from the group consisting of: short-range radio protocols, WLAN protocols, infrared, PAN protocols, and cellular protocols.

63. The method of claim 62 wherein said short-range radio protocols include Bluetooth protocol, said WLAN protocols include 802.11 and wireless medical transmission standard (WMTS) protocols, and said cellular protocols include CDPD, EDGE, HDR, CDMA, and WCDMA protocols.

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64. A system for sensing at least one physical characteristic and communicating data representing said at least one physical characteristic to a central server for processing thereon, said system comprising:

at least one sensor for sensing at least one physical characteristic and outputting data representing said at least one physical characteristic to at least one wireless communication device;

said at least one wireless communication device arranged to communicate said data in at least a first wireless protocol to a wireless gateway that is operable to communicate in a plurality of wireless protocols;

said wireless gateway for translating said data from said first wireless protocol to at least a second wireless protocol and for communicating said data to a central server via a communication path, wherein for at least a portion of said communication path said data is in said at least a second wireless protocol; and

said central server for receiving said data and processing said data.

65. The system of claim 64 further comprising:

at least one platform on which one or more of said at least one sensor is coupled.

66. The system of claim 65 wherein said at least one platform comprises fabric having an information infrastructure integrated therein.

67. The system of claim 66 wherein said fabric is fashioned into a wearable garment.

68. The system of claim 65 wherein said at least one platform provides an information infrastructure to which said at least one sensor can be removably coupled.

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69. The system of claim 65 wherein said at least one platform provides an information infrastructure to which said at least one sensor is permanently coupled.

70. The system of claim 64 wherein said at least one wireless communication device is a transmitter.

71. The system of claim 64 wherein said at least one wireless communication device is a transceiver that is further capable of receiving data.

72. The system of claim 64 wherein said central server comprises a plurality of processor-based devices communicatively coupled together.

73. The system of claim 64 wherein said central server is a web-based server.

74. The system of claim 64 further comprising:

at least one intermediary for receiving data from said wireless gateway and communicating said data to said central server.

75. The system of claim 74 wherein said at least one intermediary is arranged to receive said data from said wireless gateway in said at least a second wireless protocol and communicate said data to said central server in a protocol different from said at least a second wireless protocol.

76. The system of claim 75 wherein said at least a second wireless protocol is selected from the group consisting of WLAN, infrared, PAN, and cellular protocol.

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77. The system of claim 75 wherein said at least one intermediary communicates said data to said central server using a wireline protocol.

78. The system of claim 75 wherein said at least one intermediary communicates said data to said central server using Internet Protocol.

79. The system of claim 74 wherein said at least one intermediary communicates said data to said central server via a communication network.

80. The system of claim 79 wherein said communication network is selected from the group consisting of:

public switched telephone network (PSTN), wireless communication network, general purpose processor-based information network, dedicated communication lines, cable system, digital subscriber line (DSL), direct PC to PC connection, local area network (LAN), wide area network (WAN), modem to modem connection, the Internet, an Intranet, an Extranet, or any combination thereof suitable for providing information communication between said at least one intermediary and said central server.

81. The system of claim 74 wherein said at least one intermediary comprises a processor-based device.

82. The system of claim 74 wherein said at least one intermediary comprises a device selected from the group consisting of:

base unit and a packet data gateway within a cellular network.

83. The system of claim 64 wherein said at least one physical characteristic includes a characteristic selected from the group consisting of vital sign characteristic and environmental characteristic.

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84. The system of claim 83 wherein said vital sign characteristic includes heart rate, breathing rate, blood pressure, pulse, body temperature, and blood oxygen level.

85. The system of claim 83 wherein said environmental characteristic includes temperature, audio, atmospheric smoke and oxygen levels, gas level, light level, air flow, and radiation level.

86. The system of claim 64 wherein said at least a first wireless protocol and said at least a second wireless protocol are selected from the group consisting of: short-range radio protocols, WLAN protocols, infrared, PAN protocols, and cellular protocols.

87. The system of claim 86 wherein said short-range radio protocols include Bluetooth protocol, said WLAN protocols include 802.11 and wireless medical transmission standard (WMTS) protocols, and said cellular protocols include CDPD, EDGE, HDR, CDMA, and WCDMA protocols.

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FIG. 1
(PRIOR ART)

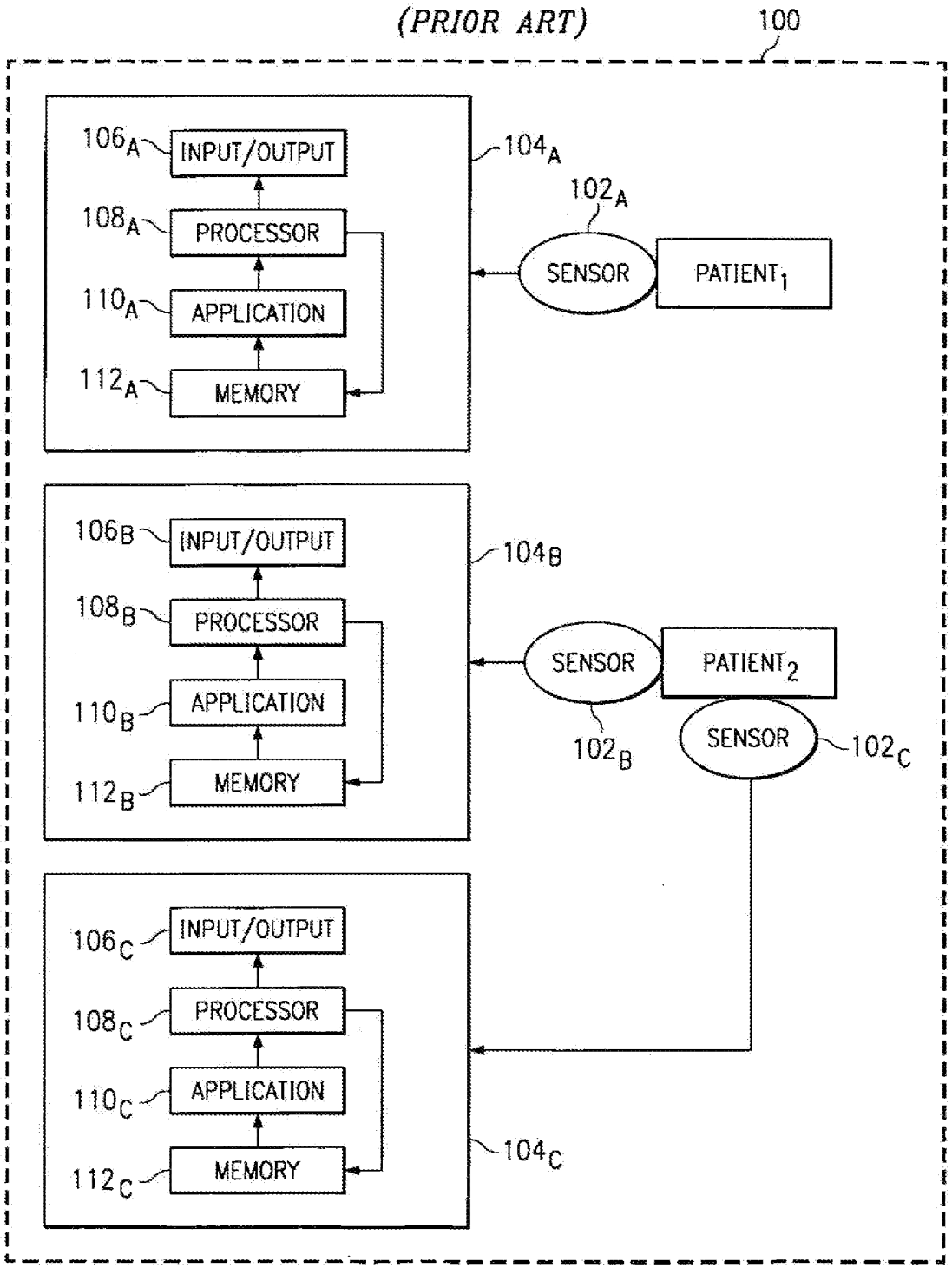


FIG. 2
(PRIOR ART)

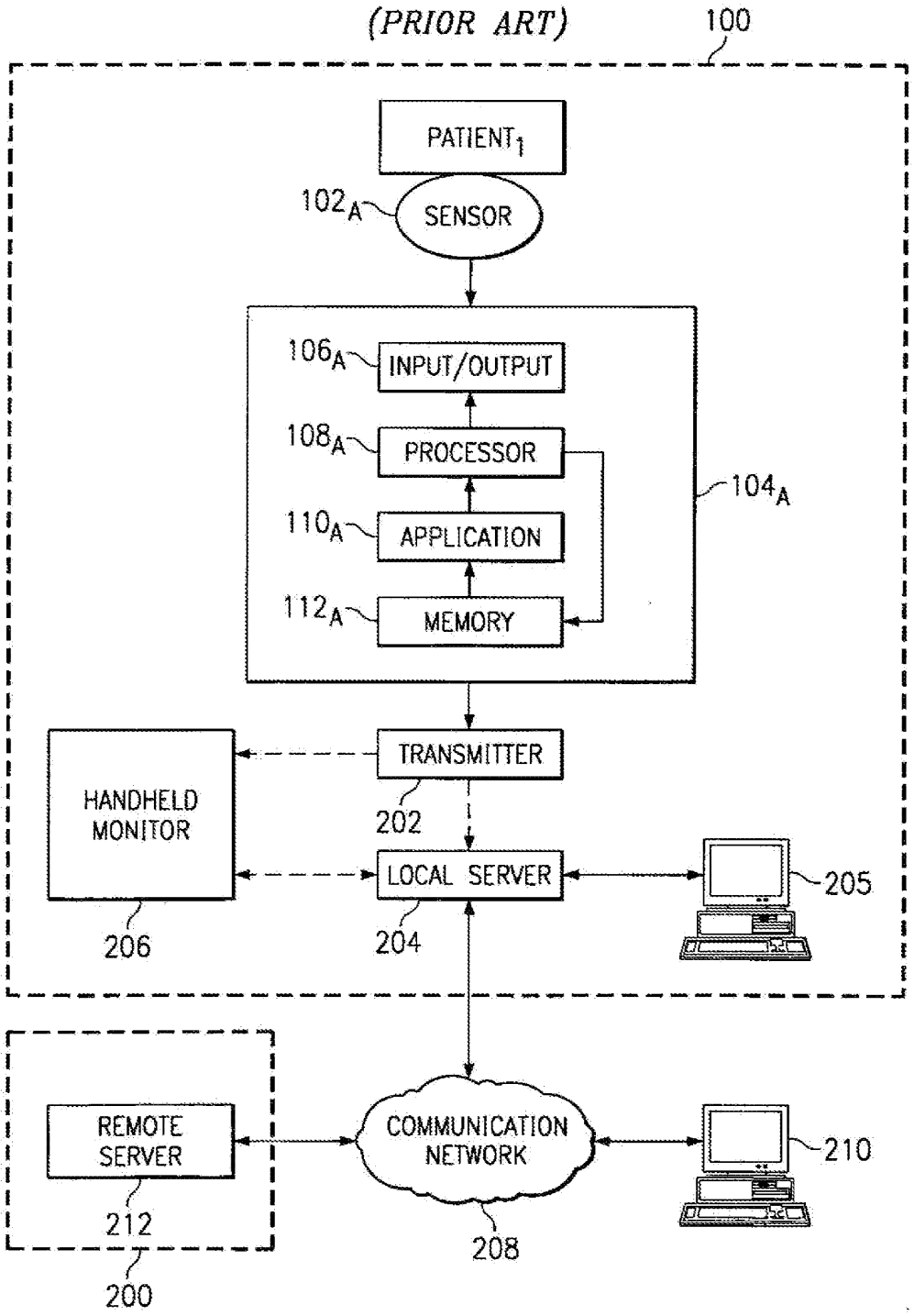


FIG. 3

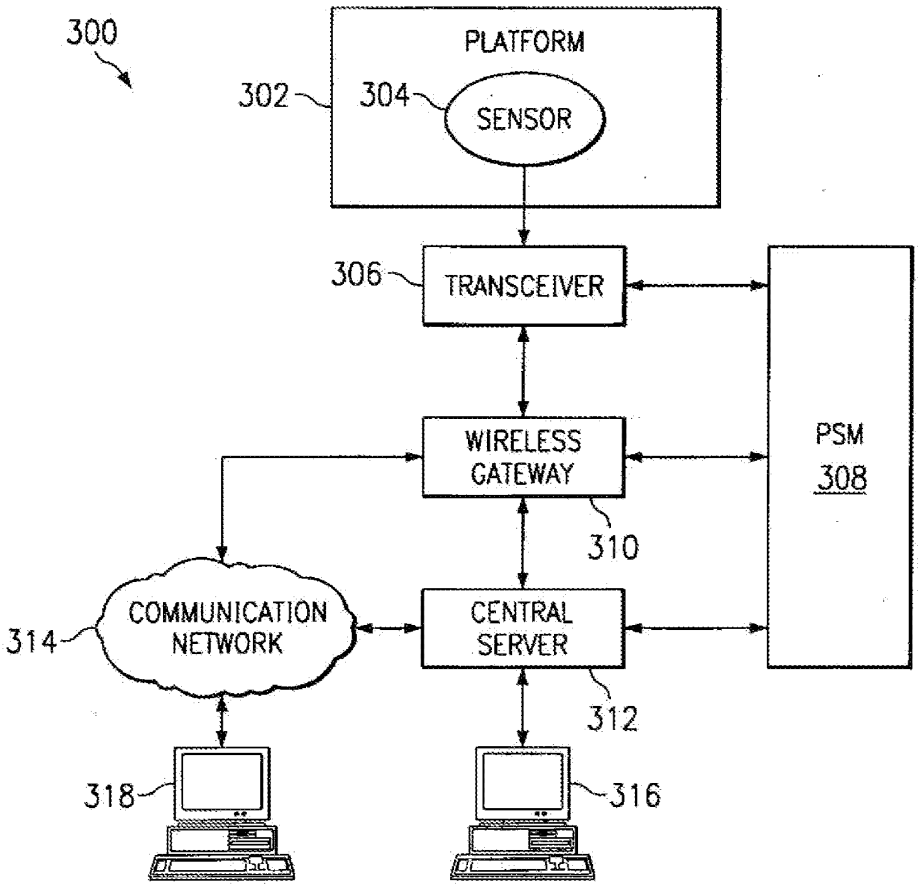

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PLATFORM
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SENSOR
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TRANSCEIVER
WIRELESS GATEWAY
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PSM
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COMMUNICATION NETWORK
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CENTRAL SERVER
312
318
316

FIG. 4

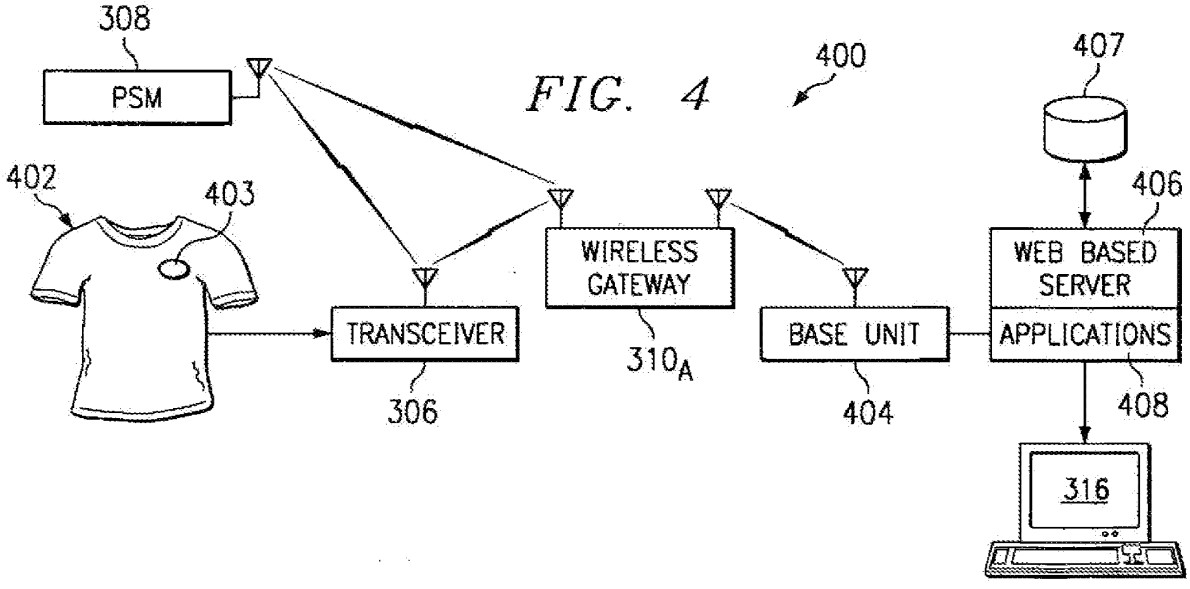

308
PSM
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WIRELESS GATEWAY
WEB BASED SERVER
TRANSCEIVER
BASE UNIT
APPLICATIONS
310A
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404
408
316

FIG. 5

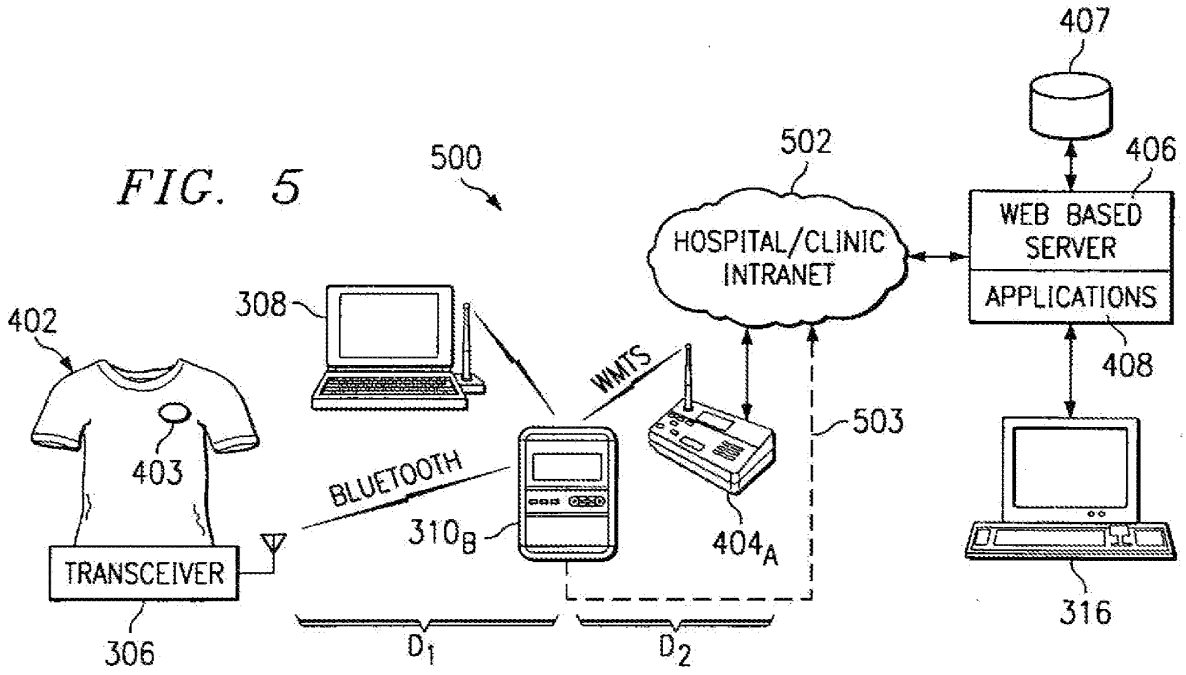

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502
HOSPITAL/CLINIC INTRANET
407
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WEB BASED SERVER
APPLICATIONS
408
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WMTS
503
BLUETOOTH
310_B
404_A
TRANSCEIVER
306
316
D_1
D_2

FIG. 6

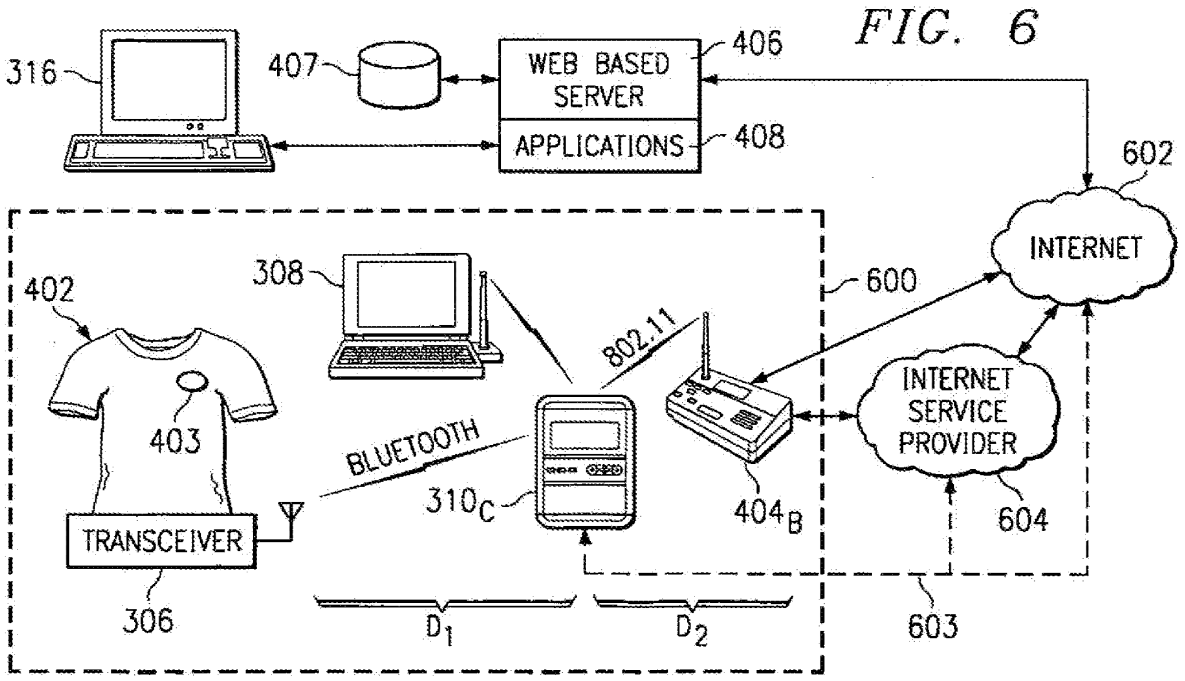

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APPLICATIONS
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INTERNET
600
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403
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D_1
D_2
603

FIG. 7

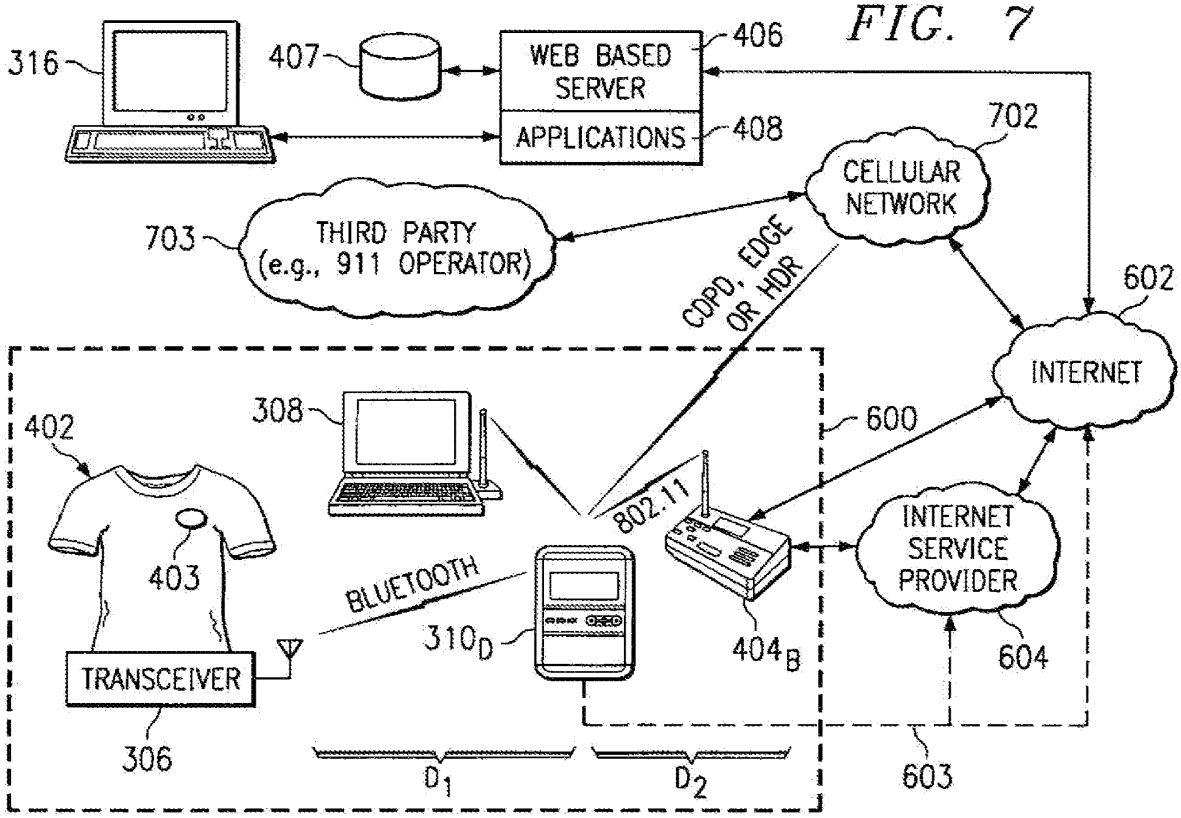
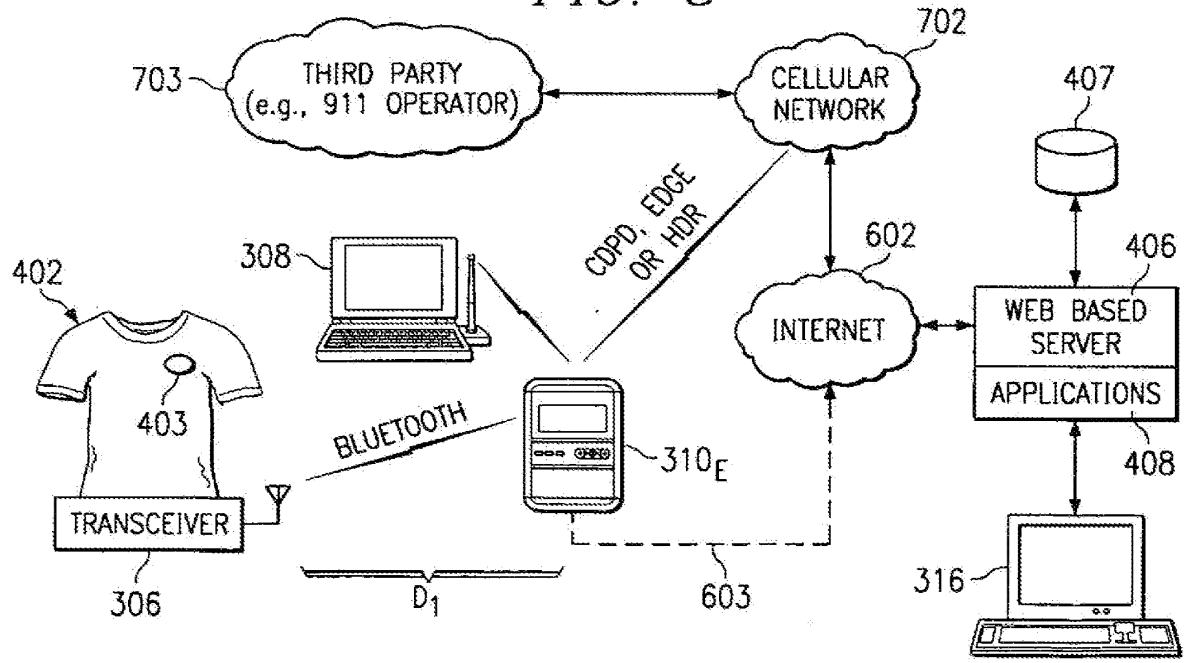

316
407
WEB BASED SERVER
406
APPLICATIONS
408
702
CELLULAR NETWORK
703
THIRD PARTY (e.g., 911 OPERATOR)
CDPD, EDGE OR HDR
602
INTERNET
600
308
402
802.11
403
BLUETOOTH
INTERNET SERVICE PROVIDER
310D
404B
604
TRANSCEIVER
306
D1
D2
603

FIG. 8


703
THIRD PARTY (e.g., 911 OPERATOR)
702
CELLULAR NETWORK
407
CDPD, EDGE OR HDR
602
406
308
402
INTERNET
WEB BASED SERVER
APPLICATIONS
403
BLUETOOTH
310E
408
TRANSCEIVER
316
306
D1
603

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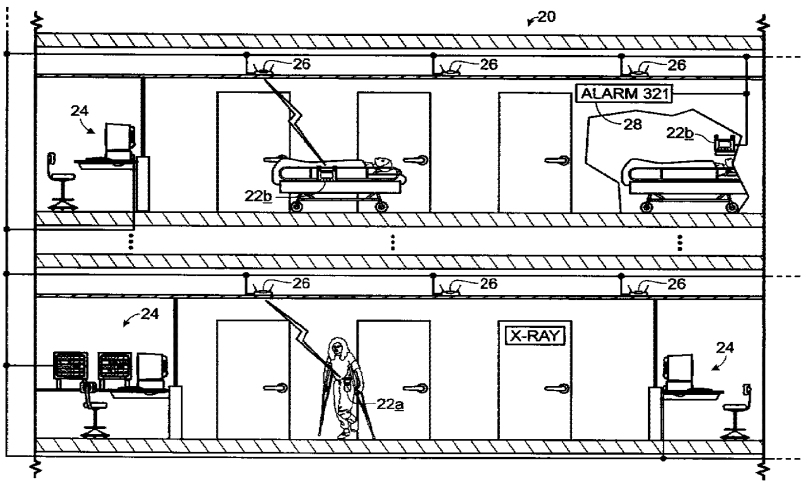
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[Continued on next page]

(54) Title: PATIENT MONITORING SYSTEM



(57) Abstract: A wireless patient monitor is adapted to communicate with any one of plural medical telemetry networks, each having one or more central stations, where each network is configured to communicate via wireless communications using one of multiple different communications settings. The monitor includes one or more sensor inputs for receiving vital signs data from a patient, a wireless transceiver; and a controller coupled to receive the vital signs data via the one or more sensor inputs and to communicate with a network via the transceiver. The monitor also includes a display device and is controllable by the controller to automatically display a notification to a user of the monitor upon establishing communications with the at least one central station. There is also a method of monitoring a patient and a wireless medical telemetry system.

WO 01/89362 A2

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

PATIENT MONITORING SYSTEM

Cross-Reference to Related Applications

This application claims priority to U.S. Provisional Patent Application Serial No. 60/205,412, filed May 19, 2000 and entitled PATIENT MONITORING SYSTEM. The subject matter of this application is incorporated herein by this reference.

Field of the Invention

The present invention relates generally to monitoring the vital signs of one or more patients, and more particularly to a system and method for monitoring patients via wireless communications.

Background

Devices for measuring various physiological parameters, or "vital signs," of a patient such as temperature, blood pressure, heart rate, heart activity, etc., have been a standard part of medical care for many years. Indeed, the vital signs of some patients (e.g., those undergoing relatively moderate to high levels of care) typically are measured on a substantially continuous basis to enable physicians, nurses and other health care providers to detect sudden changes in a patient's condition and evaluate a patient's condition over an extended period of time. However, since most hospitals and other medical facilities care for numerous patients assigned to numerous different rooms, it can be difficult for a finite number of clinicians to monitor multiple patients on a continuous basis. In an effort to alleviate this problem, some medical monitoring systems have been developed to enable the vital signs data collected from patients to be conveyed to a central location, thereby allowing one or a few clinicians to simultaneously monitor multiple patients in different locations. However, many of

such prior systems have not allowed the monitored patients to move about the hospital. Although a few "mobile" monitoring systems have been attempted, such systems are difficult to use and prone to failure resulting in the loss of a patient's vital signs data.

Summary

A wireless patient monitor is adapted to communicate with any one of plural medical telemetry networks, each having one or more central stations, where each network is configured to communicate via wireless communications using one of multiple different communications settings. The monitor includes one or more sensor inputs for receiving vital signs data from a patient, a wireless transceiver configured to transmit and receive wireless communications; and a controller coupled to receive the vital signs data via the one or more sensor inputs and to communicate with a network via the transceiver. The controller is configured, upon initial power-up, to automatically transmit a signal to a local one of the plural networks via the transceiver to request the communications settings used by the local network, and to establish communications with at least one of the central stations on the local network using the communications settings received from the local network without intervention from a user of the patient monitor.

Another version of the invention is a wireless, patient vital signs monitor adapted to communicate with a medical telemetry network having at least one central station. The monitor includes one or more sensor input ports for receiving patient vital signs data, a controller coupled to receive the vital signs data via the one or more input ports, and a wireless transceiver controllable by the controller to communicate

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with the at least one central station. The controller is configured, when not in communication with the at least one central station, to repeatedly attempt to establish communications with the at least one central station via the wireless transceiver. A display device is also included and is controllable by the controller to automatically display a notification to a user of the monitor upon establishing communications with the at least one central station.

Yet other versions of the invention include a wireless, patient vital signs monitor, a method of monitoring a patient and a wireless medical telemetry system. The advantages of the present invention will be understood more readily after a consideration of the drawings and the Detailed Description.

Brief Description of the Drawings

Fig. 1 is a fragmentary, schematic illustration of an exemplary medical telemetry network according to the present invention in the context of a hospital.

Fig. 2 is a fragmentary, schematic diagram of a system for monitoring a plurality of patients in accordance with the present invention.

Fig. 3 is a front elevation view of an exemplary central monitoring station according to the present invention.

Fig. 4 is a schematic diagram of an exemplary system for monitoring patients according to the present invention.

Fig. 5 is a front isometric view of an exemplary patient monitor according to the present invention.

Fig. 6 is a front isometric view of another exemplary patient monitor according to the present invention.

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Fig. 7 is a schematic, functional block diagram of an exemplary patient monitor according to the present invention.

Fig. 8 is an exemplary image for display on a display screen according to the present invention.

Fig. 9 is similar to the image of Fig. 8 but modified to include a message region for display on a display screen according to the present invention.

Fig. 10 is similar to the image of Fig. 8 but modified to include a user-interface for display on a display screen according to the present invention.

Fig. 11 is a flowchart illustrating an exemplary rendezvous process according to the present invention.

Fig. 12 is a flowchart illustrating an exemplary communications configuration process according to the present invention.

Fig. 13 is an exemplary image for display on a display screen, and including a user-interface operable to select a primary central station in accordance with the present invention.

Fig. 14 is an exemplary image for display on a display screen, and including a user-interface operable to confirm a monitoring configuration in accordance with the present invention.

Fig. 15 is an exemplary image for display on a display screen, and including a user-interface operable to identify a patient being monitored in accordance with the present invention.

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Fig. 16 is an exemplary image for display on a display screen, and including a user-interface operable to select a primary central station in accordance with the present invention.

Fig. 17 is an exemplary image for display on a display screen, and including a user-interface operable to change alarm condition parameters in accordance with the present invention.

Fig. 18 is an exemplary image representing ECG data from a single electrode for display on a display screen according to the present invention.

Fig. 19 is an exemplary image representing ECG data from plural electrodes for display on a display screen according to the present invention.

Fig. 20 is an exemplary image indicating an alarm condition for display on a display screen according to the present invention.

Fig. 21 is a schematic illustration of a system for monitoring a patient at plural central stations according to the present invention.

Fig. 22 is a flowchart diagram of an exemplary method for monitoring a patient at a central location in accordance with the present invention.

Fig. 23 is a flowchart diagram of another exemplary method for monitoring a patient at a central location in accordance with the present invention.

Fig. 24 is a flowchart diagram of another exemplary method for monitoring a patient at a central location in accordance with the present invention.

Fig. 25 is a flowchart diagram of another exemplary method for monitoring a patient at a central location in accordance with the present invention.

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Fig. 26 is a flowchart diagram of another exemplary method for monitoring a patient at a central location in accordance with the present invention.

Detailed Description

From an overview, and as will be described in detail below, a system and method for monitoring patients is described that affords communication between plural patient monitors and plural central monitoring stations. The system and method is designed to allow the patient monitors to communicate with the central monitoring stations by using any known communication connection (such as to-be-described access points) located anywhere using any known communications technology (such as the IEEE 802.11 standard for wireless communication) that provides a communication channel. The to-be-described system and method also makes it possible for a clinician to view patient data on a display component of the patient monitor via any known communication channel such as the Internet. For example, the clinician could view patient data using known web browsers.

The to-be described system and method also includes a so-called "rendezvous process" of establishing communications with one or more central stations. As will be shown in connection with the description of Fig. 11, the rendezvous process may be carried out in any of a variety of different ways, and may vary depending on whether wireless or wired communications are used, as well as on whether the patient monitor is establishing a new communications connection or reestablishing prior communications which were lost or terminated.

The patient monitors of the to-be-described system are also constructed to function both as part of a network of patient monitors and central stations, as well as stand-alone patient monitors.

Turning now to details, a system for monitoring patients according to the present invention is indicated generally at 20 in Fig 1. System 20 includes one or more patient monitors 22, each adapted to collect vital signs data from a patient. System 20 also includes one or more central monitoring stations 24 adapted to communicate with the patient monitors and receive, process and store the vital signs data. Thus, physicians, nurses and other health-care personnel (hereinafter referred to collectively as clinicians) are able to monitor a plurality of patients simultaneously and continuously from one or more central locations. As will be described in more detail below, patient monitors 22 and central stations 24 are coupled to communicate using wireless transmissions within a medical telemetry network, thereby allowing a patient to move about inside or outside a monitoring facility without loss of central monitoring.

In the exemplary embodiments shown and described herein, system 20 is configured for use in a hospital. However, it will be appreciated that system 20 also may be used in a variety of other environments including: (i) other types of medical facilities, research facilities, senior-care facilities, hospices, field hospitals, etc.; and (ii) types of non-medical facilities and environments such as patient residences, retail stores, or patient locations outdoors. Therefore, it will be understood that the description herein encompasses medical telemetry systems for use in all such environments.

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System 20 may be configured to provide patient monitoring within selected regions of a facility or throughout the facility. In the exemplary embodiment depicted in Fig. 1, system 20 is configured with patient monitors and central stations on multiple floors of a hospital. System 20 includes one or more wireless transceivers 26 disposed within the facility and configured to communicate with patient monitors 22 via wireless transmissions. The wireless transceivers are configured to convey communications between the patient monitors and the central stations. As a result, centralized patient monitoring will extend wherever wireless transceivers 26 are disposed within a facility.

Transceivers 26 may be also be characterized as transmitter/receivers 26, i.e. any device capable of transmitting and sending communication signals, whether it be a device operable for a wired application or a device operable for a wireless application. However, for purposes of the remainder of the description of the exemplary embodiment, the term transceivers will be used to describe for the wireless application being described.

Each floor may include a single central station (as shown on the upper floor in Fig. 1) or plural central stations (as shown on the lower floor). Alternatively, a single central station may be configured to monitor patients on multiple floors. In many hospitals, central stations 24 are assigned to sections within the hospital that perform different functions rather than to particular floors. For example, one or more central stations may be configured to monitor patients admitted to the Intensive Care Ward, one or more different central stations may be configured to monitor patients admitted to the Emergency Room, while one or more other central stations may be configured

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to monitor patients admitted to the Maternity Ward, etc. Regardless of how the central stations are arranged or assigned, system 20 may be configured to allow any patient monitor 22 to be monitored by any central station 24.

In addition to allowing multiple remote patients to be monitored at a central location, system 20 may also be configured to allow clinicians to view information about a patient's condition from various locations inside and/or outside the hospital. For example, in the embodiment depicted in Fig. 1, system 20 includes one or more annunciating devices 28, each having a display adapted to identify a particular patient (e.g., by name, room number, etc.) and to provide some information concerning the patient's condition. Typically, annunciating devices 28 are used to indicate alarm conditions for a monitored patient. Alternatively, the annunciating devices may be configured to indicate the condition of selected patients regardless of whether an alarm condition exists. In addition to annunciator devices 28, system 20 may also include other devices configured to enable clinicians to monitor a patient's condition at a location remote from either the patient or the central station. These other devices will be described in more detail below.

System 20 may be implemented in many different forms and configurations using various types and combinations of components to provide a variety of features and functions within the scope of the invention. For clarity, the invention will be described below primarily in the context of one particular exemplary embodiment. However, it will be understood that the scope of the invention is not limited to the particular embodiment described, but rather extends to all such embodiments, forms, configurations, types and combinations.

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Turning attention to Fig. 2, a schematic representation of exemplary system 20 is shown. The system includes a medical telemetry network 30 adapted to monitor a plurality of patients. In the exemplary embodiment, network 30 includes a physical data transport structure 32 (also referred to herein as a network) such as an Ethernet Local Area Network (LAN) system. Alternatively, network 30 may be any of the electrical and/or optical network communications structures known to those of skill in the art. Alternatively, physical data transport structure 32 may include any other suitable network structure, including a wireless structure, whether now known or later developed. In any event, physical data transport structure 32 is adapted to interconnect a plurality of network components, and to transmit data communications between the components.

Although not shown in Fig. 2, it will be appreciated by those of skill in the art that physical data transport structure 32 typically will include one or more devices adapted to connect the physical transmission lines together and route communications within the communications structure. Examples of such devices include switches, hubs, bridges, routers, and the like. Thus, as used her herein physical data transport structure 32 includes all such devices which may be necessary and/or beneficial to a particular implementation as well as the physical communication lines.

Communications transmitted within network 30 typically comply with one or more standard data communication protocols which are known to those of skill in the art. As will be described in more detail below, the components of exemplary network 30 use a variety of standard communication protocols including the Transmission Control Protocol/Internet Protocol (TCP/IP) suite, User Datagram Protocol (UDP),

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etc. Use of standard communication protocols allows a variety of different components to be connected to communicate over the network. Furthermore, use of standard communication protocols enables the use of standard routers, switches and other network devices as mentioned above. Alternatively or additionally, the components may communicate using one or more non-standardized protocols adapted for medical telemetry or a particular application.

Network 30 includes one or more central stations 24, each connected to communicate via physical data transport structure 32 and configured to monitor a plurality of patients. It will be appreciated that central stations 24 may take any one or more of a variety of different forms. In the exemplary embodiment, each central station takes the form of a computer workstation configured to communicate via physical data transport structure 32 and monitor a plurality of patients. Central stations 24 may be any suitable type of central station such as the ACUITY® central station available from Welch Allyn Protocol, Inc. of Beaverton, Oregon. The ACUITY® central station is a version of the invention claimed in U.S. Patent No. 5,319,313 to Welch et al.

One example of a central station in accordance with the present invention is shown in Fig. 3. Exemplary central station 24 includes a processing module 34 having at least one processor (not shown) and at least one data storage unit (not shown). The processor is adapted to execute software stored in the data storage unit to communicate with patient monitors, analyze patient data, etc. Central station 24 also includes a plurality of display devices such as display monitors 36. Alternatively, central station 24 may include a single display monitor. In any event, display

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monitors 36 are connected to processing module 34 and adapted to display vital signs data collected from a plurality of patients. Typically, central station 24 also includes one or more input devices 38 (e.g. keyboard, cursor control, mouse, remote control, touch-screen, etc.) operable by a user to control the central station. Central station 24 may also include one or more audio input/output (i/o) devices such as speakers, microphones, sirens, buzzers, etc., adapted to produce an audible message to a user of the central station n. Those of skill in the art will appreciate that central stations 24 may have a variety of different configurations within the scope of the invention.

Central stations 24 are typically disposed at selected centralized locations within the hospital such as at nursing stations, etc. Each central station is adapted to receive patient vital signs data from one or more patient monitors via physical data transport structure 32. The central stations are controllable by a user to display selected information concerning each monitored patient on the display monitor. This allows clinicians to view the information collected by a patient monitor at the centralized location. Additionally, central stations 24 may be configured to simultaneously display data from a plurality of patients, thereby enabling a single clinician to watch over several patients at different locations. In addition to communicating with patient monitors, central stations 24 may also be configured to communicate with other central stations within the network. Thus, for example, patient data received at one central station may be forwarded to a different central station. This allows two or more clinicians at different locations to simultaneously monitor a single patient. Communications among different central stations will be described in more detail below.

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Turning attention back to Fig. 2, network 30 may also include one or more database systems 40 configured to store patient information. Database system 40 is connected to physical data transport structure 32 and accessible by central stations 24 to store and retrieve data. Patient information stored on database system 40 may include a variety of information concerning each patient including personal information, medical history, room location, etc. Typically, the central stations are configured to access database system 40 to identify patients who are admitted to the hospital and display a list of the patients on display monitor 36. This allows a clinician to associate vital signs data received from a particular patient monitor with the corresponding patient. The central station also may be configured to store on database system 40 some or all of the vital signs data received from the patient monitors. While database system 40 is depicted in Fig. 2 as a single, separate system connected to physical data transport structure 32, it will be appreciated that other configurations are also within the scope of the invention. For example, database system 40 may be multiple databases distributed around network 30. Alternatively, database system 40 may be contained within some or all of the central stations. Typically, database system 40 is a system or network of data storage devices, some of which are contained within the central stations and others existing separately in network 30. In any event, it will be appreciated that database system 40 may be any of the various database systems or structures such as are known to those of skill in the art.

As discussed above, central stations 24 are configured to communicate with a plurality of patient monitors via physical data transport structure 32. Communications

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between the central stations and patient monitors may be via wire (i.e., transmitted over a physical line adapted to convey electrical or optical signals), or may be wireless communications. Considering first the wire communications, one or more patient monitors 22 may be connected to physical data transport structure 32 either directly (e.g., through an Ethernet connection), or indirectly through a terminal server 42 or similar device. Terminal server 42 includes a plurality of ports adapted to receive connections from the patient monitors. In addition, the terminal server is also connected to physical data transport structure 32. The terminal server is configured to receive communications from the patient monitors and forward the communications to the appropriate central station via physical data transport structure 32. Similarly, the terminal server also is configured to receive communications from the central stations via physical data transport structure 32 and convey the communications to the appropriate patient monitor. Terminal server 42 may be any of a variety of terminal servers such as are known to those of skill in the art. Any known wire or wireless communication technologies may be used to perform the functions described above.

In TCP/IP based networks, communications between central stations and patient monitors are directed to the appropriate component using network addresses such as IP addresses as well as hardware addresses. Typically, each central station is assigned a unique IP address and all communications to and from a particular central station will include the particular station's IP address. Similarly, all patient monitors which are directly connected to physical data transport structure 32 are assigned a unique IP address. In contrast, patient monitors which are connected to physical data transport structure 32 through a terminal server typically do not have a unique IP

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address. Instead, the terminal server has an IP address with which to communicate with the other components connected to physical data transport structure 32. Communications from a patient monitor are transmitted to the terminal server with the IP address of the destination component (e.g., a central station). The terminal server appends its own IP address to each communication and then forwards the communication to the appropriate component. Similarly, communications to a patient monitor are transmitted with the terminal server's address as the destination address. Upon receipt, the terminal server forwards the communications to the appropriate patient monitor.

As shown in Fig. 2, network 30 also includes one or more wireless transceivers 26, which are hereinafter referred to as access points 26. Each access point is connected to physical data transport structure 32 and configured to communicate with the other components connected to physical data transport structure 32. Each access point includes the software necessary to communicate via physical data transport structure 32 using the selected communications protocols of network 30 (e.g., TCP/IP, UDP, etc.). In the exemplary embodiment, each access point has a unique IP address that may be permanently coded into the access point, or may be assigned by a server such as described below. The access points also are configured to communicate, via wireless transmissions, with components which are not directly connected to physical data transport structure 32. Each access point includes a wireless receiver to receive wireless communications, and a wireless transmitter to transmit wireless communications.

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It will be appreciated that access points 26 may be configured to communicate using any of a variety of different wireless transmission technologies depending on the application, environment, governmental regulations, etc. In the exemplary implementation, the access points are configured to communicate with the patient monitors (described in more detail below) as well as other devices under the IEEE 802.11 standard using Frequency Hopping Spread Spectrum (FHSS) technology in the 2.4 GHz ISM (Industrial, Scientific, and Medical) band. The IEEE 802.11 communications standard is well known to those of skill in the art. Access points 26 essentially act as network bridges between the wireless components of network 30 and wired network physical data transport structure 32. Other wireless transmission, or communication, technologies known to those skilled in the art may be used including IEEE 802.11a, IEEE 802.11b, and IEEE 802.15.

Exemplary access points 26 may be any wireless transceivers adapted to communicate using the IEEE 802.11 FHSS technology. One example of a suitable access point is the SPECTRUM24 AP 3021 available from Symbol Technologies of Holtsville, New York. In other implementations and embodiments, access points 26 may be selected which are configured to communicate using other technologies. In any event, the access points usually are configured to simultaneously communicate with a plurality of patient monitors and/or other wireless devices. For example, the AP 3021 access points are adapted to simultaneously communicate with up to approximately 15 patient monitors.

Each access point typically has a range within which it can communicate with wireless devices. The range will vary depending on the power of the wireless

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transmitter, environmental conditions, etc. Typically, the access points are arranged within the hospital so that at least one access point is able to communicate with a patient monitor at any point within a defined region of the hospital. For example, if it is desired that wireless patient monitors be used on a particular floor of the hospital, then sufficient access points are provided and positioned so that every location on the particular floor is within the range of one or more access points. This ensures that a patient associated with a patient monitor can move about the hospital floor without loss of central monitoring. It will be understood that the access points may be arranged to provide wireless coverage within a defined region that is less than an entire floor of the hospital. Alternatively, the access points may be arranged to provide coverage for regions that span multiple floors (whether or not adjacent) and/or multiple buildings.

As will be discussed in more detail below, patient monitors and other wireless devices communicate over physical data transport structure 32 by first associating with an access point. Once a patient monitor has associated with a particular access point, communications between the patient monitor and components on physical data transport structure 32 are conveyed by the particular access point. However, as the patient monitor moves out of range of the particular access point and into the range of another access point, the patient monitor associates with the other access point and subsequent communications between the patient monitor and components on physical data transport structure 32 are conveyed by the other access point.

Use of FHSS technology allows access points to be positioned so that the ranges of the access points overlap. Such an arrangement provides for geographic

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redundancy in the event an access point fails. In addition, overlapping the access point ranges increases the monitoring capacity within the defined region or selected portions of the defined region. The access points typically are configured to communicate with one another to minimize or prevent interference. The access points may also be configured to manage and balance the communication loads experienced by each access point. In addition, one or more of the central stations may be configured to control the access points to balance communication loads.

It will be appreciated that in many implementations the communication of patient information by wireless transmission must be secure and confidential. These security needs may be met in any of a variety of ways known to those of skill in the art. For example, the 802.11 standard provides WEP (Wired Equivalent Privacy) which encrypts the wireless transmissions. In addition, some implementations may utilize additional security measures such as end-to-end data encryption, etc.

In the exemplary embodiment, network 30 also includes a router 44 or similar device connected to physical data transport structure 32 between a first portion 46 and a second portion 48 of physical data transport structure 32. Components connected to the first portion are assigned IP addresses corresponding to a first subnet, while components connected to the second portion are assigned IP addresses corresponding to a second subnet. First portion 46 is connected to central stations 24, database system 40, terminal server 42 and the other components of network 30 which are configured for wired communications via physical data transport structure 32. Second portion 48 is connected to access points 26. Thus, first portion 46 may be seen as a wired portion of network 30, while second portion 48 may be seen as a wireless

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portion of network 30. Use of router 44 between wired portion 46 and wireless portion 48 allows the wireless portion of the network to be isolated from the communication traffic on the wired portion of the network. Communications between patient monitors and central stations are passed by router 44 from wired portion 46 to wireless portion 48 and vice versa. However, communications between central stations and/or other components connected to wired portion 46 are not passed to wireless portion 48. Alternatively, wired portion 46 and wireless portion 48 may be directly connected to the same subnet, eliminating the need for a router.

In the exemplary embodiment, network 30 also includes at least one server system 50 connected to the wireless portion of the network. As will be discussed in more detail below, server system 50 is adapted to assign IP addresses to the patient monitors once the patient monitors associate with an access point. Server system 50 may be configured to assign IP addresses according to any suitable protocol such as the Dynamic Host Configuration Protocol (DHCP), the Bootstrap Protocol (BOOTP), etc. It will be appreciated that server system 50 is connected on the wireless portion of physical data transport structure 32 relative to router 44 to ensure that requests for IP addresses from the patient monitors are received at server system 50. Alternatively, router 44 may be configured to convey the requests for IP addresses between the wireless and wired portions, in which case server system 50 may be connected on the wired portion of the network.

Server system 50 may be a separate computer system adapted to manage and assign IP addresses only, or it may be configured to perform other functions including network management, etc. In alternative embodiments, one of central stations 24 is

configured to perform the functions of server system 50, thereby alleviating the need for a separate server system 50. In such embodiments, the central station which is configured to assign IP addresses in the alternative embodiment should be connected to the wireless portion of network 30 unless router 44 is adapted to pass requests for an IP address to the wired portion of the network.

Network 30 may also include one or more wireless communication devices referred to herein as clinician terminals 52. The wireless clinician terminals may take any one of a variety of different forms including Personal Digital Assistants (PDA's), Internet Protocol (IP) telephones, portable computers, etc. Clinician terminals 52 include wireless transceivers (e.g., RF network cards) that are configured to associate with access points 26. The clinician terminals also include suitable software executable by the terminals to communicate with the central stations via access points 26. The clinician terminals may also be configured to perform a variety of functions such as receiving and displaying patient vital signs data from the central station, transmitting control instructions to the central station to control a selected aspect of the central station, transmitting control instructions to the central station for forwarding to a patient monitor to control selected aspects of the patient monitor, sending and receiving textual messages, receiving and acknowledging alarm signals, etc. In the exemplary embodiment, clinician terminals 52 are configured to function as quasi-central stations, by displaying patient vital signs data and providing a user-interface operable by the clinician to control the patient monitor.

Clinician terminals 52 enable physicians, nurses and others to obtain information concerning a patient from any location within the defined region of

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network 30, rather than only at the patient's location or at a central station. Thus, for example, a clinician several floors away from a patient can receive a notification of an alarm at the patient monitor associated with the patient. Further, the clinician can evaluate the patient's condition from the vital signs data without going to the patient's location. The clinician may then take appropriate action depending on the patient's condition. It will be appreciated that clinician terminals 52 enable clinicians to work more efficiently and effectively, and to care for a larger number of patients than would otherwise be possible. Furthermore, while the clinician terminals may include paging functions, the clinician terminals provide substantially more information to the clinicians than pagers.

Exemplary telemetry network 30 also is connected to the main computer network 54 of the hospital, referred to hereinafter as the secondary or non-telemetry network. Secondary network 54 typically includes a plurality of computer terminals 56, database systems 58, etc. The secondary network interconnects the hospital's administrative computers and other non-telemetry components. Typically, secondary network 54 is connected to telemetry network 30 through router 44. This isolates the telemetry network from non-telemetry communication traffic, while allowing devices connected to the non-telemetry network to access patient vital signs data. Similarly, users of central stations 24 are able to access information on the secondary network as needed. In some implementations it may be desirable to provide security measures to ensure that only authorized users of secondary network 54 are able to access telemetry network 30. Any of a variety of suitable security measures may be employed as are known to those of skill in the art.

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Network 30 may also be connected to a communications network external to the hospital such as an extranet, virtual private network, Wide Area Network (WAN), etc. In the exemplary implementation, network 30 is connected to the Internet 60. Typically, network 30 is connected to the Internet via a firewall 62 or other suitable security device to restrict access to patient data and other confidential information.

As shown in Fig. 4, the telemetry network of one hospital 64 may be connected to the telemetry network and/or the secondary network of one or more other hospitals 66 in remote locations. The telemetry network may be connected to the remote hospitals via Internet 60 or via a direct, non-public network 68 such as is known to those of skill in the art. Central stations 24 of hospital 64 may be configured to transmit patient information including vital signs data to central stations or other computers in remote hospital 66. Similarly, the central stations of hospital 64 may be configured to request and receive patient information including vital signs data from remote hospitals 66. It will be appreciated that communication of patient information between remote hospitals allows clinicians to participate in consultations with their remote colleagues more effectively and efficiently.

In the implementation described above, access points 26 were arranged within the hospital to provide wireless monitoring in a defined region of the hospital. In alternative implementations, the defined region may extend outside the hospital. For example, system 20 may include one or more access points 26 which are positioned outside of the hospital, as shown in Fig. 4. The access points are connected to Internet 60 and configured to transmit the patient vital signs data to network 30 and one or more central stations 24. This allows patients to move outside of the hospital without

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loss of continuous central monitoring. So long as the patient remains within the range of at least one access point, the patient's vital signs data may be displayed on a central station as if the patient was still in the hospital. Similarly, emergency response workers could connect a patient monitor to an accident victim so that the hospital can monitor the victim's condition while the victim is transported to the hospital.

It will be appreciated that placement of access points outside of the hospital also allows clinicians to access patient data when outside the hospital. As shown in Fig. 4, one or more clinician terminals 52 may associate with the external access points to view patient information and control the patient monitor connected to a patient. This provides clinicians with more flexibility to leave the hospital while continuing to monitor their patients at the hospital (or patients outside the hospital). Alternatively, clinicians may monitor patients using personal computers 70 or similar devices configured to connect to Internet 60 and communicate with central stations at the hospital. Computers 70 may be located anywhere a connection is available that provides a communication channel using any communication technology. For example, computers 70 may be located anywhere a connection to the Internet is available. Alternatively, computers 70 may be configured to associate with an external access point and communicate via wireless transmissions.

As discussed above, the defined region of monitoring will extend outside the hospital wherever access points 26 are positioned. In areas where the external network of access points is undeveloped, patient monitors 22 and/or clinician terminals 52 may be configured to communicate using other wireless communication technologies. For example, the implementation depicted in Fig. 4 includes a Cellular

Digital Packet Data (CDPD) network 72, such as is currently used for cellular telephone and other communications. Patient monitors 22 and/or clinician terminals 52 may be configured to communicate with central stations in hospital 64 via CDPD network 72. Thus, for example, a patient might be discharged to go home while continuing to be monitored. It will be appreciated that this alleviates the need to have new wireless networks installed throughout a geographic region, since the components of system 20 are configured to communicate using preexisting networks. An alternate implementation (undepicted) would be to use what is known as a Global System Mobile (GSM), or any other available wide-reaching communication system.

Considering patient monitors 22 in more detail, it will be appreciated that there are a variety of different patient monitors available and suitable for use with system 20. System 20 may include one or more patient monitors of a single type, or may include multiple types of patient monitors, each configured to communicate with one or more central stations. For example, the exemplary embodiment of system 20 depicted in Figs. 1 and 2 includes a first type of patient monitor 22a adapted to be carried or worn by a patient, and a second type of patient monitor 22b adapted to be mounted on a bed, wheelchair, etc, as well as being carried. Patient monitors 22a and 22b may be configured to perform the same monitoring functions or may be configured to perform different monitoring functions. In any event, each type of patient monitor 22 is configured to collect vital signs data from a patient and communicate at least a portion of the vital signs data to a central station via physical data transport structure 32. Suitable patient monitors are available from several

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manufacturers, including the MICROPAQ and PROPAQ patient monitors available from Welch Allyn Protocol, Inc. of Beaverton, Oregon.

Turning attention now to Fig. 5, exemplary patient monitor 22a is shown in more detail. The monitor includes a portable housing 80 having one or more sensor input ports 82. The housing is sized to be held by a clinician or patient, or to be worn by the patient using a strap, belt, or similar device. Sensor input ports 82 are adapted to receive and connect to sensor cables 83. Each cable 83 is attached to one or more sensor assemblies (not shown). The sensor assemblies may include any vital signs sensor assembly adapted to detect and/or measure selected vital signs data from a patient and transmit the vital signs data via cables 83. Examples, of suitable sensor assemblies include electrocardiogram (ECG) sensor assemblies, non-invasive blood pressure sensor assemblies, invasive blood pressure sensor assemblies, temperature sensor assemblies, pulse oximetry sensor assemblies, respiration sensor assemblies, carbon dioxide sensor assemblies, etc. Suitable sensor assemblies are available from Welch Allyn Protocol, Inc. of Beaverton, Oregon. In any event, each sensor input port is adapted to receive patient vital signs data from the sensor assembly attached thereto.

Patient monitor 22a also includes a display device such as display screen 84 adapted to display the vital signs data or an image representative of the vital signs data. Exemplary display screen 84 is in the form of a liquid crystal display (LCD) device. Alternatively or additionally to display screen 84, patient monitor 22a may include any other suitable display device such as a printer, one or more indicator lights, light-emitting diodes, etc. The patient monitor also includes one or more input

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devices such as buttons 86 disposed on housing 80. Buttons 86 are operable by a user to input information into patient monitor 22a, as will be discussed in more detail below. In addition to, or in place of buttons 86, the patient monitor may include other types of input devices including switches, knobs, etc. As a further alternative, display screen 84 may be a touch-screen adapted to input information in response to contact by the user at selected locations on the screen. While the exemplary embodiment will be described below as having input devices in the form of buttons, it will be understood that any type of input device may be used.

Exemplary patient monitor 22a further includes a battery assembly 88 having one or more batteries. Battery assembly 88 is mountable in a battery compartment within housing 80. The batteries typically are rechargeable, however non-rechargeable batteries may also be used. Although not shown in Fig. 5, patient monitor 22a also includes a controller, a memory device, and an on-board wireless transceiver, all operably disposed within portable housing 80. An internal antenna 90 is mounted within the housing and coupled to the wireless transceiver. Alternatively, antenna 90 may be disposed externally to housing 80. An audio input/output device 92, (e.g., speaker, microphone, buzzer, siren, etc.) is also disposed within the housing and adapted to produce an audible notification to a clinician, patient, or other user of the monitor. An alternative to the input/output device would be a bi-directional audio device.

As shown in Fig. 6, exemplary patient monitor 22b includes a portable housing 94 adapted to attach to a bed, wheelchair or other support structure. Housing 94 includes one or more sensor input ports 82 adapted to connect to sensor cables 83 and

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receive vital signs data from one or more sensor assemblies (not shown). Similar to patient monitor 22a, patient monitor 22b includes a display device such as display screen 84 and one or more input devices such as buttons 86. Although not shown in Fig. 6, patient monitor 22b also includes a battery assembly 88, an antenna 90, and an audio output device 92. As will be described in more detail below, patient monitor 22b also includes a controller, a memory device and an on-board wireless transceiver, all operably disposed in housing 94.

Unlike patient monitor 22a, patient monitor 22b includes an output port 96 adapted to receive a hard-wired network connection cable 98 such as an Ethernet, RS-232, modem line, or similar network communications cable for connection to physical data transport structure 32 or terminal server 42. Thus, patient monitor 22b is configured to communicate with central stations 24 using either wireless communications via its on-board wireless transceiver, or wire communications via output port 96. As will be discussed in more detail below, patient monitor 22b may be configured to automatically switch between wire and wireless communications in various situations.

As mentioned above, each patient monitor 22 includes a controller disposed within the portable housing. It will be appreciated that any of a variety of different computer controllers, micro-controllers, or processors, such as are known to those of skill in the art, may be used. The controller, indicated at 100 in Fig. 7, is operably coupled to receive power from battery assembly 88. The controller may also be configured to receive power from other sources (e.g., AC line current through a wall socket, DC current through photovoltaic cells, etc.).

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Controller 100 is also connected to memory device 102. It will be appreciated that memory device 102 may be any one or a combination of devices adapted to store electronic information such as RAM, ROM, PROM, EPROM, etc. Memory device 102 may also include removable storage media such as magnetic discs and tapes, optical discs, etc. In addition to storing patient vital signs data, memory device 102 may be configured to store one or more software control programs executable by controller 100 to perform its various functions including receiving and analyzing vital signs data, presenting information to a user, etc. In addition, the software will include the necessary programs for communicating with central stations 24 (e.g., TCP/IP, DHCP, etc.) While memory device 102 has been depicted as a single device, those of skill in the art will appreciate that memory device 102 may be a plurality of either similar or different memory devices.

Controller 100 is also coupled to sensor ports 82 and configured to receive vital signs data from the sensor assemblies via the sensor ports. In addition, controller 100 may be configured to supply power and/or suitable drive signals onto one or more of the sensor ports to drive the sensor assemblies attached to the ports. In any event, vital signs data received at controller 100 may be stored in memory device 102, processed, discarded, and/or communicated immediately to a central station.

The controller is connected to control wireless transceiver 104 and communicate with central stations 24 via the transceiver. Wireless transceiver 104 may be any of a variety of wireless transceivers which are known to those of skill in the art. One example of a suitable wireless transceiver is the SPECTRUM24 LA 3021 PC card, available from Symbol Technologies of Holtsville, New York.

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Alternatively, other wireless transceivers may be used. In any event, wireless transceiver 104 is configured to communicate with access points 26 using the appropriate communications protocol of network 30. The wireless transceiver is connected to antenna 90 and transmits data received from controller 100 to access points 26. Similarly, the wireless transceiver receives transmissions from one or more access points and forwards the communications to the controller. The wireless communications between patient monitor 22 and the central stations will be discussed in more detail below.

In the case of patient monitor 22b, controller 100 is also connected to output port 96 and configured to communicate with central stations 24 via the output port rather than via wireless transceiver 104. Controller 100 may also include a network card or similar device (not shown) adapted to transmit and receive communications via output port 96. For clarity, the description below assumes that patient monitor 22 communicates with central stations 24 via wireless transceiver 104. However, it will be understood that, unless stated otherwise, and for purposes of this description, communications via output port 96 are viewed as identical to communications via the wireless transceiver, and therefore both types of communications are included within the description. A distinction between wireless and hard-wired communication is that patient location (room) is known with hard-wired communication (via the network jack to which the monitor is connected) and not known with wireless communication. However, for purposes of this description, that distinction is not seen as pertinent and that is why communications via output port 96 are viewed as identical to communications via the wireless transceiver.

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Controller 100 is also connected to receive inputs from buttons 86. The buttons are operable by a user of the patient monitor to input information to the controller, as well as to control the controller. Each button may have a single function or may have a variety of functions depending on such factors as the operating condition of the controller, status of the sensor assemblies, communications with a central station, screen displays, etc. In the exemplary embodiment, controller 100 is configured to control the function of buttons 86 and to disable the buttons under defined conditions.

Controller 100 is configured to control display screen 84 to display an image representing the vital signs data. It will be appreciated that the image displayed on display screen 84 will vary depending on the vital signs data collected by the patient monitor. Additionally, exemplary controller 100 is configured to change the display based on instructions received from the user via buttons 86. For example, the user might select between displaying a single ECG signal from a single electrode, or multiple ECG signals from multiple electrodes. Fig. 8 shows an exemplary display screen 84 on which vital signs data is being displayed. A waveform region 106 of the display shows an image representing the signal data received from an ECG sensor assembly. A numeric region 108 of the display shows images that provide numerical representations of the vital signs data (e.g., heart rate, oxygen saturation in the patient's blood, etc.). The display may also include a patient identifier 110 that uniquely identifies the patient, such as the patient's name, etc. Fig. 9 shows another exemplary display screen 84 similar to the one in Fig. 8. However, the display screen shown in Fig. 9 has been changed to include a message region 112 for displaying messages to a user. Similarly, Fig. 10 shows another exemplary display screen 84 in

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which the image has been changed to include a user-interface region 114. The user-interface region allows a user to enter information and control the patient monitor by operating buttons 86. Control of the display screen will be described in further detail below.

Controller 100 is also connected to control audio output device 92 and/or other audible indicator devices to produce audible messages or signals. The controller may be configured to control the audio output device to produce audible signals under any one or more of a variety of conditions. For example, controller 100 is typically configured to analyze at least some of the vital signs data and produce an audible alarm if the vital signs data is outside a selected nominal range. The analysis of vital signs data and detection of alarm conditions will be described in further detail below.

While one exemplary functional embodiment of patient monitors 22 has been depicted in Fig. 7 and described above, it will be appreciated that many other configurations are possible. Thus, the invention is not limited to the exemplary embodiment described, but includes any patient monitor configuration adapted to collect vital signs data from a patient and communicate the vital signs data to one or more central stations.

Typically, patient monitors 22 are configured to function as stand-alone devices capable of providing local patient monitoring regardless of whether the patient monitor is in communication with a central station. The patient monitor may be configured to begin monitoring immediately upon power-up and attachment of at least one sensor assembly. Alternatively, the patient monitor may be configured to begin monitoring upon receipt of an actuation signal.

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Patient monitors 22 are also configured to attempt to establish communications with one or more central stations and communicate the vital signs data to the central stations. In the exemplary embodiment, the patient monitors are configured to attempt to establish communications immediately at power-up and to continue the attempt until communications are established. Alternatively, one or more of the patient monitors may be configured to attempt to establish communications only in response to an instruction by a user and/or the occurrence of selected conditions. Those of skill in the art will appreciate that the process of establishing communications with one or more central stations, also referred to herein as the rendezvous process, may be carried out in any of a variety of different ways. In addition, the rendezvous process may vary depending on whether the patient monitor is communicating through wireless or wire communications, as well as on whether the patient monitor is establishing a new communications connection or reestablishing prior communications which were lost or terminated.

The rendezvous process of the exemplary embodiment is schematically illustrated in Fig. 11. The process begins with establishing a connection to physical data transport structure 32 by any one of several methods. Where patient monitor 22 is configured to communicate using only wireless communications, the patient monitor establishes a connection to physical data transport structure 32 by associating with an access point, as indicated at 200. It will be appreciated that the process of associating with an access point may vary with varying configurations of the access point and/or varying configurations of the patient monitor. In the exemplary embodiment, wireless transceiver 104 associates with a patient monitor according to

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the IEEE 802.11 standard, and the details of that standard are known to those skilled in the art. Certain features of the exemplary embodiment include that (i) the patient monitors can be used in any telemetry network described herein (such as the 802.11-standard telemetry network) without user-adjustment of the communications frequency, and (ii) the patient monitors automatically scan for access points and detect access-point configuration and synchronization information.

In addition, the wireless transceiver determines which access points are within range of the patient monitor, and the current communications load on the in-range access points. Using this information, the patient monitor selects one of the in-range access points with which to communicate, and begins the authentication process which is followed by the association process. Once the authentication and association processes are complete, the connection between the patient monitor and physical data transport structure 32 is established.

In the exemplary embodiment where communications over network 30 conform to the IP protocol, each device must have an associated IP address with which to send and receive communications. In some embodiments, patient monitor 22 may have a permanently assigned IP address stored in memory device 102. Alternatively, patient monitor 22 may not have an assigned IP address, and instead may be configured to request an IP address upon establishing a connection with physical data transport structure 32, as indicated at 202 and 204. Typically, patient monitor 22 requests an IP address by transmitting a broadcast request to server 50 using the appropriate protocol (e.g., DHCP, BOOTP, etc.). The request is answered by server 50, which responds by assigning the patient monitor an IP address from a

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store of available IP addresses, and then transmitting a notification of the assignment to the patient monitor. Alternatively, server 50 may store a pre-assigned IP address for each device, and respond with the corresponding pre-assigned IP address. Upon receiving the assigned IP address, the patient monitor is prepared to broadcast a request for communications to one or more central stations, as will be described in more detail below.

Where patient monitor 22 is adapted to communicate using either wireless or wire communications, the process for establishing a connection to physical data transport structure 32 will vary depending on whether a wireless or wire connection is established. In the former case, the process may occur as described above, i.e., first associating with an access point, and then requesting an IP address if necessary. Alternatively, if a wire connection is to be established, the patient monitor may be physically connected to a terminal server which is connected to the network, as indicated at 206. It will be appreciated that the connection indicated at 206 may alternatively take other forms, such as a modem connection to a modem server, etc. In any case, once the connection is established and any necessary hand-shaking between the patient monitor and the terminal server is completed, the patient monitor is prepared to broadcast a request for communications to one or more central stations. Patient monitor 22 will communicate using the IP address of the server, and therefore is not required to have its own IP address.

As a further alternative, the patient monitor may be directly connected to a hard-wired connection on physical data transport structure 32 with an Ethernet or similar connection technology, as indicated at 208. As with a patient monitor that is

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connected to communicate using wireless communications, a patient monitor directly connected to physical data transport structure 32 may have a permanently assigned IP address, or may request the assignment of an IP address once the physical connection is established. In any event, in the hard-wired implementation, the terminal server is then prepared to initiate a request for communications to one or more central stations.

Regardless of how a patient monitor establishes a connection with physical data transport structure 32, the patient monitor must then establish communications with a central station by broadcasting a request for communications to the central station, as indicated at 210. It will be appreciated by those of skill in the art that a patient monitor may broadcast a request for communications in any of a variety of ways. In the exemplary embodiment, the patient monitor transmits the request as a UDP broadcast to all central stations. Alternatively, other communication protocols may be used.

The UDP communications request may include a variety of parameters adapted to inform the central station about the patient monitor. For example, communications requests typically include such information as the identity, type, and/or capabilities of the patient monitor, the IP and MAC (Media Access Control) addresses of the patient monitor, the version of software installed on the patient monitor, etc. The request may also include an indicator of the type of communications desired. For example, the patient monitor may request communications to establish central monitoring of a patient, download newer versions of the patient monitoring software (discussed in more detail below), or perform network maintenance, etc. This information allows the central station to determine how to respond to the request. Unless stated otherwise,

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the description below will assume that the patient monitor's communications request is for the purposes of establishing centralized monitoring of a patient.

In the exemplary embodiment, the communications request is passed to, and received by, all central stations of network 30, as indicated at 212. Any routers or other network devices connected to physical data transport structure 32 are configured to pass on the request to the central stations as necessary. Alternatively, the request may be conveyed to fewer than all of the central stations, or to a single central station. Each central station is configured to respond to the communications request when received. Upon receiving the first response the patient monitor transmits an acknowledgement to the central station that sent the first response. The patient monitor is configured to reject subsequent responses by transmitting a "reject" message to any central station that sends a subsequent response. The central stations are configured to cease sending responses to the communications request after receiving a "reject" message, unless a new request for communications is received.

In some embodiments, the central stations may be configured to ensure that a preferred central station responds to the communications request. For example, the central stations may be configured to recognize a patient monitor that has communicated with network 30 in the past (e.g., based upon information transmitted in the communications request), and to allow the particular central station that was previously in communication with the patient monitor to respond first. Thus, in the exemplary embodiment the central stations are configured to determine if a communications request was sent by a patient monitor which was previously in communication with a particular central station within a predefined time period. If so,

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the particular central station is configured to respond to the request immediately, while the remaining central stations will wait for a relatively short period of time (e.g., 10, 15, 20, 25, or 30 seconds, etc.) before responding. This priority is based on the assumption that the patient monitor is likely still connected to the same patient as during the previous communications, and that the patient is likely to be monitored at the same central station as during the previous communications. In any event, once the patient monitor receives a first response to its communications request, the patient monitor and the central station which sent the first response (hereinafter referred to as the "provisional central station") begin communicating to configure the centralized monitoring session, as indicated at 214.

As will be described in more detail below, the particular central station which serves as the provisional central station begins the process of configuring the monitoring session. However, before the centralized monitoring begins, one of the central stations of network 30 is selected to complete the configuration process and perform the central monitoring. This selected central station is referred to herein as the "primary central station." If the provisional central station is selected to be the primary central station, then no change in communications is needed, and the provisional central station assumes the role of the primary central station. Conversely, if a different central station is selected to be the primary central station, communications with the patient monitor are transferred from the provisional central station to the selected central station, which then assumes the role of primary central station.

As is known to those of skill in the art, wireless communications which have been established between a patient monitor and a primary central station may be lost or "dropped" for any of a variety of reasons. For example, the wireless transmissions may not be received by the access point and/or the wireless transceiver of the patient monitor because the patient monitor is moved out of the defined range of network 30 (i.e., out of range of any access point). Similarly, the transmissions may have been blocked by structures between the patient monitor and the access point, such as when the patient monitor is taken into an elevator or similar enclosure. Alternatively, a portion or device of network 30 may have failed, causing the communications to be dropped. As a further alternative, the battery in the patient monitor may have been replaced or discharged, causing the patient monitor to lose communications.

The response by patient monitor 22 and central stations 24 to communications dropouts may vary depending on the length and/or cause of the dropout. In the exemplary embodiment for example, a relatively brief dropout (e.g., less than approximately 10, 20, or 30 seconds, etc.), is treated as an interruption rather than as an actual loss of communications. Lost or incomplete transmissions due to such interruptions may be resent, discarded, or ignored according to the communications protocols used by the patient monitor and central stations. Once the interruption ends, the patient monitor and primary central station resume communicating as before.

In the event of a loss of communications that extends beyond a brief interruption, exemplary patient monitor 22 is configured to detect the loss and automatically attempt to restore the communications. If the patient monitor is no longer associated with an access point, the patient monitor attempts to establish an

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association as described in the 802.11 standard, and continues to attempt to establish an association until association with an access point is regained. Once the patient monitor re-associates with an access point (or if the patient monitor never lost the association), the patient monitor broadcasts a request for communications to the central stations, and the rendezvous process proceeds as described above. Once the patient monitor is in communication with a provisional central station, the patient monitor and provisional central station begin the process of configuring the monitoring session, as indicated at 214.

It will be appreciated that the session configuration process may proceed in any of a variety of different ways to configure a variety of different monitoring parameters. For example, the configuration process may identify which patient is being monitored, which central station will monitor the patient, which central station will control the patient monitor, what types of vital signs data should be monitored, how the vital signs data should be analyzed, what alarm conditions should be detected, how the patient monitor should function, etc. An exemplary session configuration process is indicated generally at 216 in Fig. 12. During process 216 a primary central station is selected, the monitored patient is identified, and the patient's room or other location is specified.

Referring to Fig. 12, the provisional central station first determines whether the patient monitor is still connected to the same patient as before the communications dropout. If such is the case, then the provisional central station assumes that the patient monitor is attempting to restore communications which were lost, and prior values for patient identity, etc., may be used. Alternatively, if the request is to

establish new communications, then the central station determines the information needed to complete the configuration by querying a user of the patient monitor, as will be described in more detail below.

The provisional central station may be configured to employ a variety of different methods or mechanisms to determine whether the patient monitor is still connected to the same patient. In the exemplary embodiment for example, the provisional central station first sends a request to the patient monitor for an indication of whether the patient monitor was continuously monitoring the patient during the period the communications were lost, as indicated at 218. If the patient monitor responds affirmatively, then the patient currently being monitored is necessarily the same patient that was previously monitored.

Patient monitor 22 is configured to receive the request and detect whether it continuously monitored the same patient during the communication dropout. Typically, the patient monitor is configured to detect continuous monitoring by detecting whether the patient monitor was operational during the communications dropout, and whether vital signs data was continuously received via at least one of the sensor assemblies. For example, one exemplary ECG sensor assembly connectable to a patient is adapted to continuously send ECG vital signs data to patient monitor controller 100. If the patient monitor is disconnected from the patient during the dropout, the ECG signal will lapse. Any lapse in the ECG vital signs data is detected by the controller. Alternatively, the ECG sensor assembly, or other types of sensor assemblies, may be configured to detect actual contact with the patient. In any event, the patient monitor responds to the request by informing the provisional central station

of whether the patient monitor has continuously monitored the same patient. It should be noted that the patient monitor may be monitoring the patient through sensor assemblies that do not continuously send vital signs data to the controller, and that do not detect contact with the patient. In which case, the patient monitor will be unable to confirm that it has continuously monitored the same patient, and will respond to the request from the central station accordingly.

If, at step 218, the patient monitor responds that it has continuously monitored the same patient, the provisional central station proceeds to perform a reconnect process, as indicated at 220 and as described below. Alternatively, if the patient monitor responds that it has not continuously monitored the same patient, the provisional central station then determines whether the patient monitor was recently connected to network 30, as indicated at 222. In other words, if the time period during which communications between the patient monitor and the primary central station were lost is less than a predetermined length of time, then the provisional central station concludes that the patient monitor is attempting to restore a recent connection, and proceeds to perform reconnect process 220. Otherwise, the provisional monitor concludes that the patient monitor is attempting to establish a new communications session. It should be noted that if the patient monitor was continuously monitoring the same patient during the communications dropout, then the provisional central station may safely assume the patient monitor is still connected to the same patient regardless of the length of the dropout.

The predetermined length of time that defines a recent connection may be set to any desired length of time as appropriate for a particular application. In the

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exemplary embodiment, the predetermined length of time is selected to be less than the minimum time period (e.g., 1, 2, 3, 4, or 5 minutes, etc.) normally needed to disconnect a patient monitor from one patient and reconnect the patient monitor to another patient. Thus, if the patient monitor was out of communication for any period of time less than that minimum disconnection/reconnection time, the provisional central station concludes that the patient monitor is still connected to the same patient. Alternatively, other time periods may be used.

The provisional central station may determine whether the patient monitor was recently connected in various ways. Typically, each central station is adapted to store patient vital signs data in database system 40. The vital signs data includes the time of collection by the patient monitor and/or receipt by the central station. Thus, the provisional central station may be configured to access database system 40 to determine the time that the last vital signs data was received from the patient monitor. Alternatively, the patient monitor may be configured to determine the length of the dropout and to inform the provisional central station, either automatically or in response to a query from the provisional central station.

In addition to the length of time during which communications were lost, the provisional central station may be configured also to evaluate other conditions at step 222. For example, if the prior communications were dropped intentionally, i.e., in response to a command by a user, the provisional central station may be configured to assume that a new patient has been connected to the patient monitor. In which case, the patient monitor is not attempting to restore a recent connection, but instead is attempting to establish a new communications connection.

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As mentioned above, the provisional central station proceeds to perform a reconnect process, indicated at 220, if the provisional central station determines either that the patient monitor continuously monitored the same patient during the dropout, or that the patient monitor was recently connected to communicate with a primary central station. During reconnect process 220 the provisional central station automatically determines which patient is being monitored by the patient monitor, and which central station served as the primary central station before the communications dropout. Typically, this information is stored by the patient monitor in memory device 102, and is communicated to the provisional central station by the patient monitor. Alternatively, the information may be stored in database system 40 and read by the provisional central station via physical data transport structure 32.

In any event, if the provisional central station is not the primary central station, then the provisional central station conveys a message to the primary central station to take over the remainder of the rendezvous process. If the primary central station is available, it begins communicating with the patient monitor via physical data transport structure 32 and conducts the remainder of the configuration process as described below. Likewise, the patient monitor transmits all subsequent communications to the primary central station, and the provisional central station ends further communications with the patient monitor.

Alternatively, if the primary central station does not respond to the provisional central station or is otherwise unavailable, the provisional central station may be configured to transmit a message to the patient monitor that the primary central station is unavailable. In the exemplary embodiment, the patient monitor controller causes

display screen 84 to display a user-interface 114, such as shown in Fig. 13, including a message that the primary central station is unavailable. The user-interface may also include instruction elements 116 which are selectable by a user to instruct the central station to recheck the availability of the primary central station, or to try a new primary central station. The clinician or other user of the patient monitor may use buttons 86 to select the desired instruction, which the patient monitor then communicates to the provisional central station. Depending on the user's instructions, the provisional central station either sends another message to the primary central station to take over the communications, or transmits a list of central stations to the patient monitor. In the latter case, controller 100 causes the display device to display a list of central stations, from which the user may select using buttons 86. The patient monitor transmits the user's selection to the provisional central station, which sends a message to the selected central station to take over the communications. If the selected central station is not available, the provisional central station informs the patient monitor and the user either selects a different central station, or instructs the provisional central station to retry the selected central station. This process may be repeated until an available central station is selected to act as the primary central station. The selected central station then begins communicating with the patient monitor and conducts the remainder of the configuration process.

Once the primary central station takes over the communications with the patient monitor, the primary central station is configured to determine the patient identity (patient ID) of the particular patient being monitored by the patient monitor. In general, either or both the primary central station and the patient monitor may be

configured to be involved with the determination of patient ID. For example, the primary central station may determine the patient ID by transmitting a request for the patient ID to the patient monitor. If the patient monitor cannot provide the patient ID, the primary central station then accesses database system 40 to obtain the patient ID which was stored during the patient monitor's last communication session. Once the primary central station determines the identification of the particular patient being monitored by the patient monitor, the primary central station thereafter associates all vital signs data received from the patient monitor with the particular patient. In addition, the vital signs data along with other patient information may be stored on database system 40, and then retrieved for viewing and analysis at a later time.

After the primary central station has assumed the communications with the patient monitor and determined the identity of the patient being monitored, the primary central station then determines whether the patient has been assigned to a particular location, such as a room number, bed, ward, floor, etc., as indicated at 224 in Fig. 12. This information may then be displayed on central station monitor 36 to inform the clinician of the patient's assigned location. However, in view of the portability of patient monitors 22, a particular patient may be temporarily absent from his or her assigned location even though the patient is continuously monitored at the central station. In any event, the primary central station determines whether the patient has been assigned to a particular location by sending a request for the information to the patient monitor. If the patient monitor is unable to provide an assigned location, the primary central station may be configured to search database system 40 for the information.

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If the primary central station is unable to determine the assigned location, the central station is configured to query the user of the patient monitor for the patient's assigned location, as will be described in more detail below. Otherwise, the rendezvous and configuration processes are complete, and the primary central station proceeds to confirm that no other patient monitor is monitoring the same patient, as indicated at 226. In addition to checking the other patient monitors in communication with the primary central station, the primary central station also communicates with other central stations in network 30 to ensure that the same patient is not being monitored by a different central station. In the event the primary central station determines that another patient monitor is monitoring the same patient, an alarm or other indication may be displayed at the primary central station and/or the patient monitor so that a different patient ID may be selected.

As described above, the patient monitor is adapted to automatically attempt to restore communications with its primary central station in the event the communications are lost. Upon reestablishing communication, the primary central station (or a provisional central station, if different than the primary central station) is configured to automatically determine whether the patient monitor is still connected to the same patient. The central station may use a variety of mechanisms and methods to determine whether the patient monitor is still connected to the same patient, including measuring the length of time of the communications dropout, and determining whether the patient monitor disconnected from the patient data during the dropout. If the patient monitor is still connected to the same patient, the central station then associates the patient monitor with the patient so that any vital signs data received

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from the patient monitor is also associated with the patient. It will be appreciated that the capability to automatically identify the monitored patient at the central station after a communications dropout, enables the central station to monitor a large number of patients without constant intervention by a clinician to reconfigure a patient monitor each time a dropout occurs. Furthermore, the automatic configuration ensures that centralized monitoring of the patient resumes as soon as the patient monitor restores communication with the central station.

Turning attention back to Fig. 12, if the provisional central station determines that the patient monitor is not attempting to restore lost communications, the provisional central station proceeds to configure a new monitoring session by determining the identity of the patient being monitored, the primary central station which will monitor the patient, and the patient's assigned location. When the patient monitor establishes a new communications connection with the provisional central station, the patient monitor automatically displays a notification to a user of the patient monitor on display screen 84. As will be described below, the notification typically includes a user-interface operable by a user of the patient monitor to configure the communications session.

It will be appreciated that the provisional central station may determine the identity of the monitored patient in various ways. For example, even where the patient monitor has not recently been in communication with a central station and has not been monitoring the patient continuously since its last communication with a central station, it nevertheless may be more likely than not that the patient monitor has been reconnected to monitor the same patient. In the exemplary embodiment

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therefore, the provisional central station first determines whether the identity of the previous patient monitored by the patient monitor is available, as indicated at 228.

To determine whether the patient ID of the previous patient is available, the provisional central station may be configured first to query the patient monitor. Exemplary patient monitor 22 is configured to store the ID of the previous patient in memory device 102, unless the patient ID is cleared by the user. Thus, the exemplary provisional central station transmits a request to the patient monitor for the previous patient ID. If the previous patient ID is available at the patient monitor, the patient monitor communicates the previous patient ID to the provisional central station. Otherwise, the patient monitor responds that no patient ID is available.

If the patient ID is not available at the patient monitor, the provisional central station may be configured to search database system 40 for the previous patient ID associated with the patient monitor. Alternatively, if the patient monitor is connected to physical data transport structure 32 via a hard-wired connection, the provisional central station may be configured to search the database system for the previous patient ID associated with the particular location of the hard-wired connection. This strategy is based on the likelihood that the patient who was previously in the room with the hard-wired connection has not been moved since the last communications session. In the exemplary embodiment, the provisional central station is configured to search for the patient ID associated with the patient monitor if the patient monitor is communicating via wireless transmissions, and to search for the patient ID associated with the particular location of the hardwired connection if the patient monitor is communicating via wire.

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If the previous patient ID is available (either from the patient monitor or the database system), the provisional central station communicates an instruction to the patient monitor to confirm whether the patient currently being monitored is the same as the last patient monitored, as indicated at 230. In response, controller 100 automatically causes display screen 84 to display a user-interface 114, such as illustrated in Fig. 14. The user-interface displays the previous patient's identity (i.e., the patient's name, identifying number, and/or other identifying designation) and asks the user to confirm that the patient monitor is connected to the previous patient. Exemplary user-interface 114 also includes instruction elements 116 which are selectable by the user to indicate that the patient monitor is or is not connected to the previous patient. In the exemplary embodiment, the user-interface also displays the patient's assigned location, indicated at 118, and the central station that previously monitored the patient, indicated at 120. Thus, the clinician or other user is prompted by user-interface 114 to confirm that the same patient is being monitored, and is assigned to the same location, and is to be monitored by the same central station. Alternatively, the user may indicate that a new patient is being monitored, or that the patient has been assigned to a new location, or that the patient should be monitored by a different central station. The user's selection is communicated by the patient monitor to the provisional central station.

As shown in Fig. 12, if the user confirms the previous patient, location and primary central station (i.e., by selecting the instruction element labeled "YES"), the rendezvous and configuration processes are complete, and the primary central station proceeds to confirm that no other patient monitor is monitoring the same patient, as

indicated at 226 and as discussed above. It should be noted that if the provisional central station is not the primary central station, then the provisional central station sends a request to the primary central station to take over the communications and complete the configuration process, as described above.

Alternatively, if the user responds by selecting a different one of the instruction elements, the provisional central station proceeds to determine the necessary configuration information. For example, if the user indicates that the patient currently being monitored is not the previous patient (i.e., by selecting the instruction element labeled "NO"), the provisional central station determines whether the patient monitor is configured to display a list of patients, as indicated at 232. The provisional central station may determine whether the patient monitor is configured to display a list of patients in various ways, including by sending a query to the patient monitor for its capabilities, or by accessing database system 40 to ascertain the capabilities of the patient monitor based on the type of patient monitor. As mentioned above, the type of the patient monitor may be transmitted to the provisional central station during the initial portion of the rendezvous process.

If the patient monitor is not configured to display a list of patients, then the patient ID confirmation process is passed to the central station, as indicated at 226. The central station typically is configured to display a user-interface allowing a clinician to specify the patient ID and the patient's assigned location. In addition, the clinician may instruct the central station to transfer communications with the patient monitor to a different central station, as will be described in more detail below. If, on the other hand, the patient monitor is configured to display a list of patients, the

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central station accesses database system 40 to identify at least some of the patients admitted to the hospital, and transmits a list of those patients to the patient monitor.

As indicated at 234, exemplary controller 100 displays the list of patients on display screen 84. An exemplary display screen presenting a list of patients is illustrated in Fig. 15. Rather than identifying the patient at the patient monitor, the clinician may operate buttons 86 to instruct that the patient's ID be selected at the central station, as indicated at 236. In which case the patient ID confirmation process is passed to the central station, as indicated at 226 and as discussed above. Alternatively, the clinician may select the ID of the monitored-patient from the patient list. The patient's ID is then communicated to the central station by the patient monitor. Next, the central station transmits a list of locations to the patient monitor controller, which displays the list to the user, as indicated at 238. Once the user selects the patient's assigned location from the list, the controller communicates the information to the central station. Finally, the central station confirms the patient is not being monitored by a different patient monitor, as indicated at 226, at which point the rendezvous and configuration processes are complete.

If, at step 230, the clinician indicates that the patient has been assigned to a different location (i.e., by selecting the instruction element labeled "NEW ROOM"), the patient monitor communicates this information to the central station, which responds by sending a list of locations to the patient monitor, as described above. The clinician then selects the patient's assigned location from the list, as indicated at 238. The location assignment is communicated to the central station, which then completes

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the rendezvous and configuration processes by confirming that the patient is not being monitored by a different patient monitor.

Returning attention briefly to Fig. 14, if the central station that monitored the previous patient will not be the primary central station, the clinician requests communications with a different central station (e.g., by selecting the control element labeled "NEW UNIT"). The clinician's instruction is then communicated to the provisional central station, which responds by transmitting a list of central stations in network 30. Controller 100 displays the list of central stations on display screen 84, as indicated at 240 in Fig. 12. Figure 16 illustrates an exemplary user-interface on display screen 84, including a list of user-selectable central stations. Once the clinician selects the desired central station from the list, the selection is communicated to the provisional central station. If the provisional central station is not the selected central station, the provisional central station sends a request to the selected central station to take over the communications and configuration process. If the selected central station is available, it takes over the communications with the patient monitor and completes the configuration process. Otherwise, the provisional central station causes the patient monitor to notify the clinician that the selected central station is unavailable, as described above.

Once the a central station is selected to be the primary central station and assumes the communications with the patient monitor, the primary central station proceeds to determine the identity of the patient and the patient's assigned location. As described above, the identity of the patient and the patient's assigned location may be entered by the clinician at the patient monitor and then communicated to the

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primary central station. Alternatively, the patient ID and assigned location may be specified at the primary central station. In any event, once the primary central station has confirmed the identity and the assigned location of the patient, as indicated at 226, the rendezvous and configuration processes are complete.

As described above, exemplary configuration process 216 is adapted to automatically determine the patient's identity, etc., whenever possible. This tends to minimize the amount of effort required by the clinician to configure the patient monitor for centralized monitoring. However, it will be appreciated that the provisional central station may be configured also to determine the patient identity, primary central station, and assigned location in other ways. For example, if the patient ID is not available at step 228, then the exemplary provisional central station is configured to determine whether a list of central stations should be presented to the clinician, as indicated at 232. Typically, a list of central stations is presented whenever network 30 includes more than one central station. As indicated at 240 and described above, the provisional central station transmits the list of central stations to the patient monitor for display to the clinician. The clinician selects a desired central station to serve as the primary central station. The patient monitor communicates the selection to the provisional central station, which sends a message to the selected central station to take over the communications. If the selected central station is not available, the clinician is informed to make another selection, as described above. If, at step 242, the provisional central station determines that a list of central stations should not be presented to the user, the provisional central station becomes the primary central station and completes the remainder of the configuration process.

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Once the primary central station is in communication with the patient monitor, the primary central station queries the clinician for the patient ID and assigned location. Alternatively, the patient ID and assigned location may be specified at the primary central station. In any event, the primary central station then confirms that no other patient monitors are monitoring the same patient, thereby completing the rendezvous and configuration processes.

It will be appreciated by those of skill in the art that the exemplary rendezvous and configuration processes illustrated in Figs. 11 and 12 and described above, provide a variety of capabilities for monitoring patients via medical telemetry network 30. For example, a clinician may select which central station will monitor the patient by entering instructions at the patient monitor. The clinician's instructions are communicated to the provisional central station, which then sends a request to the selected central station to take over the communications. Alternatively, the patient monitor may send a request for communications directly to the selected central station in response to the clinician's instructions. In any event, the clinician is not required to configure the patient monitor at the central station, but instead may configure and initiate the central monitoring process without leaving the patient's location.

Furthermore, exemplary patient monitor 22 is configured to automatically attempt to establish communications with a central station beginning at power-up. The patient monitor determines, without user intervention, the communications settings needed to establish a connection and to communicate with network 30 such as transmission frequency, IP addresses, synchronization, etc. Thus, a patient monitor may be shipped from its manufacturing site to any location in the world and the

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patient monitor will automatically configure itself to begin communications with a local medical telemetry network according to the present invention. Similarly, a patient monitor used in a network at one location may be taken to a different location, where the patient monitor will configure itself to communicate with the local medical telemetry network at the different location. As a result, patient monitors 22 may be operated without specialized training or knowledge in network communications. Instead, clinicians may place a new patient monitor in immediate use simply by powering-up the patient monitor.

If communications between a patient monitor and central station are lost, the patient monitor automatically attempts to restore the communications without requiring reconfiguration. However, if the patient monitor is attempting to establish a new communications connection, the clinician or other user of the patient monitor is automatically notified once a communications connection (either wire or wireless) is established to allow the monitoring session to be configured. A user-interface for configuring the monitoring session is automatically displayed on the patient monitor display screen. The user-interface is at least partially defined by instructions received from the central station, and is operable by a user of the patient monitor to identify the monitored patient, and to select a primary central station to perform the central monitoring, etc. After a primary central station is identified and assumes communications with, and control of, the patient monitor, the patient is continuously monitored at the primary central station. In view of the capability of the patient monitors and central stations to automatically initiate and configure the centralized

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monitoring process, system 20 represents a substantial advancement in patient monitoring.

It will be appreciated by those of skill in the art that the rendezvous and configuration processes described above are just one of the many ways in which the central stations and patient monitors may be configured to establish new communications and/or restore lost communications. Many variations and modifications to the rendezvous and configuration processes are possible within the scope of the invention. Therefore, it will be understood that the invention is not limited to the particular exemplary processes described above, but includes all such processes, variations, and modifications suitable for establishing communications between a patient monitor and a central monitoring station via a communications network structure.

Once patient monitor 22 has established (or restored) communications with the primary central station, the patient monitor is configured to continuously communicate the vital signs data it collects to the central station. In the exemplary embodiment, patient monitor 22 is configured to communicate all vital signs data that is collected. Alternatively, the patient monitor may be configured to communicate only a portion of the vital signs data collected. In any event, the central station is configured to receive the vital signs data and associate it with the patient being monitored. As mentioned above, the central station typically is configured to communicate simultaneously with a plurality of patient monitors, in which case the vital signs data received from each patient monitor is associated with the particular patient connected to that patient monitor.

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Although patient monitor 22 is adapted to communicate with one or more central stations to establish central monitoring, the patient monitor is also configured to provide patient monitoring at the patient's location. As mentioned above, exemplary controller 100 is adapted to receive the vital signs data via sensor ports 82, and to display an image on display screen 84 that represents at least a portion of the vital signs data. It will be appreciated that the image may take any of a variety of different forms which will vary depending on the type of vital signs data collected. Thus, exemplary patient monitor 22 provides continuous local monitoring regardless of whether the patient monitor is in communication with a central station. Buttons 86 enable a clinician or other user to control a variety of functions including the information displayed on display screen 84, the format of the displayed image, the vital signs data collected, analysis of the vital signs data, alarm conditions, etc. For example, controller 100 may be controllable to display signals from selected sensor assemblies such as an ECG sensor assembly, or from a selected electrode of the ECG sensor assembly. In addition, the controller may be configured to analyze at least some of the collected vital signs data using one or more user-selectable parameters to provide additional information.

Similarly, controller 100 may be configured to analyze the vital signs data to detect whether the data is within certain defined nominal ranges, and to indicate an alarm condition if the controller detects that a portion of the data is not within the defined ranges. For example, if the upper and lower parameter values for heart rate are 120 and 50 beats per minute, respectively, the patient monitor will indicate an alarm if the detected heart rate is either greater than 120 or less than 50 beats per

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minute. Alternatively, any other portion of the collected vital signs data may be analyzed for alarm conditions, such as blood pressure, temperature, oxygen saturation in the patient's blood (SpO2), etc. Further, the defined nominal ranges typically are variable parameters and selectable by the user to specify particular alarm conditions for a particular patient. Fig. 17 illustrates an exemplary user-interface displayable on display screen 84, and operable by a clinician to specify the parameter values used by controller 100 to analyze the vital signs data. Alarm indications may include warning messages on display screen 84 and/or warning sounds from audio output device 92, etc.

Patient monitor 22 may also be configured to detect equipment or communications problems and provide an indication of the problem to the user. For example, controller 100 may be configured to detect a low power level in battery assembly 88, a sensor assembly that has become disconnected from the patient, a malfunction in buttons 86, lost communications, etc. The indication provided to the user may be the same as or different than the indication provided in response to the alarm conditions.

When patient monitor 22 is in communication with network 30, the primary central station may be configured to control some or all of the functions of the patient monitor. This enables a clinician to control a plurality of remotely distributed patient monitors from a single location. In addition, a central station may be configured to enable a clinician to control all patient monitors in communication with the central station to function identically. Alternatively, the clinician may control each patient monitor to function differently.

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In the exemplary embodiment, the primary central station is configured and operable to change the variable parameter values which define nominal data ranges. Thus, the clinician can set or change the detection of alarm conditions at the primary central station. Instructions entered by the clinician at the primary central station are communicated to controller 100. The controller is configured to change the specified variable value in response to the instruction, and to analyze the vital signs data using the new value. Similarly, the primary central station may be configured to communicate instructions to controller 100 specifying what portions of the vital signs data should be analyzed. For example, it is known to those of skill in the art that a patient's heart rate may be determined from ECG data or from SpO2 data. Thus, where the patient monitor is collecting both ECG data and SpO2 data from a patient, a clinician at the central station may specify which type of data the controller analyzes to determine heart rate.

In addition, since the central stations typically have greater data processing capability than the patient monitors, the primary central station may be configured to analyze the vital signs data received from the patient monitor to determine additional information. For example, the primary central station may be configured to perform ST and/or arrhythmia analysis on the ECG waveform data, whereas controller 100 may analyze the ECG waveform to determine only the patient's heart rate. If the primary central station detects an alarm condition as a result of the analysis, the alarm condition may be displayed on central station monitor 36. In addition, the primary central station may communicate the alarm condition to the patient monitor and instruct controller 100 to present an indication of the alarm condition at the patient

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monitor. By varying where the vital signs data analysis occurs (at the central station or at the patient monitor), the patient monitor's resources may be concentrated on collecting the vital signs data and presenting information to a clinician attending the patient.

The primary central station may also be configured to control both the types of information and the image displayed on display screen 84. For example, where the ECG sensor assembly includes a plurality of electrodes, the clinician at the primary central station may instruct the patient monitor to display the waveform from a particular one of the electrodes, as shown in Fig. 18. Alternatively, the clinician may instruct the patient monitor to display the waveforms from a plurality of the electrodes, as shown in Fig. 19. It will be appreciated that controller 100 may be configured to control display screen 84 to display any desired information or image format in response to instructions received from the primary central station. Alternatively, the controller may be configured to turn off a portion or all of the display screen in response to instructions from the central station.

As described above, the patient monitor and/or the primary central station may be configured to indicate an alarm condition, equipment problem, etc., with at least one of a visible indicator or an audible indicator. For example, Fig. 20 illustrates an exemplary image displayable on display screen 84 which indicates an alarm condition. Typically, the user-interface will include an icon or other indicia to specify the cause of the alarm or problem (e.g., high heart rate, high temperature, etc.).

The patient monitor and primary central station may be configured to continue presenting the indicator for a predetermined time period, or for as long as the

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condition or problem persists. Alternatively, the indicator may be terminated after a specified period of time, even if the condition or problem has not ended. In the exemplary embodiment, the indicator also may be terminated (or suspended for a defined time period) if the clinician acknowledges the indication at the patient monitor and/or the primary central station. Thus, an alarm condition detected at the primary central station and communicated to the patient monitor may be acknowledged at the patient monitor. The acknowledgement is communicated to the primary central station, which then terminates the indication. As a result, a clinician attending the patient need not leave the patient's location to return to the primary central station and acknowledge the alarm.

Once communications are established between a patient monitor and a primary central station of the exemplary embodiment, the patient monitor communicates all vital signs data to the primary central station and is controlled by the primary central station. While other central stations also may receive the vital signs data and send instructions for the patient monitor (as will be described in more detail below), the primary central station maintains control of the patient monitor and is responsible for providing the central monitoring. However, control and central monitoring of the patient monitor may be transferred to a different central station, in which case the different central station is configured to take over communications with the patient monitor and assume control of the central station.

In the exemplary embodiment, a clinician may transfer control of the patient monitor to a different central station by entering a transfer instruction at the patient monitor or at the primary central station. If the clinician is at the patient monitor,

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controller 100 transmits the transfer instruction to the primary central station, which responds by sending a list of central stations to the patient monitor. The controller displays the list on display screen 84 to allow the clinician to select the desired central station. Once the clinician makes a selection, the patient monitor communicates the selection to the primary central station, which sends a request to the selected central station to take over the communications. If the selected central station is unavailable, the primary central station sends a notification to the patient monitor so that the clinician can make another selection. Alternatively, the patient monitor may communicate with the selected central station directly. However, if the clinician is at the primary central station when transferring control, the primary central station sends a request to the selected central station to take over the communications, as described above. Once the selected central station takes over as the new primary central station, the patient monitor communicates all subsequent vital signs data to the new primary central station.

As mentioned above, communications dropouts between the patient monitor and the primary central station may occur for a variety of reasons. Once a dropout occurs, the patient monitor begins attempting to restore the communications. However, during the dropout, the patient is not monitored at the central station. Therefore, the patient monitor may be configured to detect when central monitoring has ended, and to take additional steps to minimize any disruption due to the dropout.

In the exemplary embodiment, the patient monitor is configured to function differently when out of communication with a central station. For example, controller 100 may disable buttons 86 (e.g., by disregarding inputs at the buttons) when the

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controller is in communication with a central station so that the functions of the patient monitor can only be changed at the central station. Alternatively, the controller may suppress alarm indications at the patient monitor when in communication with a central station. Similarly, the controller may turn off the display when in communication with a central station to conserve battery power. The controller may be configured to perform the above steps either automatically, or in response to an instruction from the central station. However, the controller typically is configured to activate the buttons, the display and the alarm indications when not in communication with a central station.

Furthermore, some embodiments of patient monitor 22 include a button 86 operable by the patient to request clincian assistance (i.e., a "Nurse Call" button). In such case, the patient monitor may be configured to respond differently to activation of the button depending on whether the patient monitor is in communication with a central station. For example, the patient monitor may be configured to sound an audible alarm if the patient monitor is not in communication with a central station, or to forward the request for assistance to a central station without sounding an audible alarm if the patient monitor is in communication with a central station.

Similarly, when communications between the patient monitor and central station are lost, the patient monitor may be configured to automatically switch from a centrally-monitored mode, in which the vital signs data is communicated to a central station that at least partially controls the patient monitor, to a stand-alone mode, in which the vital signs data are not communicated to a central station. Typically, the patient monitor also is configured to automatically switch from the stand-alone mode

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to the centrally-monitored mode when the communications are restored. In other words, the patient monitor may be configured to automatically relinquish at least partial control of the patient monitoring process when in communication with a central station, but to resume full control in the event communications are lost.

In addition to automatically switching between a stand-alone mode and a centrally-monitored mode, the patient monitor may also be configured to take any one or more of a variety of steps to return to the centrally-monitored mode with minimal disruption. As described above for example, the exemplary patient monitor is configured to automatically and continuously attempt to restore the communications during the dropout. Upon restoring a connection to physical data transport structure 32, the patient monitor is configured to reestablish communications with a primary central station and, where possible, to configure the monitoring session without intervention by a clinician.

Nevertheless, the vital signs data are not communicated to the central station during the dropout. As a result, further analysis at the central station of the vital signs data received during the dropout cannot be conducted, and the vital signs data cannot be stored on database system 40 for later access. Therefore, exemplary patient monitor 22 could be configured to store at least a portion of the vital signs data collected during the dropout, and then communicate the stored vital signs data to the central station once the communications are restored. The vital signs data may be stored in memory device 102 and/or some other data storage buffer. In any event, the data collected during a dropout period would not be lost.

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It will be appreciated that, depending on the length of the dropout, the vital signs data collected may exceed the patient monitor's storage capacity. Therefore, the patient monitor may be configured to store only a portion of the vital signs data collected once it detects the dropout. For example, the patient monitor may be configured to begin storing the data immediately after detecting the dropout, and then cease storing new data once the memory device is full. Alternatively, the patient monitor may be configured to begin storing the data immediately, and once the memory storage is full, to begin storing subsequent data in place of the oldest stored data. As a further alternative, the patient monitor may be configured to store only data from selected sensor assemblies rather than all sensor assemblies.

As another alternative, the patient monitor may be configured to store portions of the vital signs data which meet defined criteria. In the exemplary embodiment for example, controller 100 is configured to analyze the vital signs data received during a dropout, and to detect the occurrence of a medically-significant event based on the vital signs data. The controller only stores data that corresponds to the occurrence of a medically-significant event. Examples of typical medically-significant events include alarm conditions, arrhythmia, activation of the Nurse-Call button, etc. The amount of data stored may vary depending on the event. Typically, a continuous sequence of data is stored from a point in time several seconds or minutes before the event is detected to several seconds or minutes after the event ends. Thus, several running seconds or minutes of prior data are continuously buffered until an event is detected, at which point all or a portion of the data is stored until the event ends.

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It will be appreciated that the criteria defining a medically-significant event may vary depending on the type of event, the type of sensor assembly that collects the data, the condition of the patient, the clinician's judgment, etc. The patient monitor may be pre-programmed with the criteria defining medically-significant events. Alternatively, the criteria for medically-significant events may be programmed into the patient monitor by the clinician or received from the central station. In any event, by storing only data corresponding to the occurrence of medically-significant events, the patient monitor is able to conserve data storage capacity while ensuring that communication dropouts do not prevent the primary central station from receiving the most important vital signs data.

Alternatively, or additionally, exemplary patient monitor 22 may be configured to selectively store data under other conditions. For example, controller 100 may store data at selected time intervals, or in response to an instruction from a clinician via buttons 86, etc. Thus, it will be appreciated that the patient monitor may be configured to selectively store data under any conditions as desired for a particular application.

In the embodiments described above, patient monitor 22 communicates collected vital signs data to a single central station, referred to herein as the primary central station. Likewise, the patient monitor is controlled by the primary central station. However, in other embodiments, the patient monitor may be configured to broadcast the vital signs data it collects to a plurality of central stations, and to receive and execute instructions from a plurality of central stations. As a further alternative,

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the primary central station may be configured to convey vital signs data received from a patient monitor to one or more other central stations.

As shown in Fig. 21, exemplary primary central station 24a is configured to receive vital signs data from patient monitor 22, and to forward the vital signs data to one or more secondary central stations 24b. The vital signs data received from the patient monitor may then be displayed at the secondary central station(s) as well as at the primary central station. Typically, the secondary central station communicates a request to the primary central station to receive a particular patient's vital signs data. In response to the request, the primary central station is configured to continuously forward all vital signs data it receives that is associated with the particular patient. In addition, instructions entered at a secondary central station are communicated to the primary central station, which forwards the instructions to the patient monitor for execution. Thus, from the point of view of a clinician monitoring the patient, a secondary central station provides the same capabilities as the primary central station. However, some functions are performed only at the primary central station, such as storing or archiving the vital signs data to database system 40, performing arrhythmia analysis, etc.

It will be appreciated that communicating the vital signs data to one or more secondary central stations allows the patient's data to be monitored by clinicians at plural locations within the hospital. Thus, there is no need for a clinician to travel to a different floor, or care unit, etc., of the hospital to view the data from a particular patient. Similarly, a clinician endeavoring to monitor a particular patient is not

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restricted to a single location, but instead can monitor the patient from a variety of different locations.

In addition to providing central monitoring from multiple locations, secondary central stations 24b may also be configured to provide a failsafe in the event of a failure involving the primary central station. Thus, in the exemplary embodiment, at least one of the secondary central stations is configured to automatically attempt to take over communications with the patient monitor if communications between primary central station 24a and the patient monitor are lost. The secondary central station may be configured to detect the loss of communications from the primary central station in a variety of ways. In the exemplary embodiment, the secondary central station is configured to detect a loss of communications with the primary central station(even a sudden, catastrophic one such as loss of power). In response to the message, the secondary central station would then attempt to establish communications with the patient monitor. Additionally, the secondary central station is configured to monitor the communications it receives from the primary central station, and if the primary central station suddenly stops communicating (e.g., due to loss of power, malfunction, etc.) for a defined period of time, the secondary central station is configured to attempt to establish communications with the patient monitor. Alternatively, the patient monitor may be configured to transmit a request for communications to the secondary central station in the event the primary central station stops communicating.

Once the secondary central station establishes communications with the patient monitor, the secondary central station takes over the functions of the primary central

station. Alternatively, the clinician may be prompted to select a new primary central station for further monitoring. Where plural secondary central stations are monitoring the patient monitor, the first secondary central station to establish communications with the patient monitor takes over as the primary central station. The new primary central station then begins forwarding the vital signs data received from the patient monitor to the remaining secondary central stations. Thus, the patient continues to be monitored at a central location staffed by clinicians, and the vital signs data collected from the patient continues to be stored for later retrieval.

As described above, patient monitor 22 and central stations 24 are configured to automatically establish and maintain communications while the patient monitor is monitoring a patient. However, patient monitor 22 may also be operable to end the communications with the central station(s). This provides an intentional and controlled termination of communications so that the patient monitor and/or the central stations do not automatically attempt to restore communications. In the exemplary embodiment, the patient monitor is operable by a clinician (e.g., using buttons 86) to transmit an end-communications signal to the primary central station. The primary central station is configured to send a confirmation of the end-communications signal to the patient monitor, which is displayed to the clinician at the patient monitor. The primary central station may also send a notification to the secondary central stations, if any.

Once the end-communications signal has been received and confirmed, the patient monitor may be powered down by the clinician without causing the primary central station to report a loss of communications. The primary central station will of

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course detect the loss of communication, but will be configured not to report this type of loss because it is expected. Alternatively, the primary central station will terminate the communications after a defined delay period even though vital signs data were still being received. If the patient monitor is still operating and collecting data after the communications are terminated, the patient monitor would be required to initiate the rendezvous process described above to resume centralized monitoring of the patient. Any monitoring parameters, alarm conditions, etc., that were changed at the patient monitor in response to an instruction from the central station would be reset to the nominal default values stored by the patient monitor. Likewise, any monitoring parameters, alarm conditions, etc., that were changed at the central station in response to an instruction from the clinician at the patient monitor, would be reset to the nominal default values stored by the central station.

As shown in Figs. 1 and 2 and described above, patient monitor 22b is configured to establish communications with a central station and communicate vital signs data via either one of output port 96 or wireless transceiver 104 (illustrated in Fig. 7). In addition, exemplary patient monitor 22b is configured to detect whether output port 96 is connected to physical data transport structure 32 (either directly or through terminal server 42), and to switch automatically between wireless communications and wire communications depending on whether the output port is connected to the network structure. For example, where patient monitor 22b is initially in communications with a central station via output port 96 and the output port is disconnected from physical data transport structure 32, then controller 100 is configured to automatically associate with an access point and continue the

communications with the central station via wireless transceiver 104. Similarly, where patient monitor 22b is in wireless communications with a central station when output port 96 is connected to physical data transport structure 32, controller 100 is configured to automatically cease communicating via wireless transceiver 104, and instead to communicate with the central station via the output port. Thus, the clinician can select whether patient monitor 22b communicates using wire or wireless communications by connecting and disconnecting, respectively, output port 96 to physical data transport structure 32.

As mentioned above, patient monitor 22 may also be configured to establish communications with a central station to download newer versions of the control software stored in memory device 102 and executable by controller 100. It will be appreciated that the download process may be carried out in any of a variety of different ways within the scope of the invention. It should also be understood that the control software could be for any component of the patient monitor, such as by way of examples, computer cards associated with any/all of the sensor assemblies (e.g. a pulse oximetry card, an NIBP card, etc.), computer cards associated with radio telemetry, etc.

In the exemplary embodiment, patient monitor 22 is operable by a user to request a software update. In response to the user's instructions, the patient monitor attempts to establish communications with one or more central stations, and transmits a query for new versions of the software to the central stations. The query is included as a part of the request for communications which the patient monitor broadcasts to the central stations during the rendezvous process. Each central station responding to

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the request indicates the version of the software stored at the central station. The patient monitor waits a defined period (e.g., 10 seconds) to receive responses from the central stations, and then selects a central station with the newest version of the software. Thus, even where the central stations have multiple versions of the software, the patient monitor is configured to determine which central station(s) has the newest version and to download the software from the central station with the newest version. This allows a system administrator to store new versions of the software on just one or a few of the central stations, and then operate the patient monitors to automatically find and download the newest software.

Once a central station with the newest version of the software is selected, the patient monitor transmits a request to the selected central station to download the new software. The selected central station responds by transmitting the new software via either wire or wireless communications, depending on whether the patient monitor is communicating via output port 96 or wireless transceiver 104. The software download may be carried out using any of a variety of methods or protocols, such as Trivial File Transfer Protocol (TFTP), etc. Typically, the patient monitor and selected central station verify that the software was accurately received at the patient monitor using one or more of a variety of error-checking methods known to those of skill in the art. Once the patient monitor receives the new software, controller 100 updates the control software by installing the new software. The controller may carry out this updating process for control software of any of components of the patient monitor as described above.

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As described above, the invention provides a system for continuously monitoring a plurality of patients at one or more central stations using a plurality of portable patient monitors. The invention also provides a method for monitoring a patient at a central location, as indicated generally at 300 in Fig. 22. The method is implemented by software running on patient monitors 22, central stations 24, and/or other components of system 20. The method includes, at step 310 establishing wireless communications between a patient monitor and a communications network having at least one wireless transceiver and a plurality of central stations. Then communicating a list of the plural central stations to the patient monitor via the wireless transceiver, as indicated at step 320. Alternatively, the list of the plural central stations may be provided to, or stored on, the patient monitor in other ways. In any event, method 300 proceeds with selecting, at the patient monitor, one of the plural central stations, as indicated at 330. Then collecting, at the patient monitor, vital signs data from a patient, as indicated at step 340. The vital signs data are communicated to the wireless transceiver, at step 350, and then communicated from the wireless transceiver to the selected central station, at step 360.

A further method for monitoring patients according to the present invention is indicated generally at 400 in Fig. 23. Method 400 includes, at step 410, establishing communications between a wireless patient monitor and a central station adapted to receive vital signs data from a plurality of patients. Configuring the patient monitor to collect vital signs data from a particular one of the plural patients, at step 420. Communicating a list of the plural patients from the central station to the patient monitor, as indicated at step 430. Alternatively, the list of patients may be provided

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to, or stored on, the patient monitor in other ways. In any event, method 400 continues at step 440 with identifying, at the patient monitor, the particular patient. Communicating the identity of the particular patient to the central station, at step 450. Communicating the vital signs data collected from the particular patient to the central station, as indicated at step 460. Finally, associating, at the central station, the vital signs data with the particular patient, as indicated at step 470.

Another method for monitoring patients according to the present invention is indicated generally at 500 in Fig. 24. Method 500 includes, at step 510, establishing wireless communications between a patient monitor and a central station. Collecting vital signs data from a patient at the patient monitor, at step 520. Communicating the vital signs data from the patient monitor to the central station, at step 530. In the event that communications between the patient monitor and the central station are lost, detecting that loss of communications, at step 540. Storing at least a portion of the vital signs data at the patient monitor while the patient monitor is out of communications with the central station, as indicated at step 550. Restoring wireless communications between the patient monitor and the central station, at step 560. Then, communicating at least a portion of the stored vital signs data from the patient monitor to the central station, as indicated at step 570.

Another method for monitoring patients according to the present invention is indicated generally at 600 in Fig. 25, and includes establishing wireless communications between a patient monitor and a first central station, as indicated at step 610. Collecting vital signs data from a patient at the patient monitor, at step 620. Communicating the vital signs data from the patient monitor to the first central station,

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at step 630. So long as communications between the patient monitor and the first central station are maintained, the patient monitor continues to communicate the vital signs data to the first central station, as indicated at 640. However, in the event communications between the patient monitor and the first central station are lost, then wireless communications are automatically established between the patient monitor and a second central station, as indicated at step 650. Finally, communicating the vital signs data from the patient monitor to the second central station, at step 660. It should also be noted that when a clinician using the patient monitor transfers communication to a different central station, there is a transition time (presently that duration is in the range of about 5-10 seconds). During that transition time, the patient monitor could be configured to store data for later uploading to the different central station chosen by the clinician.

Another method for monitoring patients according to the present invention is indicated generally at 700 in Fig. 26. Method 700 includes, at step 710, establishing wireless communications between a patient monitor connected to a particular one of plural patients and a central station. Communicating the identity of the particular patient from the patient monitor to the central station, at step 720. As noted above in connection with the determination of patient ID, either or both the central station and the patient monitor may be involved with this determination. The patient monitor may be adapted to detect the disconnection of the particular patient from the patient monitor, and also adapted to send a patient-disconnection signal to the central station if the particular patient was disconnected from the patient monitor during the period of time the communications were lost. The central station could then determine patient

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ID by associating the patient-disconnection signal with the patient monitor and received patient vital signs data from that patient monitor. Alternatively, the patient monitor could be adapted to detect the identity of the particular patient and inform the central station of the identity of that particular patient.

Collecting vital signs data from the particular patient at the patient monitor, as indicated at 730. Then, communicating the vital signs data to the central station, at step 740, and associating, at the central station, the patient monitor with the particular patient, as indicated at step 750. So long as communications between the patient monitor and the central station are maintained, the patient monitor continues to communicate the vital signs data to the central station, which associates the vital signs data with the particular patient, as indicated at 760. In the event communications between the patient monitor and the central station are lost for a period of time, reestablishing the communications between the patient monitor and the central station, at step 770. Then, automatically determining, at the central station, whether the patient monitor is still connected to the particular patient, as indicated at step 780. Finally, if the patient monitor is still connected to the particular patient, then associating the patient monitor with the particular patient.

In addition to the exemplary methods for monitoring patients described above, it will be appreciated that the configuration and operation of system 20 is not limited to the exemplary methods as many variations and modifications are possible within the scope of the invention. Further, system 20 may be configured and operated to monitor patients according to a variety of other methods within the scope of the

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invention. Therefore, it will be understood that all such methods, variations and modifications are within the scope of the invention.

It is believed that the disclosure set forth above encompasses multiple distinct inventions with independent utility. While each of these inventions has been disclosed in its preferred form, the specific embodiments thereof as disclosed and illustrated herein are not to be considered in a limiting sense as numerous variations are possible. The subject matter of the inventions includes all novel and non-obvious combinations and subcombinations of the various elements, features, functions and/or properties disclosed herein. No single feature, function, element or property of the disclosed embodiments is essential to all of the disclosed inventions. Similarly, where the claims recite "a" or "a first" element or the equivalent thereof, such claims should be understood to include incorporation of one or more such elements, neither requiring nor excluding two or more such elements.

It is believed that the following claims particularly point out certain combinations and subcombinations that are directed to one of the disclosed inventions and are novel and non-obvious. Inventions embodied in other combinations and subcombinations of features, functions, elements and/or properties may be claimed through amendment of the present claims or presentation of new claims in this or a related application. Such amended or new claims, whether they are directed to a different invention or directed to the same invention, whether different, broader, narrower or equal in scope to the original claims, are also regarded as included within the subject matter of the inventions of the present disclosure.

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WE CLAIM

1. A wireless patient monitor adapted to communicate with any one of plural medical telemetry networks, each having one or more central stations, where each network is configured to communicate via wireless communications using one of multiple different communications settings, the monitor comprising:

one or more sensor inputs for receiving vital signs data from a patient;

a wireless transceiver configured to transmit and receive wireless communications; and

a controller coupled to receive the vital signs data via the one or more sensor inputs and to communicate with a network via the transceiver;

where the controller is configured, upon initial power-up, to automatically transmit a signal to a local one of the plural networks via the transceiver to request the communications settings used by the local network, and to establish communications with at least one of the central stations on the local network using the communications settings received from the local network without intervention from a user of the patient monitor.

2. The monitor of claim 1, where the controller is configured to transmit the vital signs data to the at least one central station using the selected communications settings.

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3. The monitor of claim 2, where the controller is configured to transmit the vital signs data to the at least one central station without intervention from the user.

4. The monitor of claim 1, where the communications settings include a communications address for the monitor.

5. The monitor of claim 1, where the communications settings include a communications address for the at least one central station.

6. A wireless, patient vital signs monitor adapted to communicate with a medical telemetry network having at least one central station, the monitor comprising:

one or more sensor input ports for receiving patient vital signs data;

a controller coupled to receive the vital signs data via the one or more input ports;

a wireless transceiver controllable by the controller to communicate with the at least one central station;

where the controller is configured, when not in communication with the at least one central station, to repeatedly attempt to establish communications with the at least one central station via the wireless transceiver; and

a display device controllable by the controller to automatically display a notification to a user of the monitor upon establishing communications with the at least one central station.

7. The monitor of claim 6, further comprising one or more user-operable input devices, and where the controller is adapted to control the display device to display a user-interface adapted to request inputs from a user via the one or more input devices.

8. The monitor of claim 7, where the controller is adapted to receive instructions from the at least one central station via the wireless transceiver, and where the user-interface is at least partially defined by the instructions.

9. The monitor of claim 8, where the medical telemetry network includes plural central stations, and where the instructions identify at least two of the plural central stations, and where the user-interface is adapted to allow a user to select one of the identified central stations via the one or more input devices.

10. The monitor of claim 9, where the controller is adapted, if not in communication with the selected central station, to attempt to establish communications with the selected central station and transmit the vital signs data to the selected central station.

11. The monitor of claim 9, where the controller is adapted to control the display device to display a notification to the user if the controller cannot establish communications with the selected central station.

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12. A wireless, patient vital signs monitor adapted to communicate with a central station, comprising:

a wireless transceiver;

a controller coupled to the wireless transceiver and configured to establish communications with the central station via the wireless transceiver; and

one or more sensor input ports for receiving patient vital signs data;

where the controller is coupled to receive the vital signs data via the one or more input ports and communicate the vital signs data to the central station via the wireless transceiver;

where the controller includes a data storage buffer for storage of the vital signs data, and where the controller is configured to automatically detect a loss of communications with the central station, and to store, in the data storage buffer, at least a portion of the vital signs data received while out of communications with the central station; and

where the controller is configured to communicate the stored vital signs data to the central station via the wireless transceiver if communications with the central station are restored.

13. The monitor of claim 12, where the controller is adapted to store only the portions of the vital signs data that meet one or more defined criteria.

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14. The monitor of claim 12, where the controller is adapted to analyze the vital signs data received while out of communications with the central station, and to detect the occurrence of a medically-significant event based on the vital signs data.

15. The monitor of claim 14, where the controller is adapted to store only those portions of the vital signs data which correspond to the occurrence of medically-significant events.

16. A method for monitoring a patient, comprising:

establishing wireless communications between a patient monitor and a central station;

collecting vital signs data from a patient at the patient monitor;

communicating the vital signs data from the patient monitor to the central station;

detecting a loss of communications between the patient monitor and the central station;

storing at least a portion of the vital signs data at the patient monitor while the patient monitor is out of communications with the central station;

restoring wireless communications between the patient monitor and the central station; and

communicating at least a portion of the stored vital signs data from the patient monitor to the central station.

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17. The method of claim 16, further comprising analyzing the vital signs data at the patient monitor while the patient monitor is out of communications with the central station to detect the occurrence of a medically-significant event, and where the step of storing includes storing only portions of the vital signs data which correspond to the occurrence of medically-significant events.

18. A wireless, patient vital signs monitor adapted to communicate with a medical telemetry network having at least one central station, the monitor comprising:

one or more sensor input ports for receiving patient vital signs data;

a wireless transceiver; and

a controller coupled to receive the vital signs data via the one or more input ports, and configured to control the wireless transceiver to establish and maintain communications with the at least one central station;

where the controller is configured to detect a loss of communications with the at least one central station, and if a loss of communications is detected, to automatically switch from a first operating mode in which the controller transmits the received vital signs data to the at least one central station, to a second operating mode in which the controller does not transmit the received vital signs data to the at least one central station.

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19. The monitor of claim 18, where the controller is adapted to attempt to reestablish communications with the at least one central station, and to automatically switch back to the first operating mode if the communications are reestablished.

20. The monitor of claim 18, further comprising an output device controllable by the controller to indicate an alarm if the vital signs data is outside one or more defined ranges, and where the controller is adapted to control the output device not to indicate the alarm when the controller is in the first operating mode.

21. The monitor of claim 18, further comprising one or more input devices operable by a user to input information to the controller, and where the controller is adapted to disregard at least some inputs by the user when the controller is in the first operating mode.

22. The monitor of claim 18, further comprising a display device controllable by the controller to display information to a user, and where the controller is adapted to control the display device not to display any information when the controller is in the first operating mode.

23. The monitor of claim 18, further comprising an output device controllable by the controller to indicate an alarm, and an input device operable by a user to input a request for assistance to the controller, and where, if the user inputs a request for assistance, the controller is configured to communicate the request to the at least one central station if in the first operating mode, and to control the output device to indicate an alarm if in the second operating mode.

24. A wireless, patient vital signs monitor adapted to communicate with at least one central station connected to receive vital signs data via a communications network, where the communications network includes one or more hard-wired ports and one or more network transceivers, the monitor comprising:

one or more sensor input ports for receiving patient vital signs data;

an output port connectable to a hard-wired port on the network;

a wireless transceiver adapted to transmit information to, and receive information from, at least one of the one or more network transceivers; and

a controller coupled to receive the vital signs data via the one or more input ports, and configured to communicate the vital signs data to the at least one central station via a selected one of the output port or the wireless transceiver.

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25. The monitor of claim 24, where the controller is configured to communicate the vital signs data to the at least one central station via the output port if the output port is connected to a hard-wired port, and to communicate the vital signs data to the at least one central station via the wireless transceiver if the output port is not connected to a hard-wired port.

26. The monitor of claim 25, where the controller is configured to automatically switch from communicating the vital signs data via the output port to communicating the vital signs data via the wireless transceiver upon the disconnection of the output port from a hard-wired port.

27. The monitor of claim 25, where the controller is configured to automatically switch from communicating the vital signs data via the wireless transceiver to communicating the vital signs data via the output port upon the connection of the output port to a hard-wired port.

28. A method for monitoring a patient, comprising:

providing a medical telemetry network having at least one central station connected to one or more wireless transceivers and to one or more hard-wired ports;

collecting vital signs data from a patient at a patient monitor;

automatically detecting whether the patient monitor is connected to one of the one or more hard-wired ports;

communicating the vital signs data to the central station via the wireless transceiver if the patient monitor is not connected to one of the one or more hard-wired ports.

29. The method of claim 28, further comprising, if the patient monitor is connected to one of the one or more hard-wired ports, then communicating the vital signs data to the central station via the connected hard-wired port.

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30. A wireless medical telemetry system, comprising:

a central station adapted to receive vital signs data associated with a plurality of patients; and

at least one wireless patient monitor including a controller and a wireless transceiver, where the patient monitor also includes control software executable by the controller to

monitor a particular one of the plurality of patients by collecting vital signs data from the particular patient, and

transmit the collected vital signs data to the central station via the wireless transceiver;

where the controller is adapted to receive new control software via the wireless transceiver, and to update the control software with new control software.

31. The system of claim 30, where the controller is adapted to receive the new control software from the central station.

32. The system of claim 31 wherein the at least one patient monitor includes plural components, and the controller is adapted to receive the new control software for use with any of the components.

33. The system of claim 32, where the controller is adapted to transmit a query to the central station to determine whether the new control software is available for transmission to the patient monitor.

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34. The system of claim 33, further comprising a second central station, and where the controller is adapted to transmit the query to both central stations, and where each central station is adapted to respond to the query.

35. The system of claim 34, where each of the central station and the second central station are adapted to store a different one of multiple versions of the new control software, and where each central station is adapted to inform the patient monitor of the version of the new control software it stores in response to the query, and

where the controller is adapted to determine which central station is storing a latest version of the new control software and to transmit a download request to the central station that is storing the latest version.

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36. A wireless medical telemetry system, comprising:

at least one wireless patient monitor configured to collect patient vital signs data; and

at least one central station adapted to establish communications with the at least one patient monitor via a wireless transceiver, and to receive the patient vital signs data from the at least one patient monitor;

where the at least one patient monitor is operable by a user to transmit an end-communications signal to the at least one central station; and

where the at least one central station is configured to terminate the communications with the at least one patient monitor in response to the end-communications signal.

37. The system of claim 36, where the at least one central station is configured to communicate a confirmation of the end-communications signal to the patient monitor.

38. The system of claim 37, where the at least one patient monitor includes a display device adapted to display a message to the user in response to the confirmation.

39. The system of claim 36, where the at least one central station is configured to continue receiving the vital signs data until the communications with the at least one patient monitor are terminated.

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40. A method for monitoring a patient, comprising:

establishing wireless communications between a patient monitor and a wireless transceiver connected to a remote central station;

collecting, at the patient monitor, vital signs data from a patient and communicating the vital signs data to the central station via the wireless transceiver;

communicating an end-communications signal from the patient monitor to the central station; and

terminating the communications by the central station in response to the end-communications signal.

41. The method of claim 40, further comprising communicating a confirmation of the end-communications signal from the central station to the patient monitor.

42. The method of claim 41, further comprising displaying a message to a user of the patient monitor in response to the confirmation.

43. The method of claim 40, further comprising discontinuing the step of collecting and communicating the vital signs data.

44. The method of claim 43, where the step of terminating is performed before the discontinuing.

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45. The method of claim 43, where the step of terminating is performed after the discontinuing.

46. A system for monitoring the vital signs of a patient from a selected remote location, the system comprising:

at least one wireless patient monitor adapted to collect vital signs data from a patient;

a medical telemetry network including a plurality of central stations adapted to receive vital signs data, and one or more wireless transceivers adapted to communicate with the at least one patient monitor;

where the at least one patient monitor is operable by a user to select one of the plural central stations, and to transmit a request to establish communications to the selected central station via the one or more wireless transceivers.

47. The system of claim 46, where the selected central station is adapted to establish communications with the at least one patient monitor in response to the request, and to receive the vital signs data via the one or more wireless transceivers.

48. The system of claim 46, where at least one of the plural central stations is configured to communicate a list of the plural central stations to the at least one patient monitor, and where the at least one patient monitor includes a display device adapted to display the list of plural central stations to the user.

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49. The system of claim 48, where the at least one patient monitor includes one or more input devices operable by the user to select one of the plural central stations on the list.

50. The system of claim 46, where the at least one patient monitor is operable by the user to select a different one of the plural central stations, and to transmit, to the selected central station, a request to change communications from the selected central station to the different central station.

51. The system of claim 50, where the selected central station is configured to terminate communications with the at least one patient monitor in response to the request to change communications.

52. The system of claim 51, where the different central station is configured to establish communications with the at least one patient monitor in response to the request to change communications, and to receive the vital signs data via the one or more wireless transceivers.

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53. A method for monitoring a patient, comprising:

establishing wireless communications between a patient monitor and a communications network having at least one wireless transceiver and a plurality of central stations;

selecting, at the patient monitor, one of the plural central stations;

collecting, at the patient monitor, vital signs data from a patient and communicating the vital signs data to the wireless transceiver; and

communicating the vital signs data from the wireless transceiver to the selected central station via the communications network.

54. The method of claim 53, further comprising:

communicating a list of the plural central stations to the patient monitor via the wireless transceiver; and

displaying the list to a user of the patient monitor.

55. The method of claim 54, further comprising receiving an input from the user selecting one of the plural central stations on the list.

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56. The method of claim 55, further comprising:

receiving a subsequent input from the user selecting a different one of the plural central stations;

communicating subsequently collected vital signs data to the wireless transceiver; and

communicating the subsequently collected vital signs data from the wireless transceiver to the different central station via the communications network.

57. A medical monitoring system, comprising:

a central station adapted to receive vital signs data concerning a plurality of patients;

one or more transmitter/receivers associated with the central station; and

at least one patient monitor configured to monitor a particular one of the plurality of patients by collecting vital signs data from the particular patient, and configured to establish communications with the central station and communicate the collected vital signs data to the central station via the one or more transmitter/receivers;

where the at least one patient monitor is operable by a user to identify the particular patient from the plurality of patients, and to inform the central station of the identity of the particular patient; and

where the central station is configured to associate the vital signs data received from the at least one patient monitor with the particular patient.

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58. The system of claim 57, where the central station is configured to transmit a list of the plurality of patients to the at least one patient monitor, and where the at least one patient monitor includes a display device adapted to display the list to the user.

59. The system of claim 57, where the central station is adapted to store the identity of the particular patient and, in the event that the communications with the central station are lost and then restored, to transmit a request to the at least one patient monitor for a confirmation that the at least one patient monitor is still configured to monitor the particular patient.

60. The system of claim 57, where the system, the one or more transmitter/receivers, and the at least one patient monitor is wireless.

61. The system of claim 60, where the central station is configured to transmit a list of the plurality of patients to the at least one patient monitor, and where the at least one patient monitor includes a display device adapted to display the list to the user.

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62. The system of claim 61, where the central station is adapted to store the identity of the particular patient and, in the event that the communications with the central station are lost and then restored, to transmit a request to the at least one patient monitor for a confirmation that the at least one patient monitor is still configured to monitor the particular patient.

63. A method for monitoring a patient, comprising:

establishing communications between a patient monitor and a central station via a transmitter/receiver associated with the central station, where the central station is adapted to receive vital signs data from a plurality of patients;

configuring the patient monitor to collect vital signs data from a particular one of the plural patients;

identifying, at the patient monitor, the particular patient;

communicating the identity of the particular patient to the central station;

communicating the vital signs data to the central station; and

associating, at the central station, the vital signs data with the particular patient.

64. The method of claim 63, further comprising:

communicating a list of the plural patients from the central station to the patient monitor; and

displaying the list to a user of the monitor.

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65. The method of claim 63, further comprising,

if the communications between the patient monitor and the central station are lost, then:

restoring the communications between the patient monitor and the central station;

communicating a request for confirmation from the central station to the patient monitor that the patient monitor is still configured to monitor the particular patient; and

communicating the confirmation from the patient monitor to the central station.

66. The method of claim 63, where the step of establishing communications is between a wireless patient monitor and a central station via a wireless transmitter/receiver associated with the central station, where the central station is adapted to receive vital signs data from a plurality of patients.

67. The method of claim 66, further comprising:

communicating a list of the plural patients from the central station to the patient monitor; and

displaying the list to a user of the monitor.

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68. The method of claim 66, further comprising,

if the communications between the patient monitor and the central station are lost, then:

restoring the communications between the patient monitor and the central station;

communicating a request for confirmation from the central station to the patient monitor that the patient monitor is still configured to monitor the particular patient; and

communicating the confirmation from the patient monitor to the central station.

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69. A medical monitoring system, comprising:

a central station associated with one or more transmitter/receivers, and adapted to receive vital signs data concerning a plurality of patients; and

a patient monitor having a transmitter/receiver, the patient monitor being adapted to establish communications with the central station and transmit an identity of a particular one of the plural patients, and adapted to collect vital signs data from the particular patient when connected to the particular patient and to transmit the vital signs data to the central station;

where the central station is configured to receive the identity of the particular patient and the vital signs data, and to associate the vital signs data with the particular patient when the communications are established; and

where, in the event that the communications between the patient monitor and central station are lost for a period of time and then restored, the central station is configured to automatically determine whether the patient monitor is still connected to the particular patient, and to associate the vital signs data with the particular patient if the patient monitor is still connected to the particular patient.

70. The system of claim 69, where the central station is configured to determine whether the patient monitor is still connected to the particular patient by measuring the period of time the communications are lost, and associating the vital signs data with the particular patient if the period of time is less than a predetermined length of time.

71. The system of claim 69, where the patient monitor is adapted to detect the disconnection of the particular patient from the patient monitor, and where the patient monitor is adapted to inform the central station if the particular patient was disconnected from the patient monitor during the period of time the communications were lost.

72. The system of claim 69, where the central station is configured to transmit a request to the patient monitor for a patient identity if the central station does not determine that the patient monitor is still connected to the particular patient.

73. The system of claim 69, where the system and the one or more transmitter/receivers are wireless.

74. The system of claim 73, where the central station is configured to determine whether the patient monitor is still connected to the particular patient by measuring the period of time the communications are lost, and associating the vital signs data with the particular patient if the period of time is less than a predetermined length of time.

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75. The system of claim 73, where the patient monitor is adapted to detect the disconnection of the particular patient from the patient monitor, and where the patient monitor is adapted to inform the central station if the particular patient was disconnected from the patient monitor during the period of time the communications were lost.

76. The system of claim 73, where the central station is configured to transmit a request to the patient monitor for a patient identity if the central station does not determine that the patient monitor is still connected to the particular patient.

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77. A method for monitoring a patient from a central station configured to monitor a plurality of patients, where each of the plural patients has an identity, the method comprising:

establishing communications between a patient monitor connected to a particular one of the plural patients and the central station;

communicating the identity of the particular patient from the patient monitor to the central station;

collecting vital signs data from the particular patient at the patient monitor;

communicating the vital signs data to the central station;

associating, at the central station, the vital signs data with the particular patient; and

in the event communications between the patient monitor and the central station are lost for a period of time:

reestablishing the communications between the patient monitor and the central station,

automatically determining, at the central station, whether the patient monitor is still connected to the particular patient, and

if the patient monitor is still connected to the particular patient, then associating the vital signs data with the particular patient.

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78. The method of claim 77, where the step of determining includes determining that the patient monitor is still connected to the particular patient if the period of time when the communications between the patient monitor and the central station were lost was less than a predetermined length of time.

79. The method of claim 77, where the step of determining includes

detecting, at the patient monitor, if the particular patient was disconnected from the patient monitor during the period of time when the communications between the patient monitor and the central station were lost; and

informing the central station whether the particular patient was disconnected from the patient monitor during the period of time when the communications between the patient monitor and the central station were lost.

80. The method of claim 77, where the step of establishing communications involves wireless communications between a patient monitor connected to a particular one of the plural patients and the central station.

81. The method of claim 80, where the step of determining includes determining that the patient monitor is still connected to the particular patient if the period of time when the communications between the patient monitor and the central station were lost was less than a predetermined length of time.

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82. The method of claim 80, where the step of determining includes

detecting, at the patient monitor, if the particular patient was disconnected from the patient monitor during the period of time when the communications between the patient monitor and the central station were lost; and

informing the central station whether the particular patient was disconnected from the patient monitor during the period of time when the communications between the patient monitor and the central station were lost.

83. A method for monitoring a patient, comprising:

collecting, by a patient monitor, vital signs data from the patient;

establishing communications between the patient monitor and a central station;

communicating the vital signs data from the patient monitor to the central station;

analyzing the vital signs data to detect an alarm condition;

indicating the alarm condition at both the patient monitor and the central station;

receiving, at the patient monitor, an acknowledgement from a user of the patient monitor;

communicating the acknowledgement from the patient monitor to the central station; and

terminating the indication of the alarm condition at the central station in response to the acknowledgement.

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84. The method of claim 84, where the step of indicating includes indicating the alarm condition at the patient monitor, and further comprising terminating the indication of the alarm condition at the patient monitor in response to the acknowledgement.

85. The method of claim 84, where the step of indicating includes producing an audible signal at the central station, and where the step of terminating includes terminating the audible signal.

86. The method of claim 84, where the step of indicating includes producing a visible signal at the central station, and where the step of terminating includes terminating the visible signal.

87. The method of claim 84, where the step of analyzing is performed by the central station.

88. The method of claim 84, where the step of analyzing is performed by the patient monitor.

89. The method of claim 84, where the step of establishing communications involves wireless communications between the patient monitor and a central station.

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90. The method of claim 89, where the step of indicating includes indicating the alarm condition at the patient monitor, and further comprising terminating the indication of the alarm condition at the patient monitor in response to the acknowledgement.

91. The method of claim 89, where the step of indicating includes producing an audible signal at the central station, and where the step of terminating includes terminating the audible signal.

92. The method of claim 89, where the step of indicating includes producing a visible signal at the central station, and where the step of terminating includes terminating the visible signal.

93. The method of claim 89, where the step of analyzing is performed by the central station.

94. The method of claim 89, where the step of analyzing is performed by the patient monitor.

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95. A medical monitoring system, comprising:

at least one patient monitor adapted to collect vital signs data from a patient; and

a central station adapted to communicate with the at least one patient monitor via transmissions;

where the at least one patient monitor includes a controller configured to analyze the vital signs data based on one or more variable parameter values; and

where the central station is configured to communicate an instruction to the at least one patient monitor to change the value of at least one of the one or more variables to a new value, and where the controller is configured to analyze the vital signs data based on the new value in response to the instruction.

96. The system of claim 95, where the one or more variable parameter values includes a nominal data range, and where the controller is configured to analyze the vital signs data to determine whether the vital signs data is within the nominal data range and to indicate an alarm condition to a user if the vital signs data is outside the nominal data range.

97. The system of claim 96, where the vital signs data includes data indicating a heart-rate of the patient, and where the one or more variable parameter values includes a nominal range of heart-rate data.

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98. The system of claim 96, where the vital signs data includes data chosen from the group consisting of the oxygen saturation of the patient's arterial blood, the patient's blood pressure, and the amount of carbon dioxide in the patient's breath, and where the one or more variable parameter values is respectively chosen from the group consisting of a nominal range of oxygen saturation data, blood pressure data, and carbon dioxide data.

99. The system of claim 95, where the system and the at least one patient monitor are wireless, and the central station is adapted to communicate with the at least one patient monitor via wireless transmissions.

100. The system of claim 99, where the one or more variable parameter values includes a nominal data range, and where the controller is configured to analyze the vital signs data to determine whether the vital signs data is within the nominal data range and to indicate an alarm condition to a user if the vital signs data is outside the nominal data range.

101. The system of claim 100, where the vital signs data includes data indicating a heart-rate of the patient, and where the one or more variable parameter values includes a nominal range of heart-rate data.

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102. The system of claim 100, where the vital signs data includes data chosen from the group consisting of the oxygen saturation of the patient's arterial blood, the patient's blood pressure, and the amount of carbon dioxide in the patient's breath, and where the one or more variable parameter values is respectively chosen from the group consisting of a nominal range of oxygen saturation data, blood pressure data, and carbon dioxide data.

103. A medical monitoring system, comprising:

a central station adapted to receive vital signs data concerning a plurality of patients;

one or more transmitter/receivers associated with the central station; and

at least one patient monitor configured to monitor a particular one of the plurality of patients by collecting vital signs data from the particular patient, and configured to establish communications with the central station and communicate the collected vital signs data to the central station via the one or more transmitter/receivers;

where the system is operable by plural users to identify the particular patient from the plurality of patients, and to inform the user of the identity of the particular patient; and

where the system is configured to associate the vital signs data received from the at least one patient monitor with the particular patient.

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104. The system of claim 103, where the central station is operable by a first user to identify the particular patient from the plurality of patients, and to inform a second user of the identity of the particular patient.

105. The system of claim 103, where the at least one patient monitor is operable by the second user to identify the particular patient from the plurality of patients, and to inform a second user of the identity of the particular patient.

106. The system of claim 104, where the central station is configured to maintain a list of the plurality of patients being monitored by the system.

107. The system of claim 104, where the central station is configured to transmit a list of the plurality of patients to the at least one patient monitor, and where the at least one patient monitor includes a display device adapted to display the list to the second user.

108. The system of claim 107, where the central station is adapted to store the identity of the particular patient and, in the event that the communications with the central station are lost and then restored, to transmit a request to the at least one patient monitor for a confirmation that the at least one patient monitor is still configured to monitor the particular patient.

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109. A medical monitoring system, comprising:

a central station associated with one or more transmitter/receivers, and adapted to receive vital signs data concerning a plurality of patients; and

a patient monitor having a transmitter/receiver, the patient monitor being adapted to establish communications with the central station and adapted to collect vital signs data from a particular one of the plural patients when connected to the particular patient and to transmit the vital signs data to the central station;

where the central station is configured to receive the vital signs data, and to associate the vital signs data with the particular patient when the communications are established; and

where, in the event that the communications between the patient monitor and central station are lost for a period of time and then restored, the central station is configured to automatically determine whether the patient monitor is still connected to the particular patient, and to associate the vital signs data with the particular patient if the patient monitor is still connected to the particular patient.

110. The system of claim 109, where the central station is configured to determine whether the patient monitor is still connected to the particular patient by measuring the period of time the communications are lost, and associating the vital signs data with the particular patient if the period of time is less than a predetermined length of time.

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111. The system of claim 109, where the patient monitor is adapted to detect the disconnection of the particular patient from the patient monitor, and where the patient monitor is adapted to send a patient-disconnection signal to the central station if the particular patient was disconnected from the patient monitor during the period of time the communications were lost.

112. The system of claim 111, wherein the patient monitor is adapted to detect the identity of the particular patient and inform the central station of the identity.

113. The system of claim 109, where the central station is configured to transmit a request to the patient monitor for a patient identity if the central station does not determine that the patient monitor is still connected to the particular patient.

114. The system of claim 109, where the system and the one or more transmitter/receivers are wireless.

115. The system of claim 114, where the central station is configured to determine whether the patient monitor is still connected to the particular patient by measuring the period of time the communications are lost, and associating the vital signs data with the particular patient if the period of time is less than a predetermined length of time.

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116. The system of claim 114, where the patient monitor is adapted to detect the disconnection of the particular patient from the patient monitor, and where the patient monitor is adapted to send a patient-disconnection signal to the central station if the particular patient was disconnected from the patient monitor during the period of time the communications were lost.

117. The system of claim 116, wherein the patient monitor is adapted to detect the identity of the particular patient and inform the central station of the identity.

118. A wireless medical telemetry system, comprising:

at least one wireless patient monitor configured to monitor a patient by collecting vital signs data from the patient;

a first central station associated with one or more wireless transceivers, and adapted to establish communications with the at least one patient monitor and receive the vital signs data via the one or more wireless transceivers; and

a second central station associated with the one or more wireless transceivers, and adapted to receive vital signs data via the one or more wireless transceivers;

where the second central station is configured to automatically attempt to establish communications with the at least one patient monitor and receive the vital signs data in place of the first central station in the event the communications between the first central station and the at least one patient monitor are lost.

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119. The system of claim 118, where the second central station is configured to monitor the communications between the first central station and the at least one patient monitor.

120. The system of claim 119, where the second central station is configured to monitor the communications between the first central station and the at least one patient monitor by receiving the vital signs data from the first central station, and to automatically attempt to establish communications with the at least one patient monitor if the second central station stops receiving the vital signs data from the first central station.

121. The system of claim 118, where the at least one patient monitor is configured to transmit a request to establish communications to the second central station via the one or more wireless transceivers in the event the communications with the first central station are lost.

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122. The system of claim 118, further comprising a third central station associated with the one or more wireless transceivers, and adapted to receive vital signs data via the one or more wireless transceivers, and where both the second and third central stations are configured to automatically attempt to establish communications with the at least one patient monitor and receive the vital signs data in place of the first central station in the event the communications between the first central station and the at least one patient monitor are lost.

123. The system of claim 118, where the first central station is configured to communicate instructions to the at least one patient monitor to control the patient monitor, and where the second central station is configured to automatically attempt to assume control of the at least one patient monitor in the event the communications between the first central station and the at least one patient monitor are lost.

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124. A method for monitoring a patient, comprising:

establishing wireless communications between a patient monitor and a first central station;

collecting vital signs data from a patient at the patient monitor;

communicating the vital signs data from the patient monitor to the first central station; and

if communications between the patient monitor and the first central station are lost, automatically establishing wireless communications between the patient monitor and a second central station, and communicating the vital signs data from the patient monitor to the second central station.

125. The method of claim 124, further comprising monitoring, at the second central station, the communications between the patient monitor and the first central station.

126. The method of claim 125, where the step of monitoring includes receiving, at the second central station, the vital signs data from the first central station.

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127. The method of claim 124, where the step of establishing wireless communications between the patient monitor and the second central station includes detecting, at the patient monitor, a loss of communications with the first central station, and transmitting a request to establish communications from the patient monitor to the second central station.

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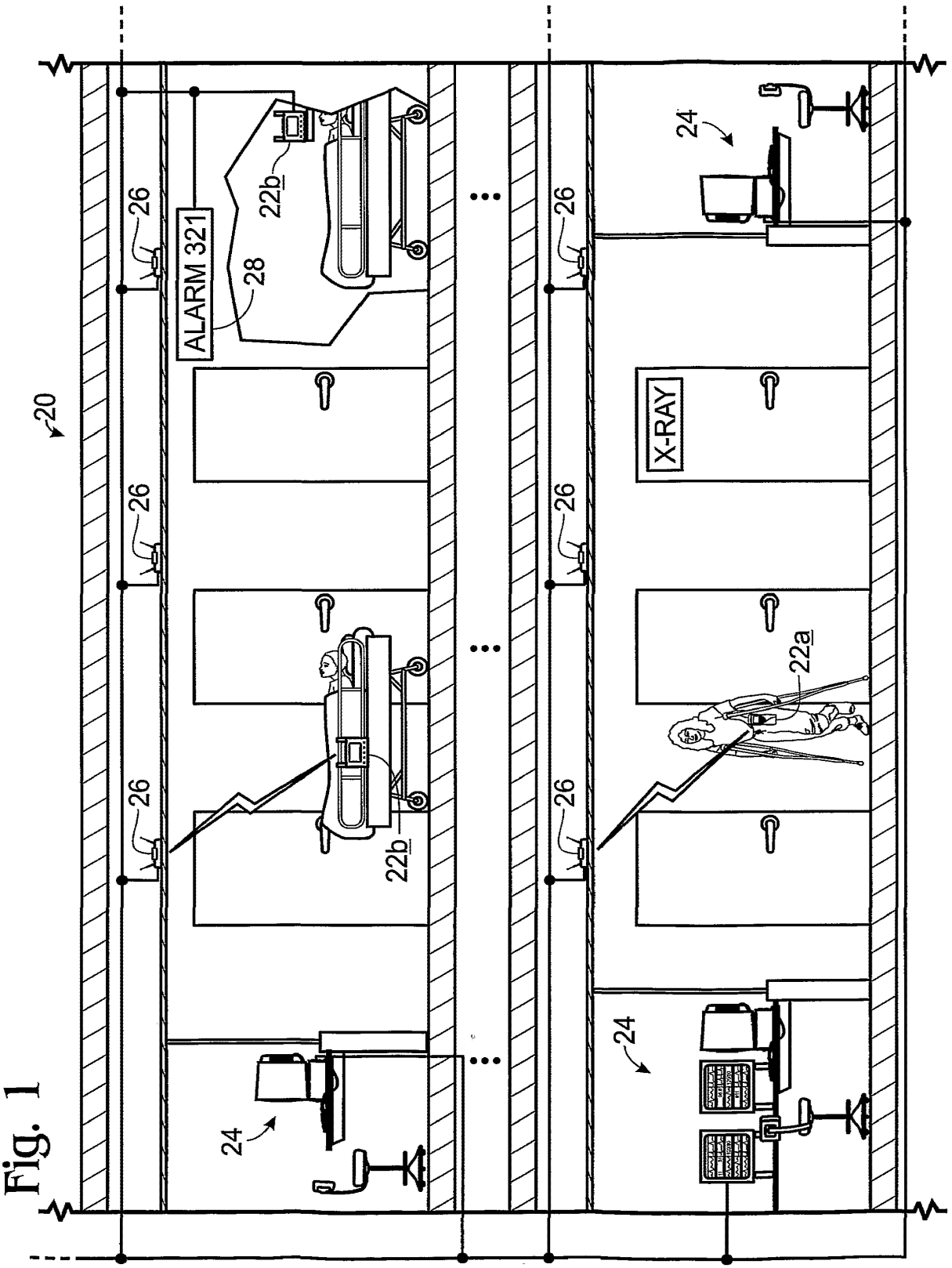


Fig. 1

Fig. 2

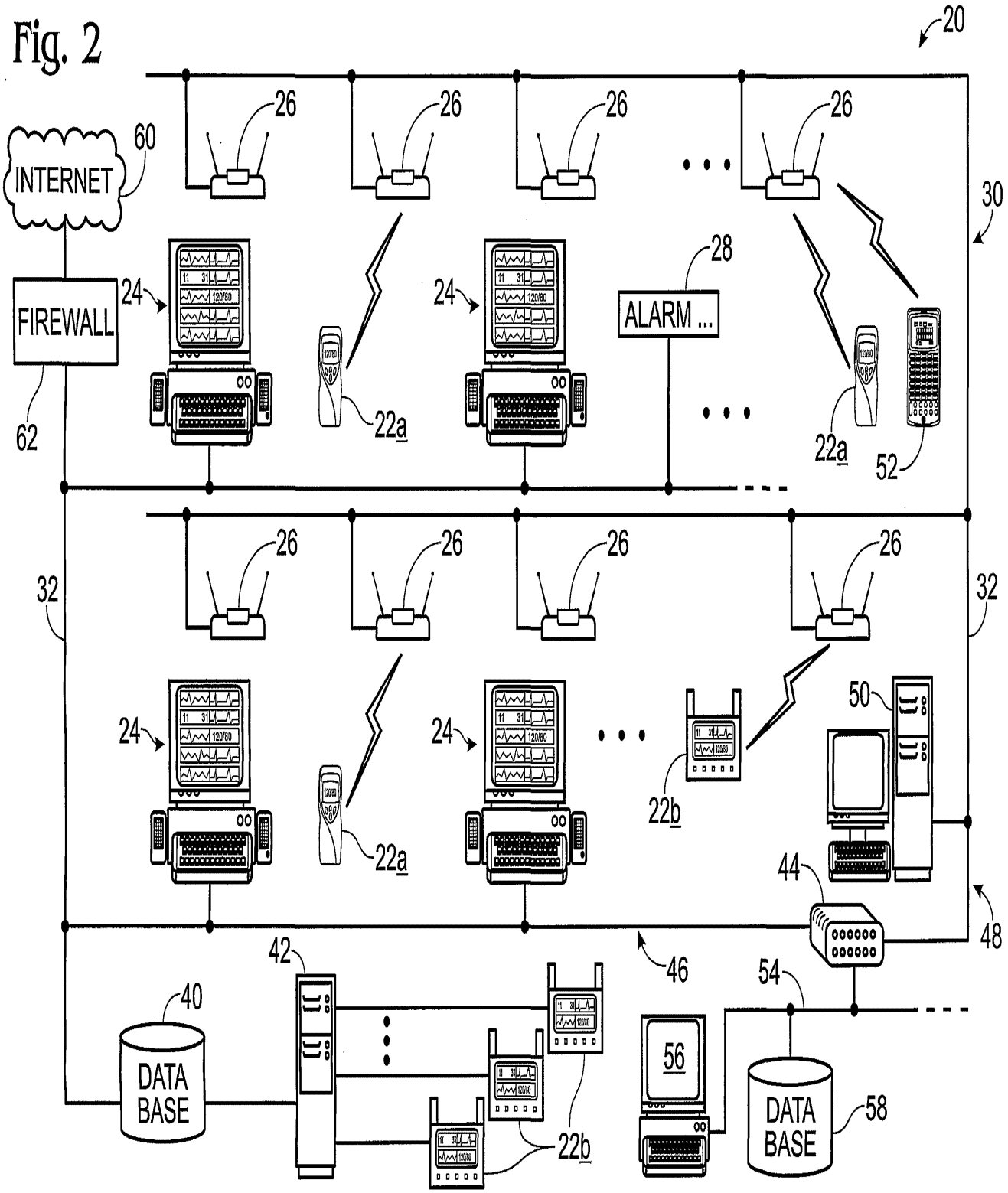

20
INTERNET
60
FIREWALL
62
24
26
30
28
ALARM ...
22a
22b
52
32
50
44
48
46
42
40
DATA BASE
54
56
58
DATA BASE

Fig. 3

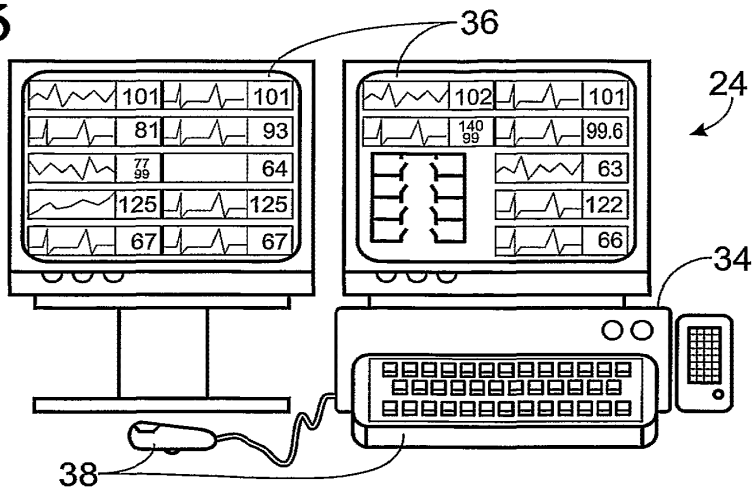

36
24
34
38
101
101
81
93
64
125
125
67
67
102
101
99.6
63
122
66

Fig. 4

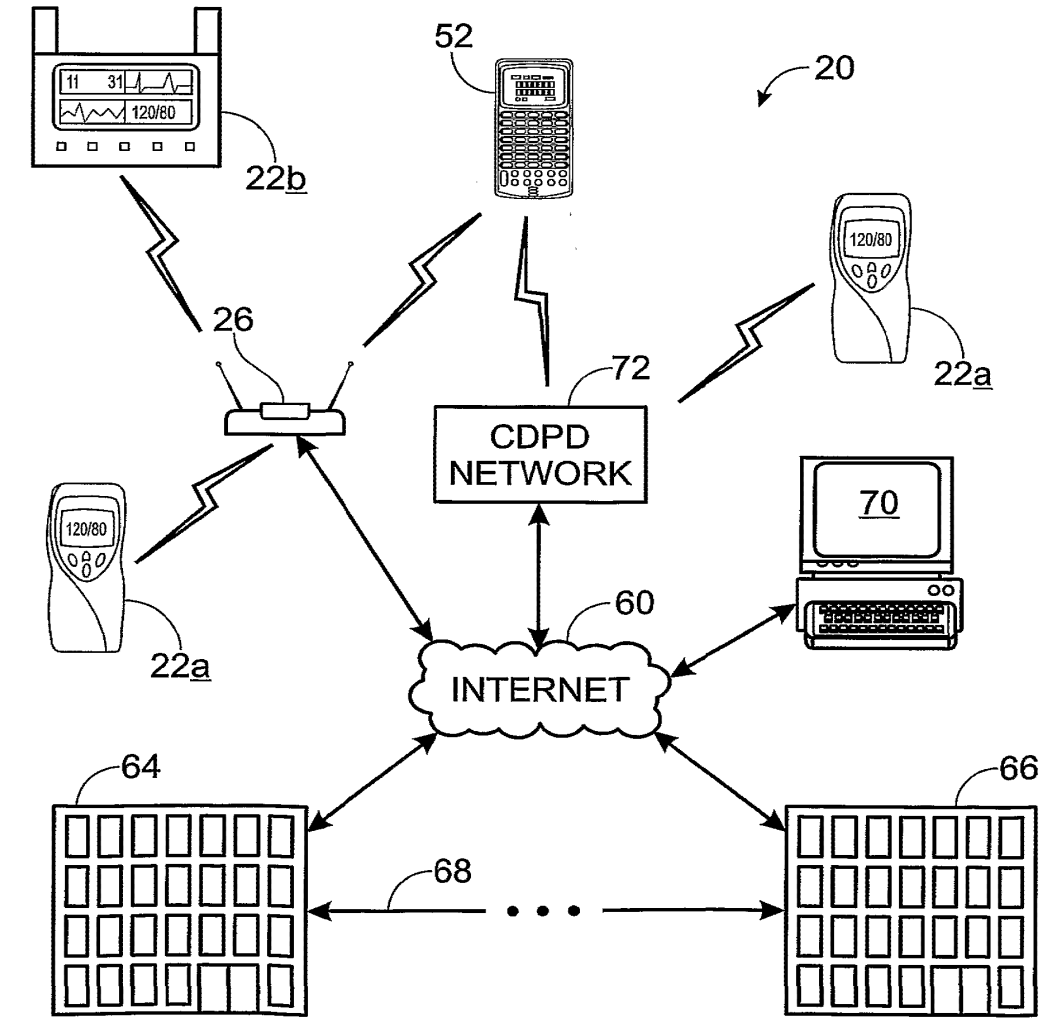

52
20
22b
26
72
CDPD
NETWORK
22a
120/80
70
60
INTERNET
64
66
68

Fig. 5

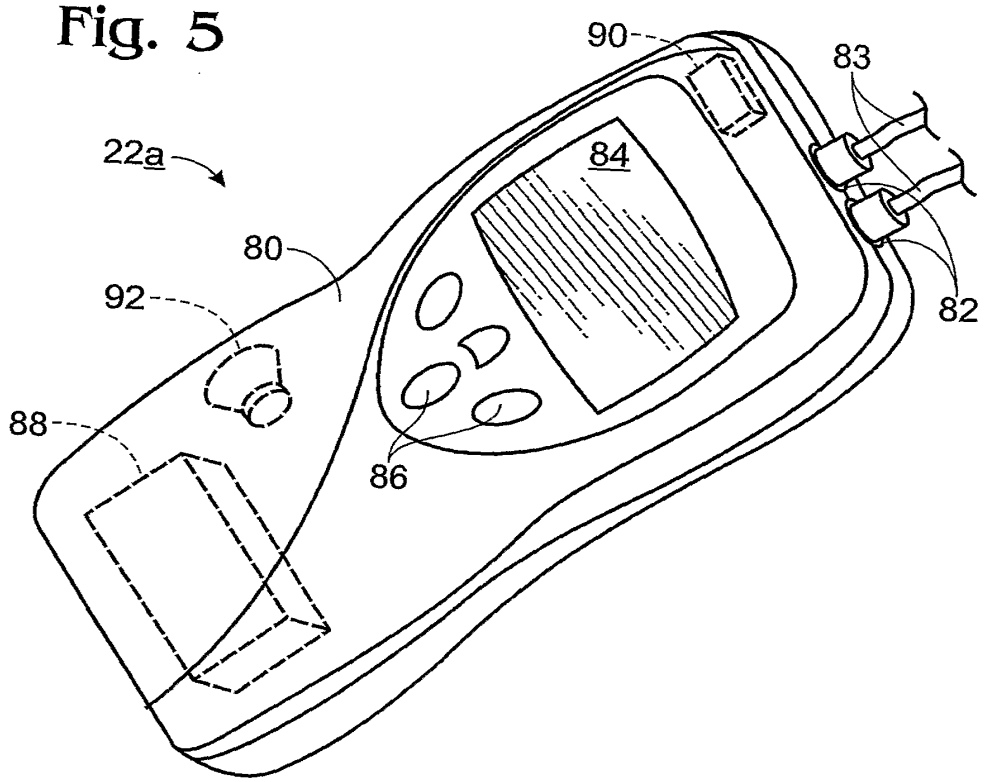


Fig. 6

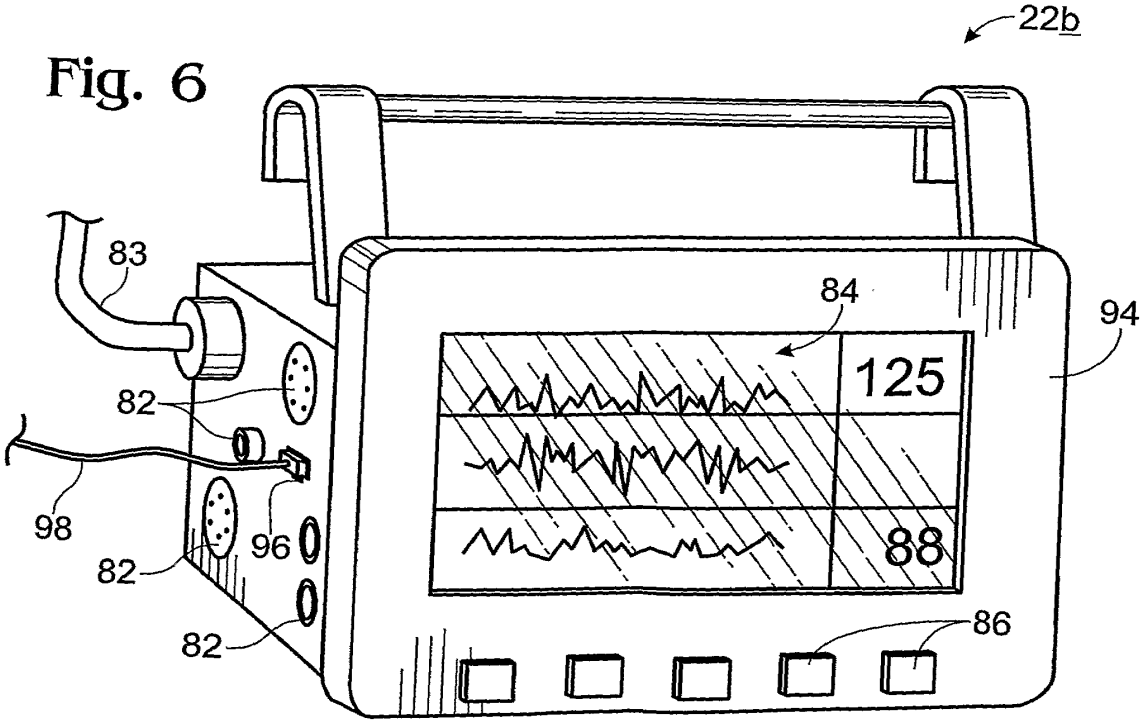


Fig. 7

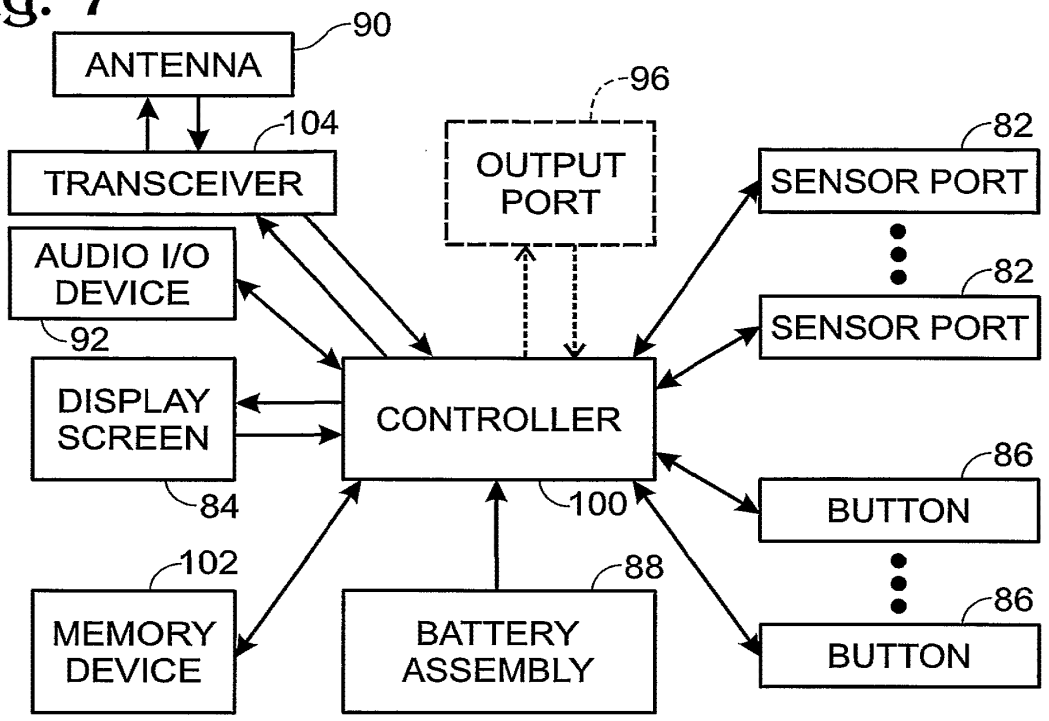

ANTENNA
90
TRANSCEIVER
104
OUTPUT PORT
96
SENSOR PORT
82
SENSOR PORT
82
AUDIO I/O DEVICE
92
DISPLAY SCREEN
84
CONTROLLER
100
BUTTON
86
BUTTON
86
MEMORY DEVICE
102
BATTERY ASSEMBLY
88

Fig. 8

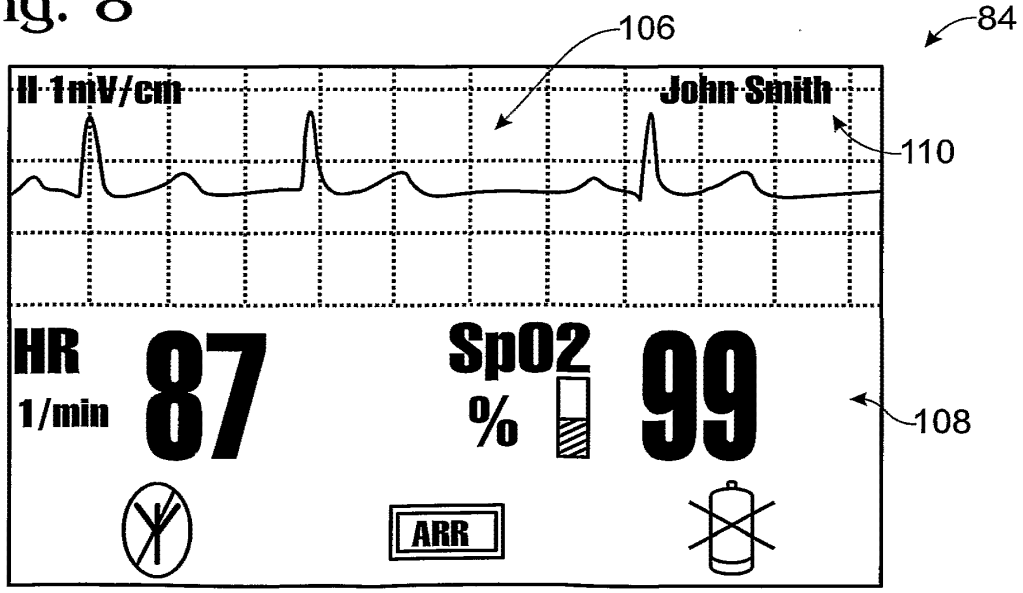

84
106
II 1mV/cm
John Smith
110
HR
1/min
87
SpO2
%
99
108
ARR

Fig. 9

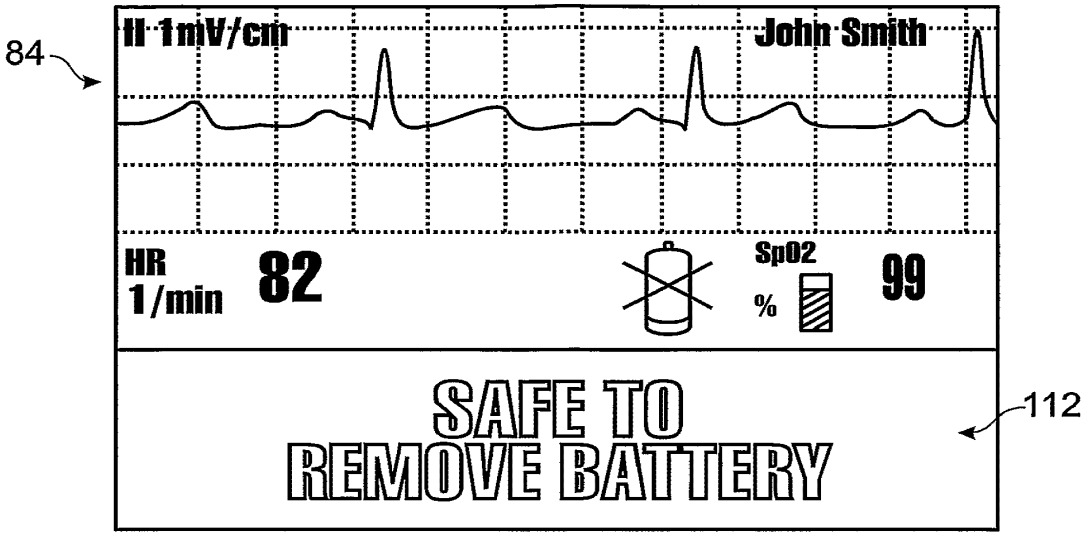

II 1mV/cm
John Smith
84
HR
1/min
82
SpO2
%
99
SAFE TO
REMOVE BATTERY
112

Fig. 10

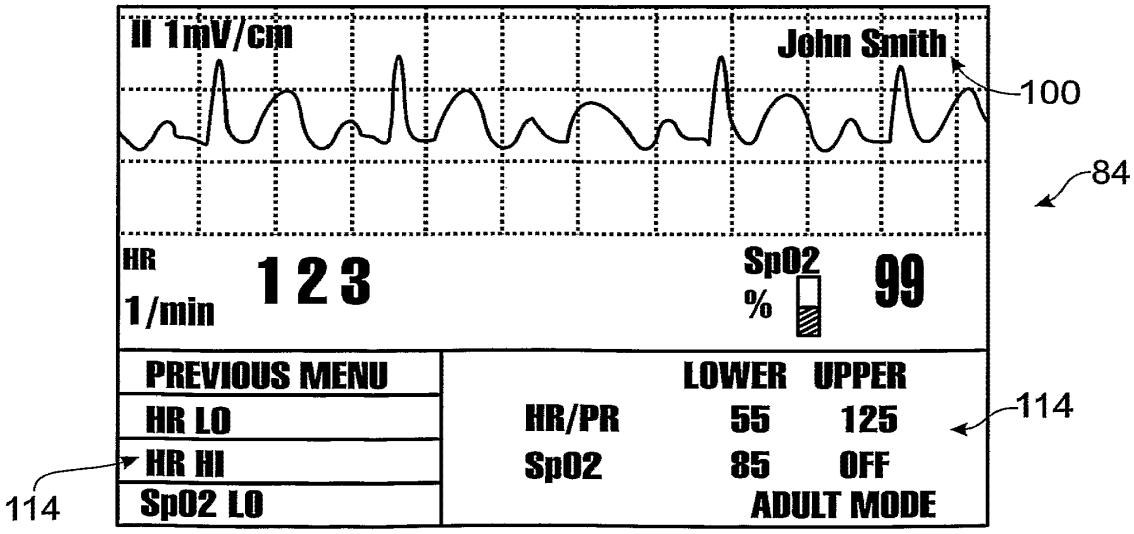

II 1mV/cm
John Smith
100
84
HR
1/min
123
SpO2
%
99
PREVIOUS MENU
HR LO
HR HI
SpO2 LO
114
LOWER UPPER
HR/PR 55 125
SpO2 85 OFF
ADULT MODE
114

Fig. 11

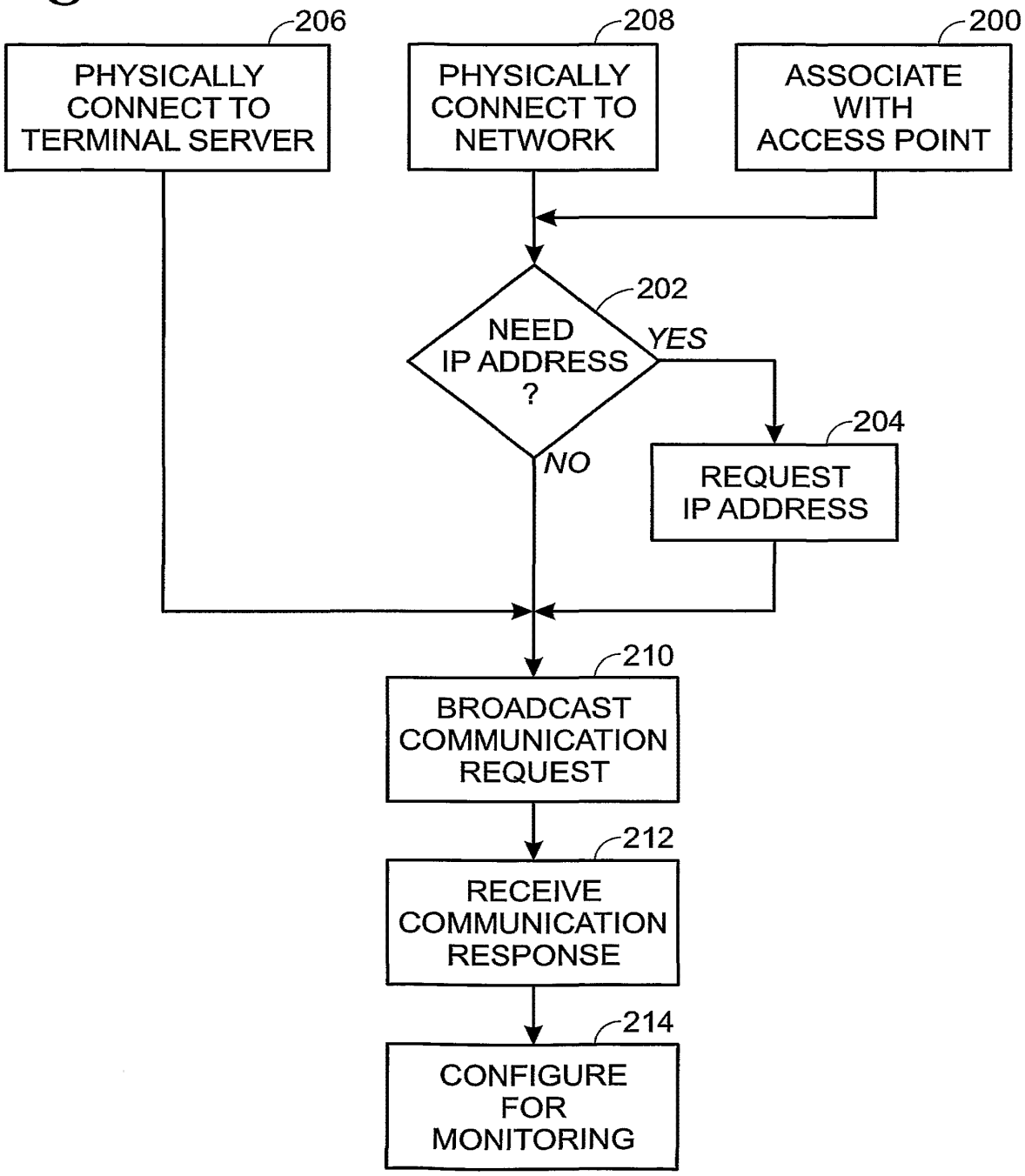

206
PHYSICALLY CONNECT TO TERMINAL SERVER
208
PHYSICALLY CONNECT TO NETWORK
200
ASSOCIATE WITH ACCESS POINT
202
NEED IP ADDRESS ?
YES
NO
204
REQUEST IP ADDRESS
210
BROADCAST COMMUNICATION REQUEST
212
RECEIVE COMMUNICATION RESPONSE
214
CONFIGURE FOR MONITORING

Fig. 12

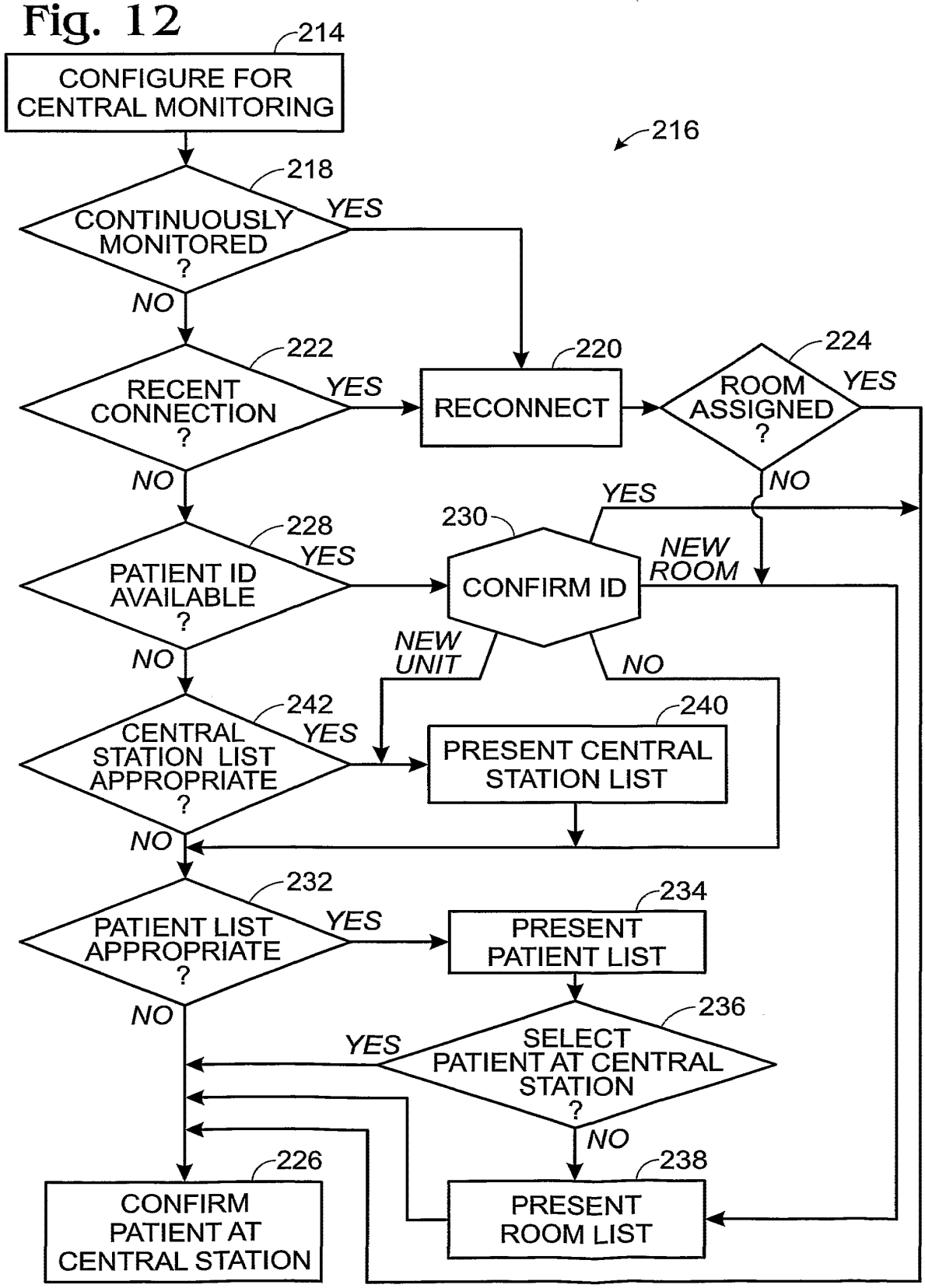

214
CONFIGURE FOR CENTRAL MONITORING
216
218
CONTINUOUSLY MONITORED ?
YES
NO
222
RECENT CONNECTION ?
YES
NO
220
RECONNECT
224
ROOM ASSIGNED ?
YES
NO
228
PATIENT ID AVAILABLE ?
YES
NO
230
CONFIRM ID
YES
NEW ROOM
NEW UNIT
NO
242
CENTRAL STATION LIST APPROPRIATE ?
YES
NO
240
PRESENT CENTRAL STATION LIST
232
PATIENT LIST APPROPRIATE ?
YES
NO
234
PRESENT PATIENT LIST
236
SELECT PATIENT AT CENTRAL STATION ?
YES
NO
226
CONFIRM PATIENT AT CENTRAL STATION
238
PRESENT ROOM LIST

Fig. 13

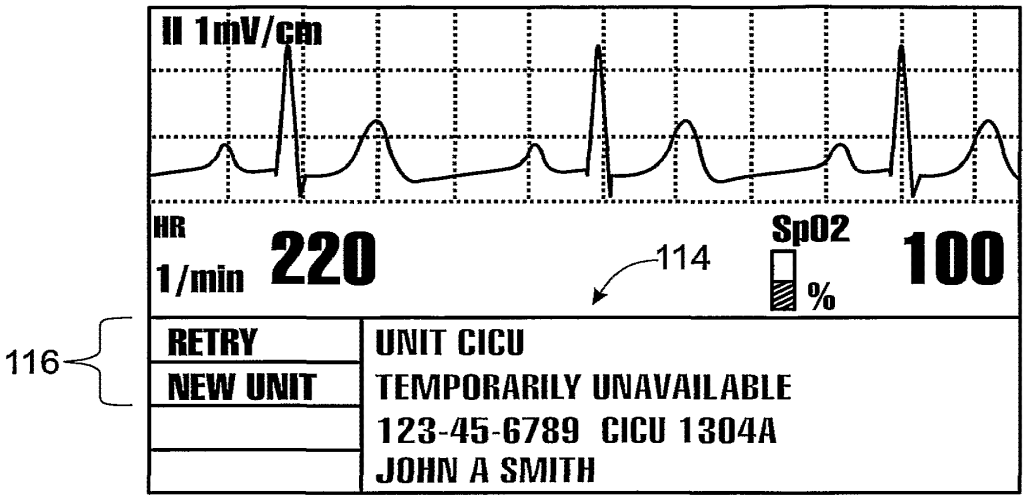

II 1mV/cm
HR
1/min
220
114
SpO2
%
100
116
RETRY
NEW UNIT
UNIT CICU
TEMPORARILY UNAVAILABLE
123-45-6789 CICU 1304A
JOHN A SMITH

Fig. 14

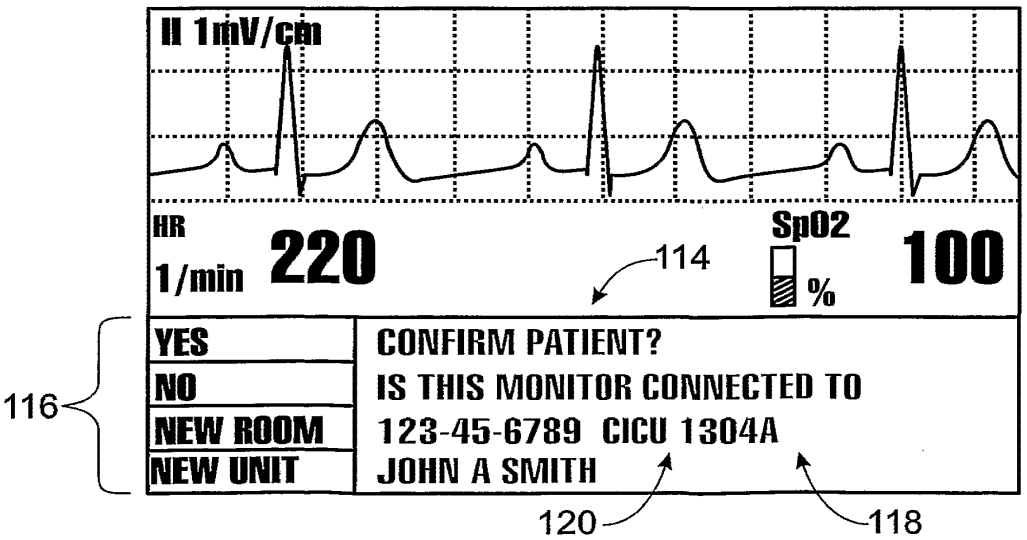

II 1mV/cm
HR
1/min
220
114
SpO2
%
100
116
YES
NO
NEW ROOM
NEW UNIT
CONFIRM PATIENT?
IS THIS MONITOR CONNECTED TO
123-45-6789 CICU 1304A
JOHN A SMITH
120
118

Fig. 15

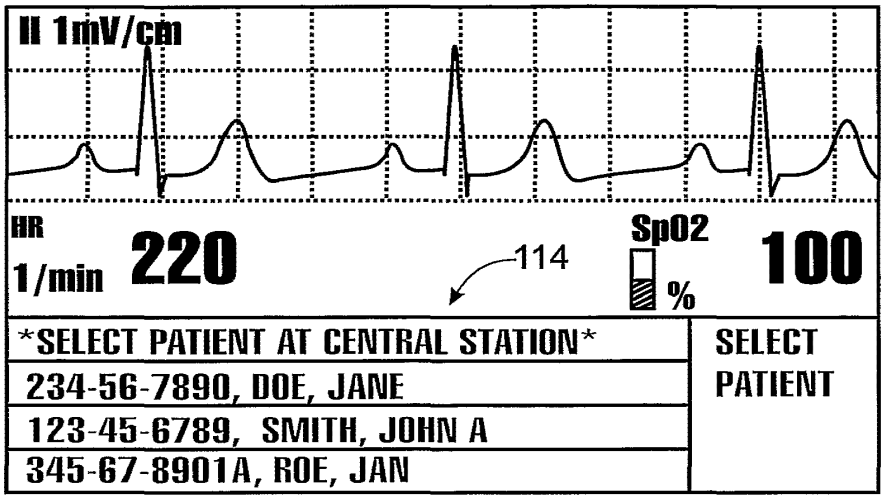

II 1mV/cm
HR
1/min 220
114
SpO2
%
100
SELECT PATIENT AT CENTRAL STATION
234-56-7890, DOE, JANE
123-45-6789, SMITH, JOHN A
345-67-8901A, ROE, JAN
SELECT
PATIENT

Fig. 16

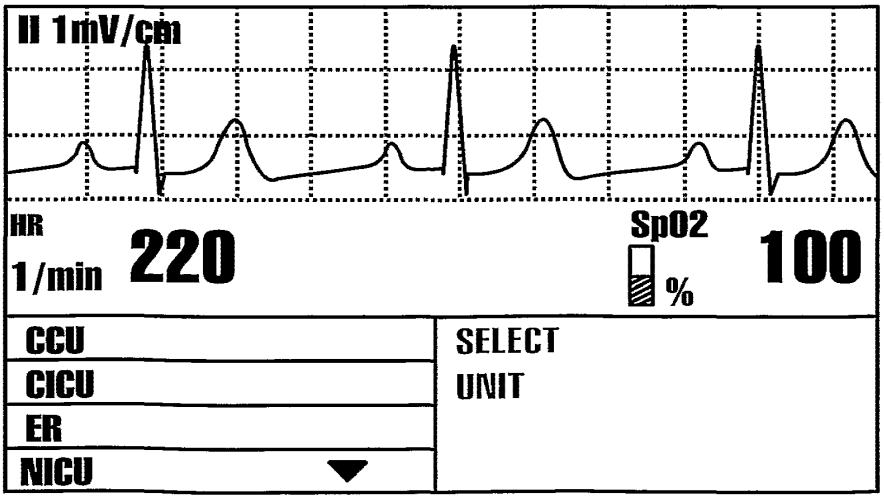

II 1mV/cm
HR
1/min 220
SpO2
%
100
CCU
CICU
ER
NICU
SELECT
UNIT

Fig. 17

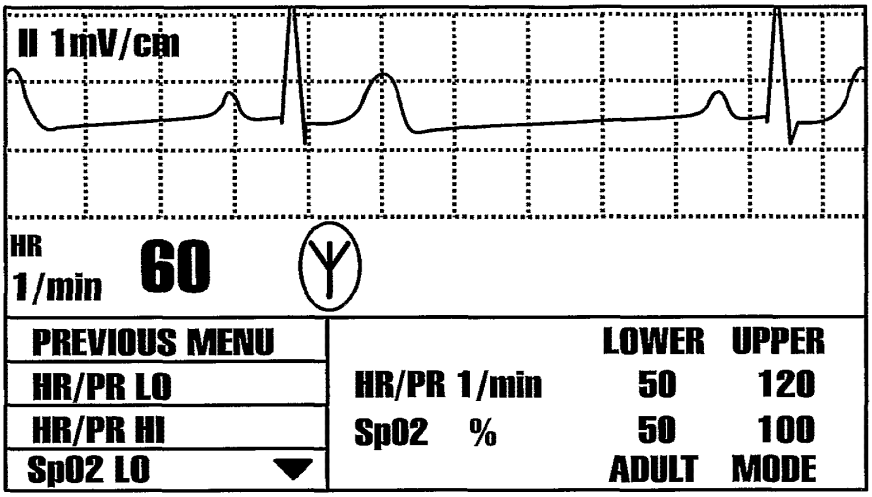

II 1mV/cm
HR
1/min
60
PREVIOUS MENU
HR/PR LO
HR/PR HI
SpO2 LO
LOWER
UPPER
HR/PR 1/min
50
120
SpO2 %
50
100
ADULT MODE

Fig. 18

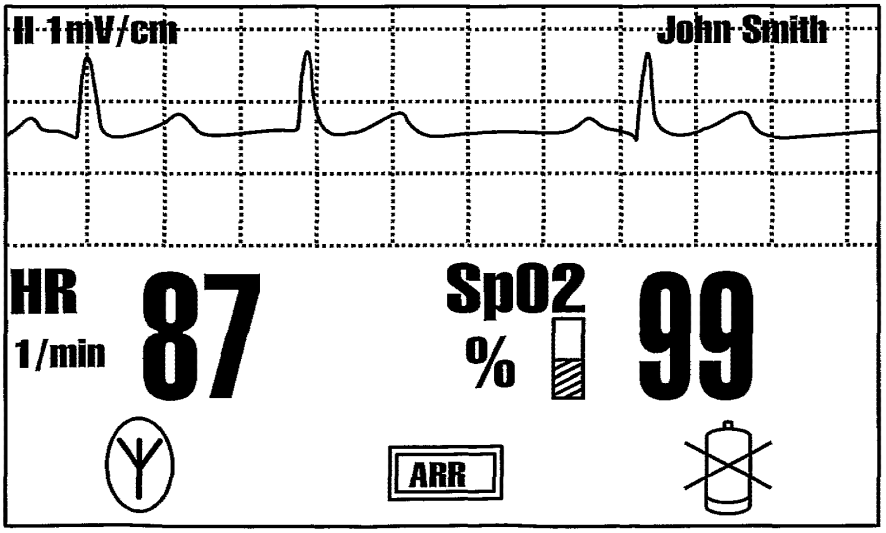

II 1mV/cm
John Smith
HR
1/min
87
SpO2
%
99
ARR

Fig. 19

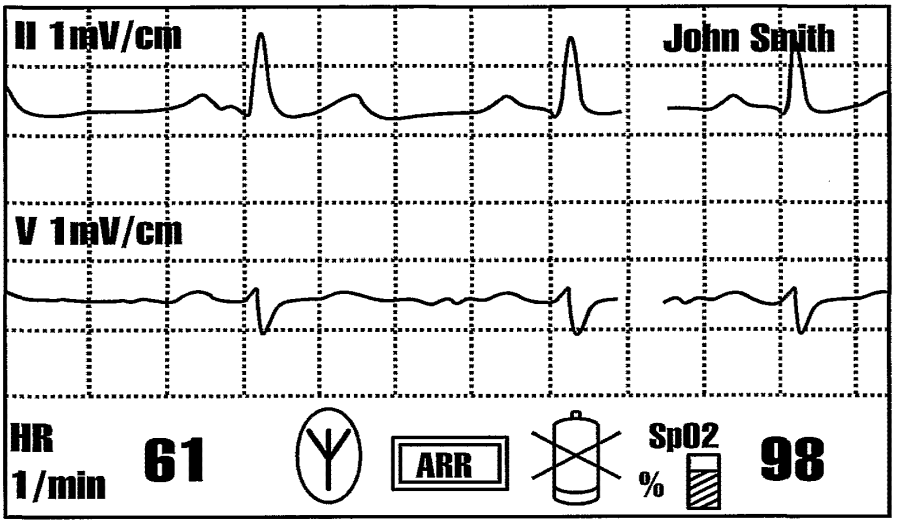

II 1mV/cm
John Smith
V 1mV/cm
HR
1/min
61
ARR
SpO2
%
98

Fig. 20


PR
BPM
SpO2
%
SRCH
ALARM
PRESS KEY TO ACKNOWLEDGE

Fig. 21

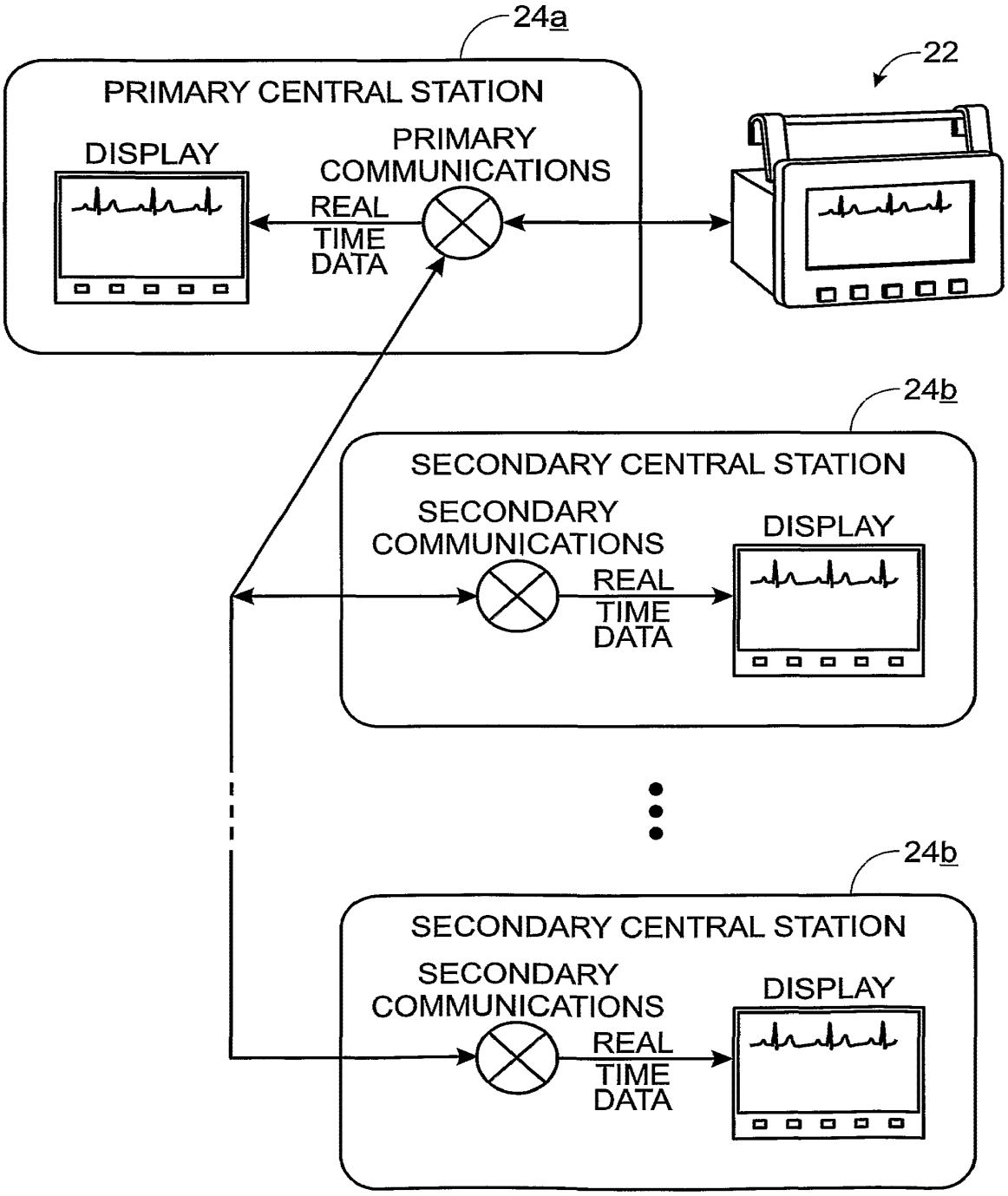

24a
22
PRIMARY CENTRAL STATION
DISPLAY
PRIMARY COMMUNICATIONS
REAL TIME DATA
24b
SECONDARY CENTRAL STATION
SECONDARY COMMUNICATIONS
DISPLAY
REAL TIME DATA
24b
SECONDARY CENTRAL STATION
SECONDARY COMMUNICATIONS
DISPLAY
REAL TIME DATA

Fig. 22

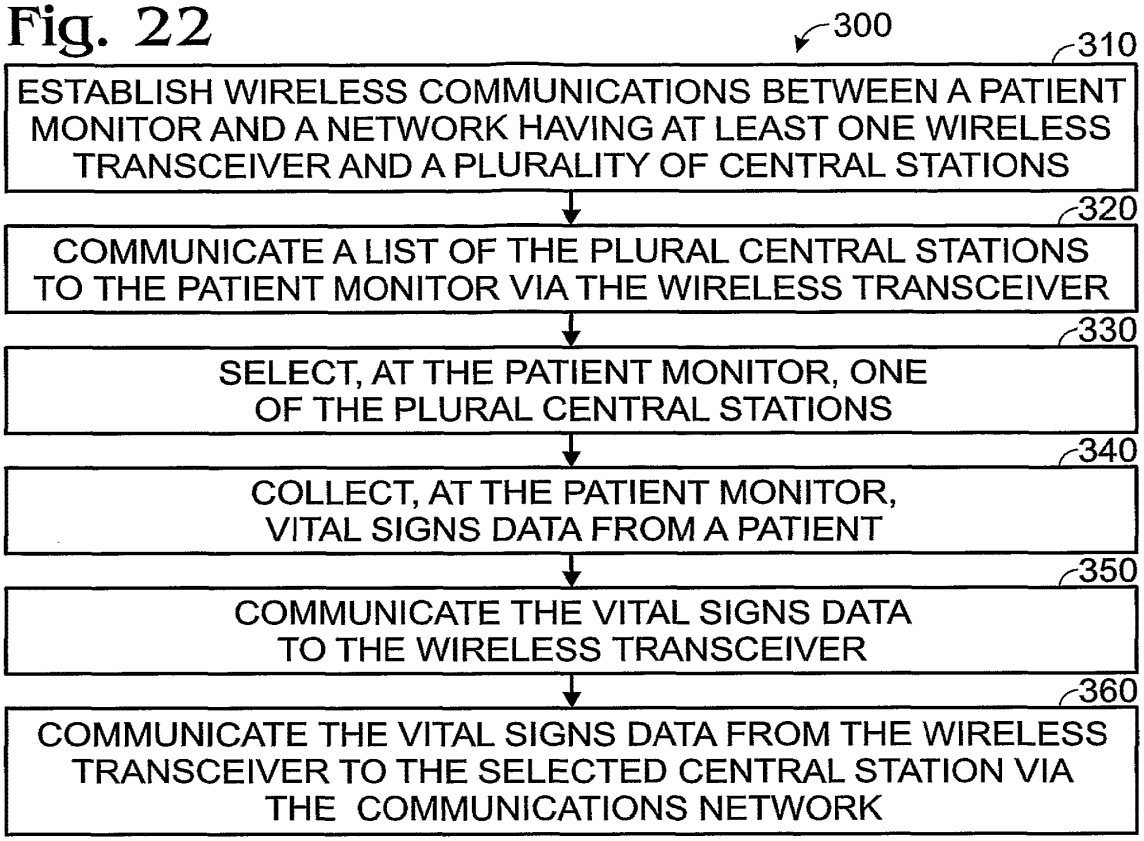

300
310
ESTABLISH WIRELESS COMMUNICATIONS BETWEEN A PATIENT MONITOR AND A NETWORK HAVING AT LEAST ONE WIRELESS TRANSCEIVER AND A PLURALITY OF CENTRAL STATIONS
320
COMMUNICATE A LIST OF THE PLURAL CENTRAL STATIONS TO THE PATIENT MONITOR VIA THE WIRELESS TRANSCEIVER
330
SELECT, AT THE PATIENT MONITOR, ONE OF THE PLURAL CENTRAL STATIONS
340
COLLECT, AT THE PATIENT MONITOR, VITAL SIGNS DATA FROM A PATIENT
350
COMMUNICATE THE VITAL SIGNS DATA TO THE WIRELESS TRANSCEIVER
360
COMMUNICATE THE VITAL SIGNS DATA FROM THE WIRELESS TRANSCEIVER TO THE SELECTED CENTRAL STATION VIA THE COMMUNICATIONS NETWORK

Fig. 23

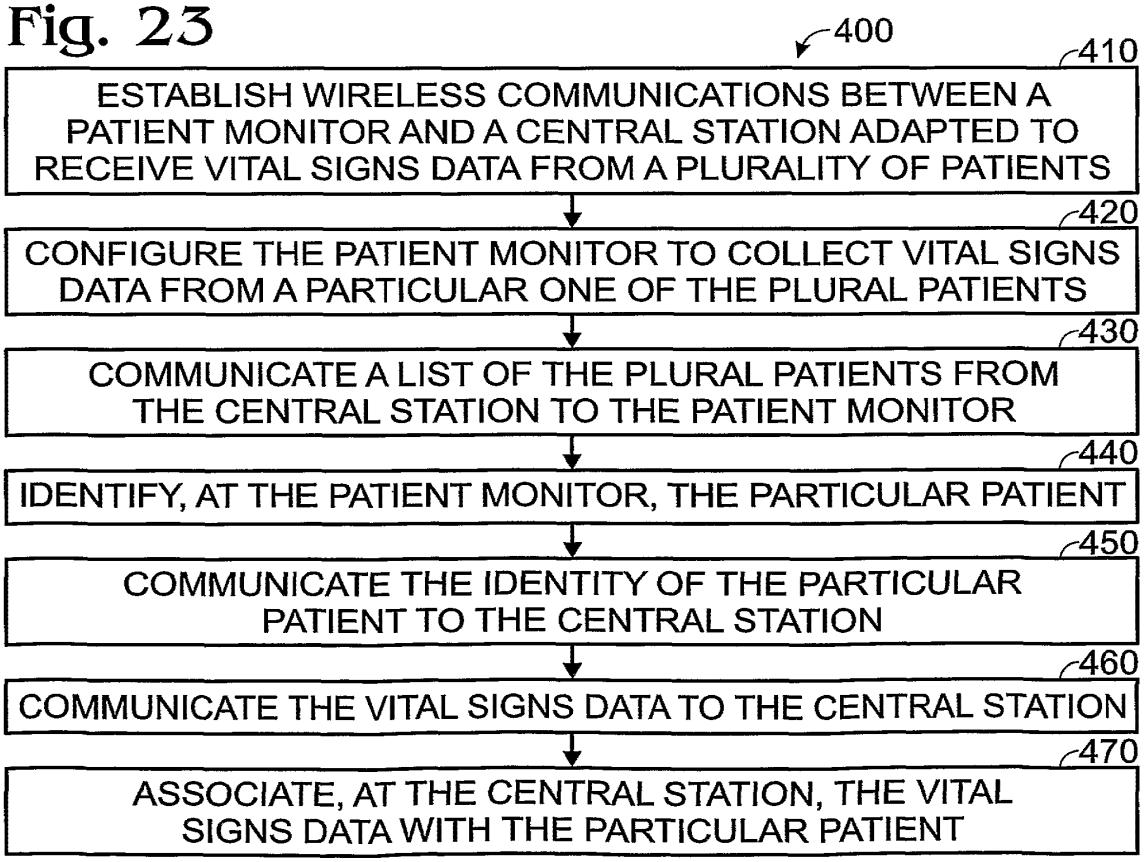

400
410
ESTABLISH WIRELESS COMMUNICATIONS BETWEEN A PATIENT MONITOR AND A CENTRAL STATION ADAPTED TO RECEIVE VITAL SIGNS DATA FROM A PLURALITY OF PATIENTS
420
CONFIGURE THE PATIENT MONITOR TO COLLECT VITAL SIGNS DATA FROM A PARTICULAR ONE OF THE PLURAL PATIENTS
430
COMMUNICATE A LIST OF THE PLURAL PATIENTS FROM THE CENTRAL STATION TO THE PATIENT MONITOR
440
IDENTIFY, AT THE PATIENT MONITOR, THE PARTICULAR PATIENT
450
COMMUNICATE THE IDENTITY OF THE PARTICULAR PATIENT TO THE CENTRAL STATION
460
COMMUNICATE THE VITAL SIGNS DATA TO THE CENTRAL STATION
470
ASSOCIATE, AT THE CENTRAL STATION, THE VITAL SIGNS DATA WITH THE PARTICULAR PATIENT

Fig. 24

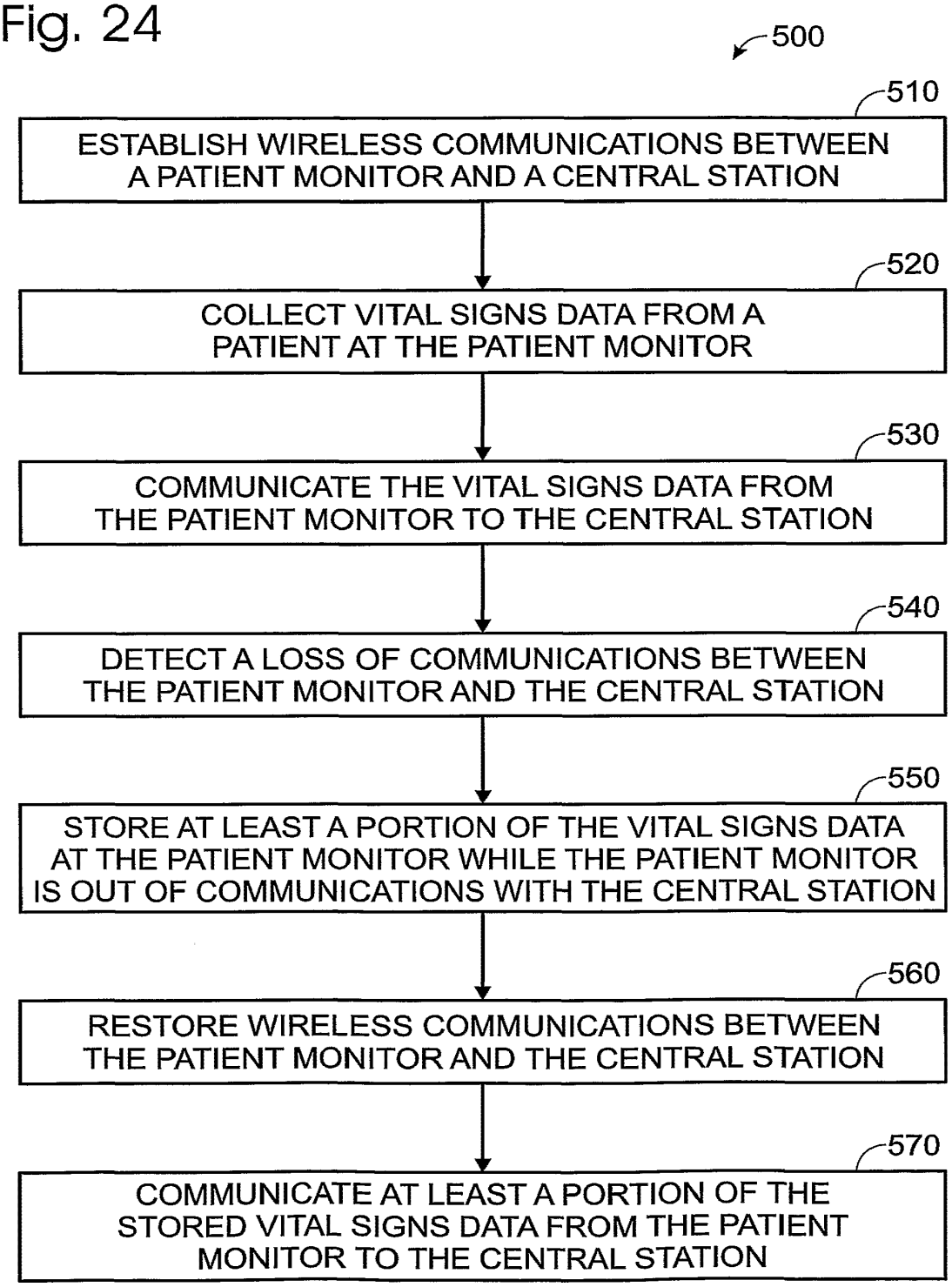

500
510
ESTABLISH WIRELESS COMMUNICATIONS BETWEEN A PATIENT MONITOR AND A CENTRAL STATION
520
COLLECT VITAL SIGNS DATA FROM A PATIENT AT THE PATIENT MONITOR
530
COMMUNICATE THE VITAL SIGNS DATA FROM THE PATIENT MONITOR TO THE CENTRAL STATION
540
DETECT A LOSS OF COMMUNICATIONS BETWEEN THE PATIENT MONITOR AND THE CENTRAL STATION
550
STORE AT LEAST A PORTION OF THE VITAL SIGNS DATA AT THE PATIENT MONITOR WHILE THE PATIENT MONITOR IS OUT OF COMMUNICATIONS WITH THE CENTRAL STATION
560
RESTORE WIRELESS COMMUNICATIONS BETWEEN THE PATIENT MONITOR AND THE CENTRAL STATION
570
COMMUNICATE AT LEAST A PORTION OF THE STORED VITAL SIGNS DATA FROM THE PATIENT MONITOR TO THE CENTRAL STATION

Fig. 25

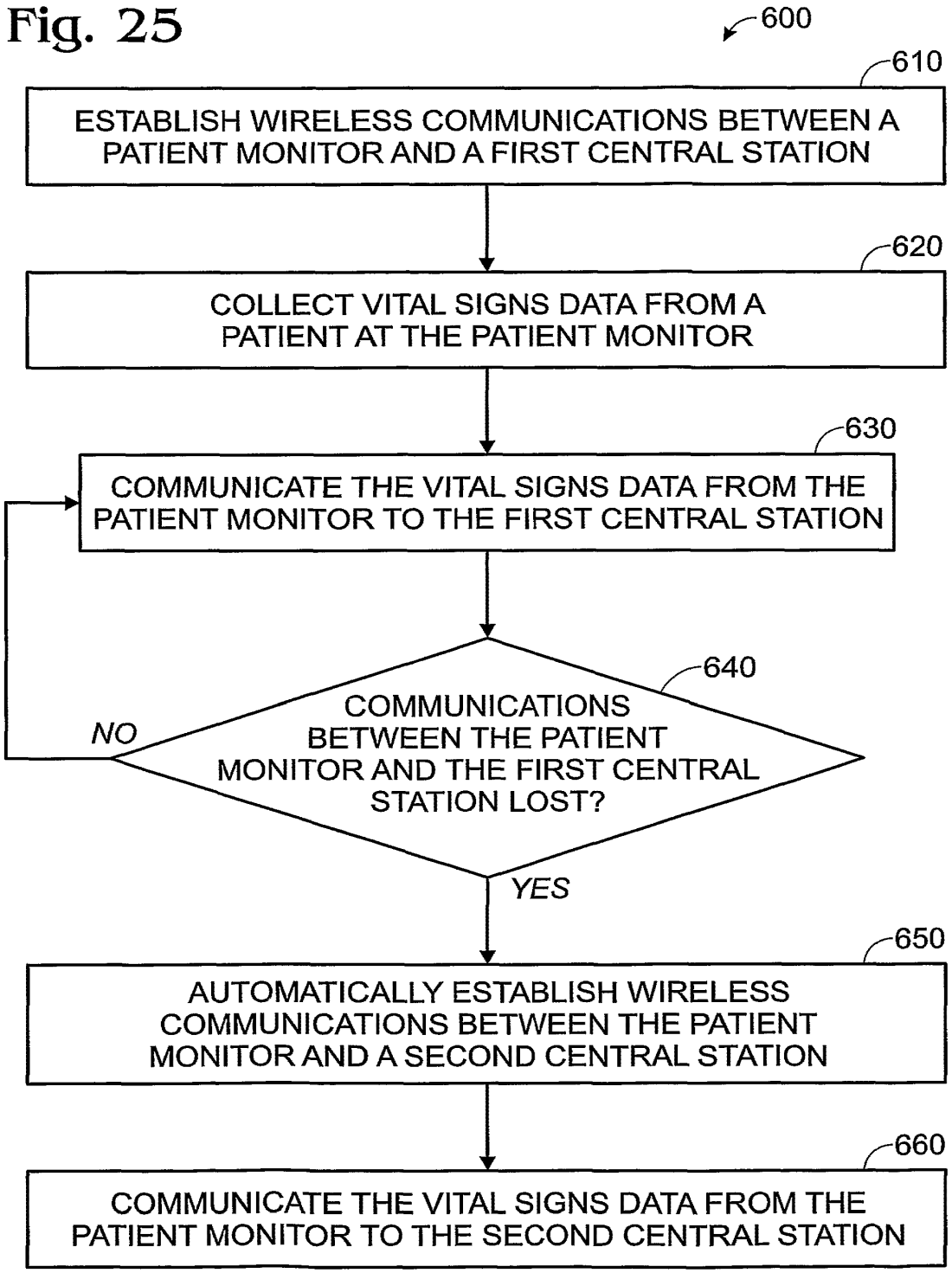
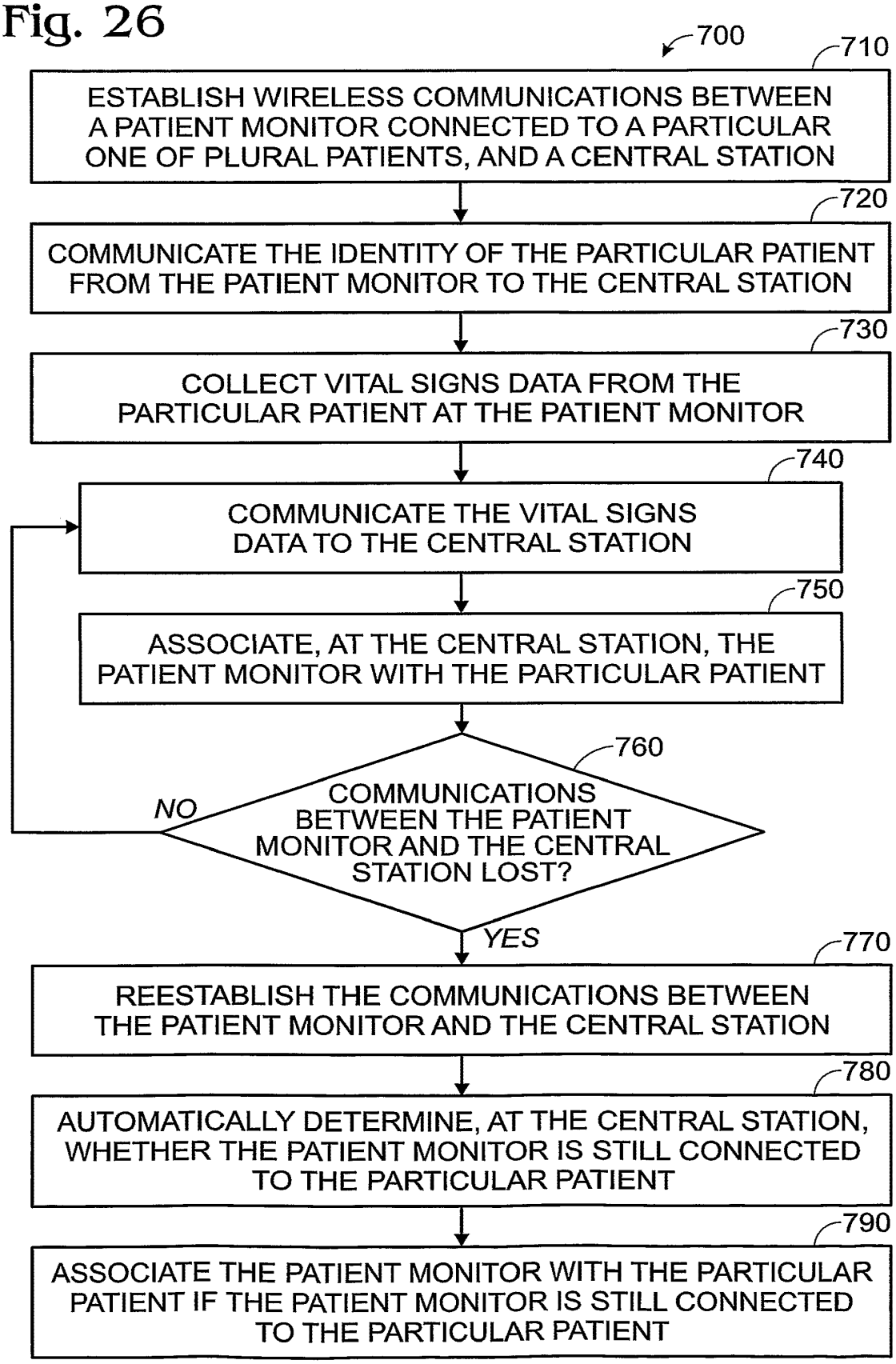

600
610
ESTABLISH WIRELESS COMMUNICATIONS BETWEEN A PATIENT MONITOR AND A FIRST CENTRAL STATION
620
COLLECT VITAL SIGNS DATA FROM A PATIENT AT THE PATIENT MONITOR
630
COMMUNICATE THE VITAL SIGNS DATA FROM THE PATIENT MONITOR TO THE FIRST CENTRAL STATION
640
COMMUNICATIONS BETWEEN THE PATIENT MONITOR AND THE FIRST CENTRAL STATION LOST?
NO
YES
650
AUTOMATICALLY ESTABLISH WIRELESS COMMUNICATIONS BETWEEN THE PATIENT MONITOR AND A SECOND CENTRAL STATION
660
COMMUNICATE THE VITAL SIGNS DATA FROM THE PATIENT MONITOR TO THE SECOND CENTRAL STATION

Fig. 26


700
710
ESTABLISH WIRELESS COMMUNICATIONS BETWEEN A PATIENT MONITOR CONNECTED TO A PARTICULAR ONE OF PLURAL PATIENTS, AND A CENTRAL STATION
720
COMMUNICATE THE IDENTITY OF THE PARTICULAR PATIENT FROM THE PATIENT MONITOR TO THE CENTRAL STATION
730
COLLECT VITAL SIGNS DATA FROM THE PARTICULAR PATIENT AT THE PATIENT MONITOR
740
COMMUNICATE THE VITAL SIGNS DATA TO THE CENTRAL STATION
750
ASSOCIATE, AT THE CENTRAL STATION, THE PATIENT MONITOR WITH THE PARTICULAR PATIENT
760
COMMUNICATIONS BETWEEN THE PATIENT MONITOR AND THE CENTRAL STATION LOST?
NO
YES
770
REESTABLISH THE COMMUNICATIONS BETWEEN THE PATIENT MONITOR AND THE CENTRAL STATION
780
AUTOMATICALLY DETERMINE, AT THE CENTRAL STATION, WHETHER THE PATIENT MONITOR IS STILL CONNECTED TO THE PARTICULAR PATIENT
790
ASSOCIATE THE PATIENT MONITOR WITH THE PARTICULAR PATIENT IF THE PATIENT MONITOR IS STILL CONNECTED TO THE PARTICULAR PATIENT

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International Bureau

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A61B 6/14 (2006.01)

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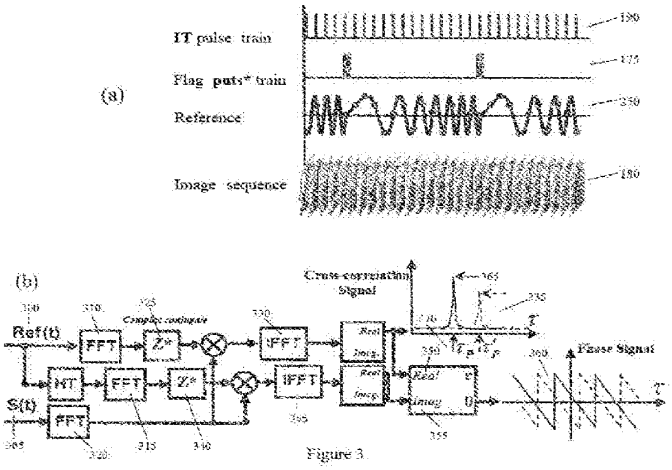


Figure 3

(57) Abstract: Systems and methods for improved thermophotonic imaging are provided in which both amplitude and phase image information is obtained with a high signal to noise ratio and depth-resolved capabilities. Image data obtained from an imaging camera is dynamically averaged and subsequently processed to extract amplitude and/or phase image data. The system may be configured for a wide range of imaging modalities, including single frequency modulation (thermophotonic lock-in imaging), Thermal-Wave Radar imaging or Thermophotonic Radar imaging involving chirp modulation, and Binary Phase Coded Modulation. Such imaging modalities may find application in many diverse areas, including non-destructive testing and biomedical diagnostic imaging including the imaging of teeth and monitoring changes in the tooth over time which are due to pathology such as dental caries or erosion.

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SYSTEMS AND METHODS FOR THERMOPHOTONIC DYNAMIC IMAGING

CROSS-REFERENCE TO RELATED APPLICATION

This application claims priority to U.S. Provisional Application No. 61/471,772, titled "SYSTEMS AND METHODS FOR THERMOPHOTONIC DYNAMIC IMAGING" and filed on April 5, 2011, the entire contents of which are incorporated herein by reference.

BACKGROUND OF THE INVENTION

This invention relates to systems and methods of non-destructive subsurface imaging. More particularly, this invention relates to systems and methods for thermophotonic imaging.

Thermographic and thermophotonic imaging methods have found widespread use in applications such as non-destructive testing of various materials and biomedical diagnostic imaging. While numerous methods have been developed and described in the literature, most solutions proposed to date have relied on methods involving single frequency analysis of amplitude and phase images. Such methods, while well suited for some specific applications, often fail in applications that demand higher sensitivity. Another disadvantage of known thermographic and thermophotonic imaging methods is the use of low speed imaging techniques, which can place significant limitations on depth and/or spatial resolution.

Accordingly, despite the existence of a number of thermographic and thermophotonic imaging modalities, there remains a need for imaging solutions that deliver higher sensitivity, lower detection limit, increased speed, and improved depth

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resolution. In industrial quality control, there is a need for fast and reliable monitoring of substrate integrity and process-induced defects during manufacturing and component reliability testing, for example in identifying subsurface cracks and delaminations in automotive and aerospace components and surface coatings, respectively. In oral health care, there is a need to have an imaging system that can image an entire tooth surface or group of teeth so as to provide the oral health care provider with the location of dental caries or defects in teeth and or dental materials.

As compared to conventional thermographic imaging, which monitors contrast due to thermal and/or mechanical property inhomogeneities of materials (thermographic contrast), thermophotonic imaging, in addition to thermographic contrast, involves amplified contrast due to optical property inhomogeneities. Both modalities are based on the generation and detection of (photo)thermal waves in a sample.

SUMMARY

Systems and methods for improved thermophotonic imaging are provided in which both amplitude and phase image information is obtained with a high signal to noise ratio and depth-resolved capabilities. Image data obtained from an imaging camera is dynamically averaged and subsequently processed to extract amplitude and/or phase image data. The system may be configured for a wide range of imaging modalities, including single frequency modulation (thermophotonic lock-in imaging), Thermal-Wave Radar imaging or Thermophotonic Radar imaging involving chirp modulation, and Binary Phase Coded Modulation. Such imaging modalities may find application in many diverse areas, including non-destructive testing and biomedical diagnostic imaging including the imaging of teeth and monitoring changes in the tooth

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over time which are due to pathology such as dental caries or erosion.

In a first aspect, there is provided a method of performing thermophotonic imaging, the method comprising the steps of: providing a sample; providing an optical source having a wavelength selected to generate photothermal radiation within the sample; providing an imaging camera with an optical bandwidth selected for detection of the photothermal radiation; generating a reference waveform comprising a plurality of modulation cycles; producing a modulated optical beam by modulating an intensity of an optical beam emitted by the optical source according to the reference waveform; illuminating the sample with the modulated optical beam;

imaging the photothermal radiation with the imaging camera; recording a plurality of dynamically averaged image frames at time offsets corresponding to different values of the reference waveform; and processing the dynamically averaged image frames and the reference waveform to obtain an image relating to the photothermal radiation.

The dynamically averaged image frames may be obtained according to the following steps: recording a plurality of image frames at times corresponding to different values of the reference waveform; repeating, one or more times, the step of recording the image frames at times corresponding to different values of the reference waveform, and dynamically averaging the recorded images for each the different value of the reference waveform, thereby obtaining dynamically averaged image frames.

The step of recording the plurality of image frames at different values of the reference waveform may comprise recording the plurality of image frames over a single modulation cycle/correlation period, and may be obtained over more than one modulation cycle, where a frame acquisition rate of the imaging camera may less than

a modulation frequency of the reference waveform.

The method may further comprise the step of recording, for each image frame of the plurality of image frames, a substantially instantaneous value of the reference waveform, and may further comprise generating a quadrature waveform based on the reference waveform, and recording, for each image frame of the plurality of image frames, a substantially instantaneous value of the quadrature waveform.

An integration pulse train may be generated comprising a series of pulses, wherein each pulse is generated at a time at which an image frame is acquired by the imaging camera, wherein the step of generating of the reference waveform is triggered according to the integration pulse train. The integration pulse train may be generated by the imaging camera.

A flag pulse train may be generated comprising a series of pulses, wherein each pulse is generated at a commencement of a given modulation cycle/correlation period, and identifying one or both of a beginning and an end of the given modulation cycle/correlation period according to the flag pulse train. A modulation frequency of the reference waveform may be greater than approximately 0.01 Hz.

The reference waveform may comprise a single frequency and wherein the image is obtained by lock-in processing, and the step of processing the dynamically averaged image frames and the reference waveform may comprise, for each pixel in the image frame, performing the steps of: multiplying the dynamically averaged image frames by the reference waveform to obtain in-phase product values; and summing the in-phase product values to obtain an in-phase sum; generating a quadrature waveform based on the reference waveform; multiplying the dynamically averaged image frames by the quadrature waveform to obtain phase-shifted product values; and summing the phase-shifted product values to obtain a phase-shifted sum.

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The image may be an amplitude image, and wherein the processing further comprises calculating a magnitude of a complex quantity based on the in-phase sum and the phase-shifted sum. The image may be a phase image wherein the processing further comprises: calculating a phase angle of a complex quantity based on the in-phase sum and the phase-shifted sum.

The reference waveform may comprise multiple frequency components, and the reference waveform may comprise a frequency chirp and may be a binary phase coded waveform.

The image may be a cross-correlation peak amplitude image obtained by the steps of: obtaining a complex cross-correlation signal of the reference waveform and each pixel of the dynamically averaged image frames; and determining, for each the pixel, a peak amplitude value of a peak in a real part of the cross-correlation signal.

The image may be a cross-correlation peak delay image obtained by the steps of: obtaining a complex cross-correlation signal of the reference waveform and each pixel of the dynamically averaged image frames; and determining, for each the pixel, a delay of a peak in a real part of the complex cross-correlation signal.

The image may be a cross-correlation phase image obtained by the steps of: obtaining a first complex cross-correlation signal of the reference waveform and each pixel of the dynamically averaged image frames; obtaining a second complex cross-correlation signal of a quadrature waveform and each pixel of the dynamically averaged image frames, wherein the quadrature waveform is based on the reference waveform; forming a complex quantity comprising a real portion of first complex cross-correlation signal and a real portion of the second complex cross-correlation signal; and obtaining the phase image by determining, for each pixel, a phase angle of the complex quantity at a pre-selected time delay.

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The sample may be selected from the group consisting of automotive components, aerospace components, an optical material, a laser material, a biomedical material, and a biological tissue.

The sample may be a material comprising one or more of a subsurface crack and a delamination. The sample may be an unsintered component in a green state.

The method may further comprise the step of determining a case hardness depth.

The sample may be a dental sample, tooth sample or whole groups of teeth. The method may further comprise the step of analyzing the image to determine one or more of a presence and a location of demineralization, erosion or dental caries in the dental or tooth sample. The method may further comprise the step of monitoring an evolution of one or more of demineralization, erosion and dental caries by comparing the image to one or more other images. The sample may be a dental or medical instrument and may be selected from the group consisting of endodontic instruments, catheters and other indwelling instruments.

The wavelength may be selected to lie within a range of approximately 600 nm to 2000 nm. The imaging camera may be selected to have a spectral response overlapping with at least a portion of the mid-infrared spectrum.

In another aspect, there is provided a system for performing thermophotonic imaging, the system comprising: an optical source having a wavelength selected to generate photothermal radiation within a sample; an imaging camera with an optical bandwidth selected for detection of the photothermal radiation, wherein the imaging camera is configured to acquire image frames a given frame rate and output an integration pulse train comprising a series of pulses, each pulse corresponding to a time at which an image frame is acquired by the imaging camera; a waveform

generating system for generating a reference waveform, wherein an output of the waveform generating system is connected to an input of the optical source for modulating an intensity of an optical beam emitted by the optical source; a processor programmed to dynamically average image frames obtained by the imaging camera, and to process the dynamically averaged image frames, the reference waveform and a quadrature waveform based on the reference waveform, to provide one or more of an amplitude image and a phase image; and a memory for storing dynamically averaged image frames.

A modulation frequency of the reference waveform may be greater than approximately 0.01 Hz. The imaging camera may comprise a frame acquisition rate that is less than a modulation frequency of the reference waveform. The wavelength may lie within approximately 600 nm to 2000 nm. A spectral response of the imaging camera may overlap at least a portion of the mid-infrared spectrum.

A further understanding of the functional and advantageous aspects of the disclosure can be realized by reference to the following detailed description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments will now be described, by way of example only, with reference to the drawings, in which:

Figure 1 shows of a system that may be employed for thermophotonic imaging.

Figure 2 illustrates a method of thermophotonic lock-in imaging.

Figure 3 illustrates thermal-wave radar imaging, where (a) shows the waveforms and frames captured, and (b) provides a flow chart illustrating the method.

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Figure 4 (a) illustrates a method of binary phase code imaging. Theoretical simulation of CC signals using frequency (dashed) and phase (solid) modulation for absorbers at depths (b) 50 μm and (c) 1 mm below the surface using thermal and optical properties of dental enamel. Chirp: 0.1-4.9 Hz, 6.4 s; BPC: 2.5 Hz, 16 bit, 6.4 s.

Figure 5 shows (a) an optical image, (b) front (F) and side (S) dental radiographs of sample A1(human bicuspid tooth) before treatment; and (c) front (F) and side (S) dental radiographs (d) optical image of sample A1 after 10 days of demineralization treatment with an artificial caries solution within the treatment window; thermophotonic lock-in phase images of sample A1 (e) before treatment and after (f) 2, (g) 4, (h) 8, and (i) 10 days of demineralization with an artificial caries solution within the treatment window; (j) phase profiles along the dashed line shown in figure 5i for samples at several demineralization stages (dashed vertical lines show the location of the treatment window); and (k) Transverse micro-radiographic mineral profile along the center of the treatment window of the 10-day demineralized sample.

Figure 6 shows (a) an optical image of sample A2, the occlusal surface of a maxillary molar with stained pits and fissures; thermophotonic (b) amplitude and (c) phase images of sample A2 obtained at 10 Hz; thermophotonic (d) amplitude and (e) phase images of sample A2 obtained at 100 Hz; and (f)-(i) transverse micro-radiographic mineral profiles of points f-i, respectively, as indicated in (e).

Figure 7 provides images of (a) sample B1, (left) the plastic step wedge (right) inside the scattering medium, (b) sample B2, strip pattern left to right: green, transparent, black, and (c) sample B3, where the squares in (c) indicate the locations of two demineralization (artificial caries) treatment windows.

Figure 8 plots thermal wave radar and phase lock-in (LI) imaging of sample

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B2 , with LI thermography phase images at (a) 0.01Hz and (b) IHz; (c) Cross-correlation (CC) amplitude image (chirp frequency bandwidth: 0.01-1 Hz in 6s); (d) mean horizontal LI phase profile of figure (a); and distribution of (e) LI phase and (f) CC amplitude values over the steps.

Figure 9 plots thermal wave radar imaging of sample B2 using (a) CC amplitude, (b) CC peak delay time, (c) CC phase and their mean horizontal profiles (d), (e), and (f), respectively (chirp frequency bandwidth: 0.01-1 Hz in 6s).

Figure 10 plots thermal wave radar and thermophotonic lock-in imaging of sample B3, showing (a) CC amplitude image, (b) CC peak delay time image, (c) CC phase image (chirp frequency bandwidth: 0.01-1 Hz in 6s); thermophotonic lock-in phase images at (d) 0.01 Hz and (e) 1 Hz; and (f) transverse micro-radiographic mineral profiles at points 1-3 indicated in figure (c)

Figure 11 plots (a) binary phase code and (b) phase LI imaging of sample Bl, and distribution of (c) binary phase code image and (d) phase LI image values over the steps of sample B2.

Figure 12 provides thermophotonic lock-in and binary phase code images of sample B3, with thermophotonic lock-in (a) amplitude and (b) phase images 1 Hz; and binary phase code (c) amplitude image (d) peak delay time image and (e) phase image.

Figure 13 (a) Exploded view of the cross-shaped sample simulating two absorbers at different depths. Conventional LIT (b) Amplitude and (c) phase image. binary phase code peak delay time image matched to the camera temporal data of (d) point 1 and (e) point 2, as indicated in part (b), using a 3-bit [1 1 -1] code.

Figure 14 (a) Teeth matrix with hidden inter-proximal early caries. The rectangle shows the imaged area. (b) Conventional LIT and (c) binary phase code

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phase images of teeth matrix. (d-f) thermal coherence tomographic images obtained as several delay times differentiating between the defective (e) and healthy (f) regions.

Figure 15 (a) Optical image of goat bone. The rectangle shows the images area. (b) binary phase code phase images at 1 Hz using a 7 bit binary code.

Figure 16 illustrates the method of asynchronous undersampling for lower frame acquisition rate imaging cameras.

DETAILED DESCRIPTION

Various embodiments and aspects of the disclosure will be described with reference to details discussed below. The following description and drawings are illustrative of the disclosure and are not to be construed as limiting the disclosure. Numerous specific details are described to provide a thorough understanding of various embodiments of the present disclosure. However, in certain instances, well-known or conventional details are not described in order to provide a concise discussion of embodiments of the present disclosure. It should be understood that the order of the steps of the methods disclosed herein is immaterial so long as the methods remain operable. Moreover, two or more steps may be conducted simultaneously or in a different order than recited herein unless otherwise specified.

As used herein, the terms, "comprises" and "comprising" are to be construed as being inclusive and open ended, and not exclusive. Specifically, when used in the specification and claims, the terms, "comprises" and "comprising" and variations thereof mean the specified features, steps or components are included. These terms are not to be interpreted to exclude the presence of other features, steps or components.

As used herein, the term "exemplary" means "serving as an example, instance,

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or illustration," and should not be construed as preferred or advantageous over other configurations disclosed herein.

As used herein, the terms "about" and "approximately", when used in conjunction with ranges of dimensions of particles, compositions of mixtures or other physical properties or characteristics, are meant to cover slight variations that may exist in the upper and lower limits of the ranges of dimensions so as to not exclude embodiments where on average most of the dimensions are satisfied but where statistically dimensions may exist outside this region. It is not the intention to exclude embodiments such as these from the present disclosure.

As used herein, the term "thermophotonic imaging" relates to the generation of images based on thermal infrared photons emitted from surface and subsurface regions of opaque or non-opaque matter, resulting from photothermal excitation of a sample with a light source such as a laser. The emitted infrared photons carry optical absorption information at the excitation wavelength as well as at the detection spectral band determined by the spectral response of the infrared imaging detector. The case of optically opaque samples, conventionally known as "infrared thermographic imaging", which involves only thermal properties, is understood to be incorporated by implication in the opaque limit of thermophotonic imaging. As compared to conventional thermographic imaging which monitors contrast due to thermal and/or mechanical property inhomogeneities of materials (thermographic contrast), thermophotonic imaging, in addition to thermographic contrast, involves amplified contrast due to optical property inhomogeneities. Both modalities are based on the generation and detection of (photo)thermal waves in a sample.

Embodiments described below provide systems and methods for improved thermophotonic imaging. In a first embodiment, a system and method is provided in

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which photothermal image data are dynamically averaged and subsequently processed to determine both amplitude and phase image information with high signal to noise ratio. The system may be configured for a wide range of imaging modalities, including, but not limited to, single frequency modulation (thermophotonic lock-in imaging or thermophotonic lock-in imaging), chirp modulation (thermal-wave radar imaging or thermal wave radar imaging), and binary phase coded modulation (Binary Phase Coding imaging or binary phase code imaging).

Figure 1 shows a schematic of a thermophotonic imaging system 100 that may be utilized for a number of different imaging modalities. System 100 includes imaging camera 110 for detecting and imaging thermophotonic radiation, laser 120 for exciting a photothermal response in a sample 130, data acquisition system 140, and computing system 150 that is interfaced to camera 110 and/or data acquisition system 140 (in the example embodiment shown in Figure 1, computing system 150 is directly interfaced to camera 110 for reading both image data and data acquisition header data in image frames, as described further below). Sample 130 may be positioned using a sample positioning device, such as a 3-axis (XYZ) sample positioning system (not shown).

Laser 120 is modulated to produce a modulated optical beam that is directed onto the surface of an extracted sample tooth 130, which in turn leads to the generation of photothermal radiation from sample 130 that is subsequently detected by imaging camera 110. In order to obtain high signal-to-noise ratio (SNR) via phase-sensitive detection, a synchronous driving and data acquisition approach is employed, in which frames outputted by imaging camera 110 are synchronized with the modulation of laser 110 for further processing.

Referring now to Figure 2, system 100 is further described in the context of a

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thermophotonic imaging modality involving thermophotonic lock-in detection, which represents an illustrative yet non-limiting embodiment of an imaging modality compatible with system 100. Data acquisition system 140 generates analog in-phase reference waveform 160 and analog quadrature reference waveform 165, where quadrature waveform 165 is phase shifted by 90° relative to in-phase waveform 160. Alternatively, the quadrature reference waveform may be computed from the Hilbert Transform of the in-phase reference signal.

In-phase waveform 160 is provided to the modulation input 170 of laser system 120, (shown in Figure 1). In response to in-phase waveform 160, the intensity of the emitted laser light is modulated, where the modulation profile of the laser intensity follows that of in-phase waveform 160 plus a DC offset.

Imaging camera 110 obtains image frames at a defined frequency as shown by integration pulse train (IT pulse train) 190 in Figure 2. Integration pulse train 190 is provided (e.g. as a TTL pulse train) from imaging camera 110 to data acquisition system 140 to trigger the generation of in-phase waveform 160 and quadrature waveform 165 by data acquisition system 140. Integration pulse train 190 also triggers the generation of flag pulse train 175 by data acquisition system 140, where flag pulse train 175 provides a "high" pulse at the beginning of each modulation cycle, as shown in Figure 2.

In the embodiment shown in Figure 1, imaging camera 110 is capable of providing a header for each recorded image frame, where the header includes the measurement of two values that are measured at a time that is substantially instantaneous with the detection of an image frame. The two values are obtained from two analog signals corresponding to instantaneous values of waveforms 160 and 165. Data acquisition system 140 provides these waveforms to imaging camera 110 for

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inclusion of the two values in the frame header, thereby providing a measurement of their values at a time that is substantially simultaneous to the instant that the frame is captured. Values from flag pulse train 175 are also stored in the frame header to allow for the determination of the beginning of each waveform period, which is used for averaging purposes as further described below. It is to be understood that the direct interfacing of computing system 150 to camera 110, as shown in Figure 1, is but one of many different possible system implementations. In other embodiments, computing system may be interfaced to camera 110 and/or data acquisition system 140 for synchronous acquisition of both image and modulation waveform instantaneous data, as further described below.

During image acquisition, computing system 150 reads image frames from imaging camera 110 via image sequence 180, and queries the frame headers until it finds a frame whose flag pulse train is "high" (the beginning of a modulation cycle). After a "high" pulse is detected, computing system 150 reads a sequence of frames that correspond to one complete modulation cycle, where the number of frames and delay between frame acquisition events is determined based on the frame rate of imaging camera 110 and the modulation frequency of the in-phase waveform 160. The frames are stored in a buffer (e.g. a 3D buffer) in a memory (such as computer RAM). By performing these steps, system 100 obtains a series of individual imaging frames corresponding to one modulation cycle.

To obtain an improved SNR of the acquired image frames, the above steps are repeated and the values for each frame of one complete modulation cycle are averaged in the buffer to reduce the stochastic noise. Most averaging algorithms read the signal corresponding to all recorded cycles and then initiate the averaging processes. Unfortunately, due to the huge flow of data needed to meet the bandwidth

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demands of the image frames, such an averaging methodology fails at high frame rates, such as those that are preferably used in the present embodiment.

Accordingly, in a one embodiment, the image frames are dynamically averaged, where the frames corresponding to one modulation cycle are collected and dynamically processed to determine a running average. Initially, a first set of image frames corresponding to a first modulation cycle are collected and stored in a memory location. Subsequently, image frames are obtained for a second modulation cycle, and the recorded image frame values are dynamically averaged. This process is repeated for subsequent modulation cycles, with the averaging based on the number of modulation cycles that have been processed, with the result that an averaged set of image frames with improved SNR is obtained. This provides a dramatic improvement in memory management and speed, and requires significantly less sophisticated computer hardware.

After having obtained an averaged set of image frames over a modulation cycle, the averaged frame sequence, shown at 180 as f(t) in Figure 2, corresponding to averaged image frames, is processed to obtain amplitude and phase images. This is performed by weighting each pixel in the image for each frame obtained, where the pixel value is weighted once by the in-phase reference signal 160 and once by the quadrature reference signal 165 in two separate channels. The weighted sequences are then separately summed to get the S^{0} and S^{90} images, as shown in steps 200 and 210 of Figure 2, respectively. Finally, using equation 1 for each pixel the amplitude and phase images are calculated:

$$A = \sqrt{(S^{0})^{2} + (S^{90})^{2}} \quad \text{and} \quad \Phi = \arctan(S^{90} / S^{0}) \quad (1)$$

Computing system 150 may be programmed with a signal acquisition and/or processing program for processing the data received from imaging camera 110 and/or

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data acquisition device 140, and for performing the aforementioned averaging steps and calculation of the amplitude and phase images. For example, generic data processing programs may be provided commercially or created for specific applications associated with the thermophotonic imaging modalities disclosed herein. A suitable programming medium for the creation of such a program is the LabView environment. This environment provides a flexible platform for adapting the imaging software to non-destructive / diagnostic groups of equipment (set-ups) for application specific to particular materials and configurations (e.g. engineering materials NDT, biomaterials diagnostics, dental caries imaging).

Unlike lock-in thermography, which is mostly used in non-destructive testing of metals and other opaque structural materials at very low modulation frequencies (on the order of 0.01Hz or so), and in which low camera frame rates (usually 20 fps), and high optical excitation power (high SNR signal) are used without averaging, in thermophotonic imaging of biological samples and industrial materials with defects very close to surface, one may need high frequency thermal waves and low optical excitation power (poor SNR signal) to meet safety criteria. Therefore, in such cases, it can be advantageous to employ very high camera frame rates and a real-time averaging methodology, as provided, according to the present embodiment.

While the above embodiments provide exemplary systems and methods for obtaining thermophotonic images, it is to be understood that the systems and methods may be varied without departing from the spirit and scope of the aforementioned embodiments. For example, referring now to Figure 1, although system 100 is shown as comprising computing system 150 and data acquisition system 140, these elements of the apparatus may be provided in a number of different formats. Computing system 150, which comprises a processor and a memory, may be directly integrated with data

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acquisition system 140. For example, data acquisition system 140 may reside in total or in part on a hardware card housed within an apparatus that also comprises a processor and a memory.

Laser system 120 may further comprise additional sub-components or subsystems such as, but not limited to, a laser diode emitter, laser driver, fiber coupled output, collimator, and thermoelectric cooler and controller. In one exemplary embodiment, laser system 120 has two laser diodes so as to provide improved optical contrast of a type of sample through large differential absorption (for example, 808 nm and 1120 nm). Typically, laser diodes are mounted on thermoelectric coolers and the diode assembly is fixed on an air cooled heat sink through a heat conductive thermal pad. The laser light may be delivered to the sample through an optical fiber and a collimator. A collimator and/or spatial filter may be provided to maintain a relatively uniform optical intensity on the interrogated surface. The thermoelectric controller provides the cooling power to the thermoelectric coolers and controls the temperature of the laser diode. The laser driver may be employed to provide the electrical power needed to operate the laser diode and can modulate the laser light intensity according to the analog modulation signal it receives at its "mod in" terminal.

Furthermore, it is to be understood that optical source need not be a coherent light source such as a laser, but may instead be an incoherent source such as a LED, provided that sufficient optical intensity is achieved to obtain a measurable thermophotonic image signal. With the advent of high-power LEDs, one may employ a high-power infrared LED or LED array in place of a laser source. LED arrays are significantly less expensive than laser sources and generally do not require complicated cooling systems. This strategy can be used because in the proposed

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methodologies it is the thermal (conductive and radiative) response from the sample that is investigated, and not the purely optical response.

As noted in the example embodiment provided above, data acquisition system 140 is capable of generating and/or providing waveforms 160 and 165 in response to the integration pulse train 175 generated by the imaging camera. In a non-limiting example, data acquisition system may be a DAQ board such as National Instrument Multi Data acquisition device (NI USB-6229 BNC), and the like, which may be directly integrated with or housed within computing system 150. Such a multifunction data acquisition (multiDAQ) system can generate and acquire analog signals simultaneously and has two independent counters and 48 digital I/O channels for synchronization applications. The data acquisition system may be connected to the computer with a USB port and may be configured to communicate with other devices through BNC connections.

Computing system 150 may be interfaced to imaging camera 110 through an interfacing device such as a networking card. For example, the GigE network PCI card may be employed to provide a suitable interface between the camera and the computer for rapidly transferring image frames to the memory of the computing system 150 according to the GigE standard.

As noted above, the sample 130 and/or laser source may be positionable relative to one another. For example, a sample positioning system may be provided that consists of one or more single axis translation stages mounted to move the sample relative to the incident laser beam in X, and optionally Y and Z directions. A rotational stage may be added to this assembly to assist in the placement of the sample in the focal plane of the camera.

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While system 100 as disclosed above is capable of averaging numerous modulation cycles of the signals before processing them, it is also possible to perform that averaging based on the computed amplitude and phase images as opposed to the image frames.

Such an embodiment may be achieved by reading, at a given point in time, a sequence of frames corresponding to one or more modulation cycles, processing the image frames as outlined above, and calculating the desired diagnostic images (i.e. amplitude, phase) and then repeating these steps and averaging the amplitude and phase images. While this "processing, then averaging" mode is less effective in eliminating the stochastic noise than the "averaging, then processing" strategy, it requires less sophisticated triggering/synchronization equipment. For example, this embodiment involves the simplification of the control section of the camera and signal processing system with respect to triggering. This approach will yield non-triggered, yet synchronized, data arrays resulting in an image of somewhat compromised quality.

Furthermore, although system 100 is shown in Figure 1 in which the waveforms 160, 165 and 175 are provided by data acquisition system 140 to imaging camera 110 for incorporation of the substantially instantaneously measured values into the frame header, it is to be understood that the values may be provided according to alternative system implementations. Such embodiments may be useful in cases where imaging camera 110 is not equipped or configured for the incorporation of a header in each image frame. For example, in one non-limiting embodiment, the waveforms 160, 165 and 175 may be directly provided to computing system 150 by data acquisition system 140, optionally along with integration pulse train 190 from imaging camera 110 for triggering. Provided that the relative time delay between the

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reception of the waveforms and the generation and/or reception of image frames may be determined (for example, by measuring a delay between system components), the appropriate values of the waveforms corresponding to the measurement of image frames may be determined.

Alternatively, the waveforms 160, 165 and 175 may be generated directly by computing system 150 (optionally triggered by integration pulse train 190 provided by imaging camera 110), and the correlation between the appropriate values of the waveforms and the acquisition of image frames may be determined based on a known system delay. These embodiments may be applied to the system shown in Figure 1, or in the system described above in which the synchronization of triggering is not necessary.

In one embodiment, imaging camera 110 is an infrared imaging camera that is sensitive in the infrared spectrum. Imaging camera 110 may incorporate the necessary optical components for the collection and detection of photothermal radiation, or one or more of the optical components may be externally mounted or otherwise provided. For example, imaging camera may include an extension tube supporting an objective lens.

In one exemplary embodiment, imaging camera 110 is a focal plane array (FPA) mid-infrared camera. A suitable but non-limiting example of such a camera is the Cedip Titanium 520M (France), which has a spectral range of 3.6 - 5.1 μm and maximum frame rate of 175 Hz at full frame. The camera's detector array consists of 320x256 Indium Antimonide (InSb) elements with element size of 30x30 μm^2. An extension tube and a objective lens (such as Cedip MW50 L0106, a 50-mm-focal-length lens) may be employed to obtain a magnification of (for example, of unity) relative to the interrogated surface of sample 130.

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While the mid-infrared camera may be preferred for obtaining optimum results for some sample types, one may also employ less expensive near- or far-infrared cameras, generally with the performance trade-off of a reduced signal-to-noise ratio. However, the low signal to noise ratio can be mitigated, at least in part, by a number of methods such as, for example, increasing the number of averages, using matched filtering signal processing methods (thermal wave radar and binary phase code) described above, increasing the optical source intensity, increasing the camera integration time, and/or improving the optical collection efficiency. It is expected to be more effective to employ a far infrared camera to capture thermal infrared photons due to the peak of the blackbody radiation being located in that spectral range, although the spectral transmissivity of the interrogated material must also be considered in determining the thermal infrared photon emission flux to the camera following self-absorption.

Furthermore, in selected embodiments, uncooled imaging cameras may be employed to simplify the system and/or reduce cost. The cooling system of a camera is one of the factors that make the camera expensive. Uncooled cameras are significantly less expensive but at the same time less sensitive. This problem can be solved by increasing compensation for a reduced performance by using one of the mitigating methods described above.

In another embodiment, a camera with a lower frame acquisition rate may be employed. While lowering the frame rate does not significantly affect the performance of thermophotonic lock-in imaging, the sampling period can be critical in matched filtering methodologies (thermal wave radar and binary phase code) as it determines the depth resolution. Two strategies can be followed to overcome the depth resolution limitation while using a low-grade (low frame rate) camera.

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In a first method, synchronous/asynchronous undersampling may be employed, whereby the frame rate is chosen such that the data are captured from many modulation cycles instead of just one. This embodiment is illustrated in Figure 16. Although this sampling strategy increases the total sampling duration, this alternative implementation enables the use of a lower-grade camera to access image depth resolution commensurate with that of the foregoing high-grade camera. The combination of critical undersampling determination with the desired thermal-wave depth penetration, and their software implementation thus provide a unique and important benefit to system performance.

The undersampling frequency (f_s) can be determined as follows:

$$f_s = f_{lock\text{-}in} / [m+(1/n)] \qquad (1a)$$

where f_s is the undersampling frequency, $f_{lock\text{-}in}$ is the desired lock-in frequency (or alternatively, chirp/binary phase code repetition rate), m is an integer number and is called the order of undersampling, and n is the number of frames per correlation period. In Figure 13, m=1 and n=12, that is one frame is captured in every m=1 modulation cycle and at the end of the process the sampled modulation cycle (i.e. correlation period) consists of n=12 frames[8].

In a second method, artificial oversampling is performed as per the sampling theorem, which states that if the Fourier transform of a function $h(t)$ is zero for all frequencies above a certain frequency f_c, then the continuous function $h(t)$ can be uniquely determined from a knowledge of the sampled values. So, if the function is sampled at $T= 1/2f_c$, then one can use the expression below to reconstruct the waveform at any sampling/frame rate:

$$h(t) = T \sum_{n=-\infty}^{\infty} h(nT) \frac{\sin(2\pi f_c (t - nT))}{\pi (t - nT)} \qquad (2)$$

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The methodology is also known as "Sine interpolation". Therefore, one can use a low frame rate camera and then use Sine interpolation to improve the sampling resolution. The determination of cut off frequency, f_c, satisfying the requirement of a predetermined thermal diffusion length (depth resolution) may be performed according to equation 5, as further described below.

An alternative option for an infrared camera for use with system 100 may be provided by modifying a digital visible spectrum camera such as a commercial digital camera or a webcam. Such cameras may be modified to be sensitive in the near-infrared spectral region by removing the infrared filter and then inserting an infrared band pass filter in the optical path of the detector array. The performance degradation that is likely based on use of such a camera may be mitigated, at least in part, by the methods listed above.

An alternative option for an infrared camera for use with system 100 may be provided by modifying a digital visible spectrum camera as noted above and using methods listed above to handle performance degradation. The output from this camera would be in color with color linked to the status of the specimen under examination. In another embodiment, the camera may be a monochrome camera, and the defect region may be displayed in a unique false colour. The defect may be identified automatically by image processing (for example, using known methods to identify regions of an image based on intensity and/or the presence of a border feature). Alternatively, the defect may be identified in response to input from a user or operator viewing the image.

In one example embodiment, the defect size may be correlated with its displayed colour. For example, an area where there is a large defect may be displayed (and optionally imaged) in red while an area which is sound or healthy may be

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displayed (and optionally imaged) in green. An area where the defect is small can be displayed (and optionally imaged) in yellow. This gradation from green to yellow to red would help the operator visually understand the relative size of the defect, and in the case of dental imaging, would assist in visually assessing the severity of any detected defects.

Another imaging modality that is suitable with system 100 employs thermal-wave radar imaging. In thermal wave radar imaging chirp modulation is used instead of the aforementioned method of single frequency modulation (thermophotonic lock-in) modality and the matched filtering signal processing method is employed to increase the SNR. For non-opaque targets, this method is referred to "thermophotonic radar imaging". It should be noted that this methodology is completely different from thermophotonic lock-in imaging and is a depth selective method as opposed to a depth integrated method in thermophotonic lock-in imaging. As a result, thermal wave radar not only probes deeper into a sample, but also provides improved resolution of details and faster image acquisition due to its high SNR (i.e. requires less averaging).

Figure 3(a) explains the thermal wave radar imaging method graphically. As in the thermophotonic lock-in method, a sequence of image frames are acquired in combination with the values indicating the values of the waveforms 160, 165 and 175. The role of the flag pulse train 175, the integration pulse train 190, and the averaging method, are the same as in the thermophotonic lock-in method described above. However, unlike the case of thermophotonic lock-in in which one modulation cycle is being averaged, it is one chirp cycle of the chirped reference signal 250 that is averaged in the thermal wave radar imaging or the thermophotonic radar imaging method.

Figure 3(b) depicts the signal processing block diagram of thermal wave radar

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imaging according to the cross-correlation (CC) theory (matched filtering theory):

$$CC(\tau)=\varepsilon\times\Im^{-1}\left\{REF(\omega)^{*}\ S(\omega)\right\} \qquad (3)$$

where REF (ω) 300 and S(ω) are the Fourier transforms of the reference/modulation signal (Ref(t)) and the highly noised photothermal signal (s(t)), ε is the emissivity and $\Im^{-1}$ and * denote the inverse Fourier transform and complex conjugate operators, respectively. In matched filtering, the role of chirped modulation is to compress the energy delivered by the chirp into a narrow correlation peak which enables imaging with high axial resolution. The result is a reduction in the width of the CC main lobe (peak) and an increase in the amplitude of the peak as the area below it needs to be conserved. In the case of a linear frequency sweep, the signal-to-noise ratio (SNR) gain factor of the ideal matched filter is equal to the time-bandwidth product of the chirp. Theoretical and experimental studies have shown that this increase in SNR also holds in the photothermal fields.

While the amplitude of the CC peak relies strongly on the amplitude of the received signal, its location in the delay time axis (τ_p) is linked to the depth of the signal source. One can further develop this concept by calculating the CC phase (schematically in figure 3(b)) and find:

$$\theta_{CC}=\frac{\varepsilon\times\Im^{-1}\left\{REF(\omega)^{*}\ S(\omega)\right\}}{\varepsilon\times\Im^{-1}\left\{\left[-i\,\mathrm{sgn}(\omega)REF(\omega)\right]^{*}\ S(\omega)\right\}} \qquad (4)$$

where sgn(ro) and i are the signum function and standard imaginary unit, respectively. The expression inside the squared bracket is the Fourier transform of the quadrature reference signal. The significance of CC phase is that according to equation 4 the emissivity is cancelled out and as a result the CC phase is an emissivity-normalized quantity.

In light of the above, after the averaging step, the temporal signal from each

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pixel is processed according to figure 3(b). Initially, the Fourier transform of reference *Refit)* 300, quadrature signal (i.e. Hilbert transformed reference signal), and averaged photothermal signal *S(t)* 305 are obtained at 310, 315 and 320, respectively. The complex conjugate 325 of the reference spectrum is then multiplied by the spectrum of the photothermal signal which is proportional to the emissivity, and the inverse Fourier transform is obtained at 330, the real part of which generates cross-correlation signal 335. Similarly, the complex conjugate 340 of the Hilbert transform of the reference spectrum is multiplied by the spectrum of the photothermal signal which is also proportional to the emissivity, and the inverse Fourier transform is obtained at 345. The phase signal 360 is then provided by taking, as its real part, the real part 350 of the inverse transform 330, and as its imaginary part, the real part 355 of inverse transform 345.

From these calculated signals, contrast parameters may be generated and displayed as images. The following are a non-limiting list of parameters that may be provided for generating images:

(a) the *cross-correlation amplitude image,* in which the contrast parameter is the amplitude of the cross-correlation peak;

(b) the *cross-correlation peak delay time image,* in which the contrast parameter is the location of the cross-correlation peak in the delay time axis (τ_p); and

(c) the *emissivity normalized cross-correlation phase image,* in which the contrast parameter is the phase value at zero delay time calculated from equation 4.

In one example embodiment, one or more of these images, namely the cross-correlation amplitude image, the cross-correlation peak delay time image, and/or the

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emissivity normalized cross-correlation phase image, are generated and employed to infer information about the sample 130.

The above images are to be contrasted with known methods of processing thermophotonic image data. In the Radar sciences, matched filtering has been used since the early 1940s to detect pre-known (deterministic) signals within highly noised channels and to augment the range resolution. In 1986 Mandelis et al. in a series of papers introduced this method to the photothermal field through the mirage (photothermal beam deflection) effect[4(a-c)]. Recently, Mulaveesala et al.[5] and Tabatabaei and Mandelis[6] (Thermal-Wave Radar) have applied this methodology to imaging in the photothermal field. For example, in the method of Mulaveesala et al.[5](which is based on a pulse compression technique), a completely different approach is taken to calculate a so-called "phase image" from a chirped reference signal. Instead of processing the phase image according to all components in the frequency domain as in equation 4, the method of Mulaveesala et al. is based on demodulating the camera signal at a specific frequency. This method is completely different from the inventive methods disclosed herein and has long been used in the field of Pulse Phase Thermography[9]. More specifically, the phase image of Mulaveesala et al. is obtained by computing the Fourier transform of a pixel signal, and the value of this Fourier transform at the desired frequency will be a complex number. The phase is obtained by calculating, based on this complex frequency, the phase value *tan^*imaginary part/real part). In fact, those skilled in the art will appreciate that this approach of phase calculation was first introduced in Pulse Phase Thermography[9]. This phase value is the phase of a single frequency thermal-wave; it is not a true matched filtering/cross-correlation calculation.

In contrast, according to the methodology disclosed herein, which is shown in

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the block diagram of Figure 3, the complex conjugate phase is calculated using *all the frequency components of the chirp through cross-correlation/matchedfiltering* of reference and quadrature signals. In summary, the phase images that are obtained according to the methods of Mulaveesala et al. result in depth integrated images over a thermal diffusion length controlled by the modulation frequency, in contrast to the method disclosed herein which results in depth-resolved (or depth-selective) imaging. The method disclosed herein is the result of correlation processing, otherwise known as "matched filter compression". As will be seen in the single frequency image of Figs 10d and 10e, compared to the matched filter compression generated images of Figs. 10b and 10c, this difference in approach has huge contrast enhancement implications in favor of matched filter compression.

Furthermore, unlike known imaging modalities such as those disclosed by Mulaveesala et al. , the present embodiments utilize thermophotonic imaging, which is applicable to a wide range of imaging applications beyond opaque sample imaging applications (such as imaging of metals). In particular, and as further described below, the optical scattering and absorption properties of dental and other biomaterials introduce a non-extrapolatable factor in imaging, which cannot be readily perceived by one skilled in the thermographic imaging, as frequency ranges, wavelengths, delay times etc. are all very different and image contrast optimization is controlled by the diffusion-wave centroid determined by the thermal diffusion length and optical absorption depth (or extinction depth, in case of turbid media) according to equation 5(b) as shown below.

Embodiments provided herein also improve over known imaging modalities that employ very low frequencies, such as those typical of thermography. Such methods that rely on low frequencies may be applicable for deep subsurface metal

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defects, but are insufficient for thermal-wave radar in materials such as teeth and surface coatings, where high frequencies are needed for critical spatial and temporal (axial) resolution. In contrast to such low-frequency applications, the present embodiments may be employed for frequencies up to several hundred Hz via the aforementioned signal processing and data handling methods. Moreover, the embodiments disclosed herein may be adapted for use with inexpensive slower IR cameras in place of more expensive IR imaging cameras. Accordingly, the embodiments provided herein are especially adapted for thermophotonic imaging of non-opaque solids, but are also valid in the limit of opaque targets upon appropriate parameter adjustment.

The aforementioned embodiment, in which chirp modulation is employed in thermal wave radar imaging and thermophotonic radar imaging, provides a reduction in the width of the cross-correlation peak. This not only improves the depth resolution and allows for depth-selective imaging, but also increases the height of the peak (i.e. SNR) as the area below it needs to be conserved.

In another embodiment, an alternative approach is employed in which binary phase coding is utilized instead of a chirp to obtain an improved SNR. Binary phase coding is an alternative method that uses single frequency modulation but inverts some of the modulation cycles in a prescribed manner in order to achieve this goal. The signal processing method is the same as the aforementioned thermal wave radar imaging and thermophotonic radar imaging embodiment, and uses matched and mismatched filtering to detect a signal source. However, in the case of binary phase code imaging, the modulation waveform is a binary phase coded single frequency waveform. As a result, binary phase code imaging is considered as a narrow-band detection compared to thermal wave radar imaging/thermophotonic radar imaging and

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experiences lower background noise level.

Figure 4 illustrates this method graphically for a 3-bit coded signal 260 ([1, 1, -1]) shown at reference waveform 400. The third cycle is inverted with respect to the other cycles to generate the binary phase code waveform, forming a single frequency signal that is coded according to the 3-bit sequence in Table 1.

Table 1. Binary phase code sequences[10].

length N	sequence c_k	Oller coefficients w_k	relative efficiency
3	1 1 −1	1 1 0	66.67 percent
4	1 1 1 −1	1 1 1 −1	100.00 percent
5	1 1 1 1 −1	1 1 1 1 −2	90.00 percent
6	1 1 1 1 1 −1	1 1 1 1 1 −3	76.19 percent
7	1 1 1 1 1 1 −1	1 1 1 1 1 1 −4	64.93 percent
8	1 1 1 1 −1 −1 1 −1	1 1 3 1 −1 −1 3 −1	75.00 percent
9	1 1 1 1 1 −1 1 1 −1	1 1 6 1 1 −4 1 1 −4	60.11 percent
10	1 1 1 1 1 −1 1 −1 1 −1	9 19 1 7 5 −9 25 −1 −7 −5	59.66 percent
11	1 1 1 1 1 −1 1 1 −1 −1 −1	71 20 47 17 80 −79 68 53 −49 5 −55	77.47 percent
12	1 1 1 1 1 −1 −1 1 1 −1 1 −1	2 1 1 2 1 −1 −2 1 1 −2 1 −1	88.92 percent
13	1 1 1 1 1 −1 −1 1 1 −1 1 −1 1	2 2 2 2 2 −3 −3 2 2 −3 2	96.15 percent
14	1 1 1 1 1 1 −1 −1 1 1 −1 1 −1	1 4 4 1 4 1 −5 −8 4 −5 4 −5 1	82.29 percent
15	1 1 1 1 1 1 −1 1 −1 −1 1 1 −1 −1	4 4 −5 4 −5 1	86.81 percent
16	1 1 1 1 1 1 −1 1 1 −1 1 −1 1 −1	3 21 45 39 27 5 −27 −39 −45 21 −3 −25 43 37 −43 −25	79.43 percent

While the optical excitation is binary phase coded in accordance to weighting sequence c_k in table 1, one can choose to use Matched Filtering (weighting sequence c_k in table 1) or MisMatched filtering (weighting sequence w_k in table 1) as the 300 reference signal in figure 3(b) to calculate the binary phase code amplitude, peak delay time, and phase images using the method illustrated in the block diagram of thermal wave radar or thermophotonic radar imaging modality (shown in Figure 3(b)). The advantage of MisMatched filtering over Matched filtering is the significant reduction of side lobes at the expense of lower SNR[10].

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The binary phase code signal, *f(t)*, consists of a single frequency carrier, *C(t)*, and a binary coded envelope, *E(t)*. The signal is formed by either multiplying these components in the time-domain or alternatively by convolving their spectra in the frequency-domain. In general, an arbitrary binary sequence can be defined as $a_j=[a_1, a_2, \ldots, a_N]$. In the special case where the temporal length of each code element equals the period of the carrier (T_0), the binary coded envelope can be modeled as a series of rectangular pulses of width T_0 and height a_j shifted in the time axis by $(j-0.5)\ T_0$. Therefore, starting with the Fourier transform of a pulse, the analytical spectrum of the binary coded envelope can be obtained using the time-frequency shifting property of the Fourier transform:

$$\Im\{E(t)\} = E(\omega) = \frac{\sqrt{2\pi}}{\omega_c} Sinc\left(\frac{\omega}{\omega_c}\right) \sum_{j=1}^{N} a_j \exp\left[-i\omega T_0 (j-0.5)\right] \qquad (5)$$

where ω_0 and i are the carrier angular frequency and the imaginary unit, respectively. Finally, the analytical spectrum of the binary phase coded signal can be calculated through the convolution of equation (5) and the spectrum of the carrier waveform:

$$\Im\{f(t)\} = F(\omega) = \frac{\pi}{i\omega_c} \sum_{j=1}^{N} \left[a_j Sinc\left(\frac{\omega-\omega_0}{\omega_c}\right) \exp\left[-iT_0 (j-0.5)(\omega-\omega_0)\right] - a_j Sinc\left(\frac{\omega+\omega_0}{\omega_c}\right) \exp\left[-iT_0 (j-0.5)(\omega+\omega_0)\right] \right] \qquad (6)$$

Equation (6) suggests that the spectrum of the binary coded signal consists of a series of weighted "sine" functions yielding a narrow-band waveform with most of its energy located at the carrier frequency (narrow-band signal).

The thermophotonic response (Planck radiation emission) of a non-opaque turbid medium to a binary phase code excitation can be obtained through coupling of the optical and thermal-wave fields, where the total optical field (coherent + scattered)

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is the source of thermal-wave generation. As a simple example, the response of black body absorbers in a turbid medium is investigated. That is, the binary phase code excitation is applied to the surface (z=0) of a turbid medium with known scattering and absorption coefficients ϕ_s and μ_{α}, respectively), where, after interaction with the turbid medium, the attenuated light is completely absorbed at $z=l$ and thermal waves are generated. The energy fluence, $I(z)$, of the one-dimensional, uniform, collimated beam normally incident on a homogeneous scattering and absorbing medium has been calculated by Prahl *et al.*[7]. Using this approximation, the thermal-wave problem can be formulated by adding a depth dependent source term to the heat diffusion differential equation (due to absorption by the medium) as well as an attenuated heat source at $z=l$ through a boundary condition:

$$\begin{cases} \frac{d^2\theta(z;\omega)}{dz^2} - \sigma^2 f(z;\omega) = -\eta(z)F(\omega) \\ -k\left.\frac{\partial\theta(z;\omega)}{\partial z}\right|_{z=0} = 0 \qquad \text{(I)} \\ -k\left.\frac{\partial\theta(z;\omega)}{\partial z}\right|_{z=l} = I(l)F(\omega) \qquad \text{(II)} \\ \theta(z;\omega) = \Im\{T(z,t) - T_\infty\} \end{cases} \tag{7}$$

where k, α, and $F(\omega)$ are thermal conductivity, thermal diffusivity and the spectrum of the applied binary phase code excitation **Error! Reference source not found.**, respectively, and $\sigma=\sqrt{i\omega/\alpha}$ is the complex wavenumber. Solving the frequency-domain differential equation subject to the boundary conditions and considering an average value for the infrared absorption coefficient within the spectral range of the detector ($\bar{\mu}_{IR}$), the conductive heat transfer spectrum of the thermophotonic signal can be calculated as:

$$S_c(l;\omega) \propto \bar{\mu}_{IR}\int_0^l \theta(z;\omega)\exp(-\bar{\mu}_{IR}z)dz = \bar{\mu}_{IR}\left[\begin{array}{l} \frac{A}{\sigma-\bar{\mu}_{IR}}\left(\exp[(\sigma-\bar{\mu}_{IR})l]-1\right) - \frac{B}{\sigma+\bar{\mu}_{IR}}\left(\exp[-(\sigma+\bar{\mu}_{IR})l]-1\right) \\ -\frac{C}{\mu_{eff}+\bar{\mu}_{IR}}\left(\exp\left[-(\mu_{eff}+\bar{\mu}_{IR})l\right]-1\right) - \frac{D}{\mu_s+\bar{\mu}_{IR}}\left(\exp[-(\mu_s+\bar{\mu}_{IR})l]-1\right) \end{array}\right]$$

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(8)

However, the infrared emission captured by the detector is the superposition of (8) and the direct Planck emission from the black-body absorber, attenuated through the turbid medium (9).

$$S(t,\omega_j) \propto S_r(t,\omega_j) + \theta(t,\omega_j)\exp(-\bar{a}_{ir}l) \quad (9)$$

Equations (6) and (9) formulate the spectra of the applied binary phase coded excitation (i.e. the matched/mismatched filter) and the thermophotonic response of a subsurface absorber at depth l to such excitation, respectively. Consequently, one can calculate the matched-filter cross-correlation signal and its phase analytically as (3) and (4), respectively, or experimentally via the algorithm depicted in figure 3(b).

Figures 4(b) and 4(c) plot theoretical comparisons of the CC signals obtained from chirp (dashed lines) and binary phase coded (solid lines) modulation techniques. Optical and thermal properties of dental enamel were used as the properties of the turbid medium. The CC responses clearly show that binary phase code modulation significantly improves the axial resolution (FWHM of the main peaks) as well as the SNR. Moreover, the plots suggest that matched/mismatched filtering using phase modulation can exhibit energy localization normally encountered in propagating hyperbolic wave-fields. As a result, one can obtain localized information from absorbers at different depths by investigating the CC plots at the corresponding delay times or alternatively obtain iso-delay (iso-depth) images in a thermophotonic radar imaging system. Consequently, by scanning the image plane in the delay time axis one can obtain thermal coherence tomographic images and locally resolve absorbers in a diffuse field.

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In another example embodiment, the aforementioned systems and methods are employed for the detection and/or monitoring of teeth. Teeth (including enamel, dentin, root and or cementum) are an optically turbid medium, therefore when light enters the tooth it scatters and gets absorbed along its path. Optical extinction depth is defined as the effective depth within which the light can get absorbed and generates heat, including both absorption and scattering effects. Interpolating the enamel extinction coefficient from the IR spectrum of dental enamel reported by Jones and Fried, the optical extinction depth is roughly 250 μm for the 808-nm laser light. However, as photon absorption events are responsible for generating thermal signals, it is the optical absorption depth (~ 1 cm) that is the controlling factor, or, more precisely, a superposition of 1) a conduction heat transfer mode whose depth is controlled by the thermal-wave centroid determined by the optical extinction depth and thermal diffusion length; and 2) a radiation heat transfer mode whose depth is controlled by the optical extinction depth: When modulated optical excitation is absorbed inside the tooth, the subsequent heat generation gives two contributions to the infrared camera signal. First, an oscillatory heat distribution (thermal-wave) is formed at or near the surface within a thermal diffusion length (at the modulation frequency of the absorbed optical excitation) which will conductively reach the surface of the tooth and contribute to the camera signal in the form of a depth integral through infrared emission.

Second, direct thermal infrared (Planck) emission occurs from all absorption locations (surface and subsurface) with IR photon back-propagation through the enamel due to the 15 to 20 % transmittance of enamel in the mid-infrared region. Considering the speed of light and the thickness of enamel, the latter contribution is instantaneous and therefore there will be no phase shift between the direct infrared

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(Planck) emission responses received from different depths in the tooth. Consequently, it is believed that there will be no contrast contribution from this type of direct emission in the thermophotonic lock-in phase image; however, direct emission will contribute to the amplitude image contrast as these images are concerned with the amplitude of infrared emission (number of IR photons) received at a specific modulation frequency, a function of the local absorption coefficient and optical-to-thermal energy conversion efficiency.

On the other hand, the thermal- wave contribution to the infrared camera signal is not instantaneous as speed of propagation of heat is significantly smaller than that of light. As a result, absorption at different depths will result in different phase values at a fixed modulation frequency. Unlike pure thermal waves generated in opaque media, optically non-saturated photothermal waves carry optical as well as thermal information. The most important feature of thermal waves is that their effective penetration depth can be controlled through the modulation frequency:

$$\mu_{\Lambda}(f) = \sqrt{\alpha/\pi f} \qquad (10a)$$

and the signal carries optical absorption information from depths $d \leq \mu_{th}(f)$. When the optical extinction depth, $\mu_{ex}(\lambda)$ contribution to the thermal-wave distribution is taken into account, where λ is the wavelength of the optical excitation source, in the concept of the thermophotonic-wave centroid, $L(\omega,\lambda)$:

$$L^{-1}(\omega,\lambda) = \mu^{-1}_{th}(\omega) + \mu^{-1}_{ex}(\lambda) \qquad (10b)$$

Equation 10(b) comprises the physical principle on which thermophotonic lock-in imaging hinges. In equation 10(b), μ_{th}, μ_{ex}, α, and/are thermal diffusion length, optical extinction depth, thermal diffusivity, and modulation frequency, respectively.

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Therefore, as photothermal-wave generated infrared emission is the dominant source of contrast in thermophotonic lock-in phase images, one can control the imaging depth by adjusting the modulation frequency according to equation 10. Due to the small thermal diffusivity, a , of enamel, dentin and root cementum, the maximum thermal diffusion length (i.e. at modulation frequency ~ 1 Hz) is on the order of ~300 μm. Therefore, phase images are best used for detecting inhomogeneities at short subsurface distances within the enamel such as the early demineralization and carious lesions while amplitude images can be used to detect deep features due to the large optical absorption depth of enamel. Moreover, biofilm, surface stains and dental plaque which are expected, in principle, to produce contrast in the thermophotonic lock-in images, they will do so minimally and only in the image amplitude due to their transparency to 808nm NIR excitation source used in this study. The thermophotonic lock-in phase image is physically immune to thin surface absorbers as it is independent of the optical properties of the surface.

The same situation holds for thermal wave radar/thermophotonic radar and binary phase code imaging as well. That is, the cross-correlation amplitude images obtain contributions from both the conductive and direct emission sources while the cross-correlation peak delay time and phase images only receive contribution from the conductive part.

The preceding theoretical arguments related to mechanisms of photothermal generation in teeth and other non-opaque turbid matter are not intended to limit the scope of the embodiments disclosed herein. Moreover, although the above embodiments have been focusing on teeth, it is to be understood that the sample may be any suitable sample that is capable of generating detectable photothermal radiation. For example, sample 130 may be processed or finished material, where the methods

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described herein are employed for non-destructive testing purposes, especially those that benefit from the characterization of subsurface absorption. These include, but are not confined to, subsurface cracks and defects in metals and coatings; automotive component inspection and quality assurance, including unsintered parts in the green state; aerospace component inspection such as gears and hardened steels, and the determination of the hardness case depth; optical and laser materials and coatings with visually imperceptible blemishes; coatings and alloys, biomedical materials and soft and hard tissue diagnostics, cracks and defects in dental restorations including direct placed and indirect fabricated prosthetics, defects or ill-fitting prosthetics linked to dental implants, defects at the margins or junctions of tooth and dental restorations, and all other materials applications to which photothermal diagnostics has been and can be applied[11]. In dental applications, cracks and defects in dental restorations including direct placed and indirect fabricated prosthetics, defects or ill-fitting prosthetics linked to dental implants, defects at the margins or junctions of tooth and dental restorations.

Additional applications of the preceding embodiments to the detection of defects in dental materials includes the following: detecting and monitoring the effect of various agents, treatments and therapies on in-vivo or in-vitro teeth or samples to determine whether or not they create lesions or erosions, stabilize these areas of tissue loss or promote regeneration of lost tissue; detecting and monitoring changes in tooth structure as additional evidence of various disease process such as bruxism, gastro-esophagel reflux, TemproMandibular Joint Dysfunction, and the like; detecting, examining and scanning a tooth surface whether intact or prepared for the placement of a direct or indirect restoration to ensure that the surface is clean, free of defects including cracks or accumulations of debris, cements, plaque etc. before

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placement of the restoration; detecting and monitoring defects and or dental caries around the edges of direct placed (amalgam, composite resin and other) dental materials; detecting and monitoring the integrity of dental materials including detection of cracks, craze lines etc. on both direct placed and indirect fabricated dental prosthetics; detecting and monitoring defects at the margins of dental sealants and caries beneath these dental sealants which are placed in the tooth; detecting and monitoring defects and or dental caries at the margins of indirectly placed dental restorations including full crowns, inlays, onlays, bridges etc. made of gold, composite and or porcelain or other dental materials; detecting, monitoring and confirming the fit and marginal integrity of direct and indirect placed dental materials into prepared tooth surfaces; detecting and monitoring the fit of precision attached dental restorations to ensure that the attachments are completely seated; detecting and monitoring the fit of mesostructures onto osseous integrated dental implants on initial placement and over the lifetime of the prosthesis; detecting and monitoring the integrity of materials used in the manufacture of dental prosthesis including osseous integrated implants, mesostructures and or superstructures, frameworks of fixed and removable prosthesis made of metal alloy, sintered porcelain and other materials; detecting and monitoring carious lesions and or defects around orthodontic brackets and other materials that are bonded on to the tooth surface not excluding bonded bridgework, veneers and retainers or other surface sealants; detecting the pulp chamber and or root canal system inside the tooth surface while performing endodontic therapy; confirming the marginal integrity of the endodontic obturation or filling of the root canal system of a tooth; detecting cracks both on the outside of the tooth surface and from within a cavity preparation or within the confines of the pulp chamber or root canal system; detecting and examining the anatomical structure of

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root apices while performing surgery in this area; detecting, examining and locating neurovascular bundle while performing surgery in the maxilla and or mandible; detecting and monitoring the recession or movement or migration of the gingival tissue from the CEJ; detecting and monitoring the evolution of erosion lesions or lesions due to the exposure of acids on the tooth surface or surface of the dental restorative materials; detecting and monitoring the evolution of carious lesions or erosion lesions and how various therapies can enhance, stabilize or reduce lesions size; and incorporating this into a preventive based program that can be used in a clinical practice or a public health programme; combining the images, information into a data base that is patient specific, specific for a particular dental practice, for a particular age group, particular group of teeth, particular sex or ethnic group or particular postal code or geographic region to provide information on the health and status of the teeth, prosthesis or other entities studied; taking the combined images and information from this data base to provide historical information and or epidemiologic information on the caries present, size of lesion, state of dental materials in various environments, and other information on the oral health and integrity of the dental materials and prosthetics; taking the combined images and information from this data base on a patient specific, gender specific or other groupings and comparing it against known risk factors for caries, erosion, bruxism and other oral disorders and conditions to develop a risk profile or risk ranking for a patient or a population group; using the information in this data base to provide guidance on the various therapies, pathologic situations to patients, oral health providers, providers of the various dental programs and manufacturers of the various therapies; and detecting and monitoring the integrity of various dental instruments including but not limited to dental burs, diamond dental burs, surgical elevators,

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endodontic files and instruments and or dental scalers and or curettes to ensure that there are no defects that would affect the integrity of the material or instrument while it is being used during a procedure.

The following examples are presented to enable those skilled in the art to understand and to practice embodiments of the present disclosure. They should not be considered as a limitation on the scope of the present embodiments, but merely as being illustrative and representative thereof.

EXAMPLES

Example 1: Early Detection of Dental Caries

In order to apply controlled demineralization to tooth samples, a demineralizing / artificial caries solution was prepared. The solution was an acidified gel, consisting of 0.1 M lactic acid gelled to a thick consistency with 6% w/v hydroxyethylcellulose and the pH adjusted to 4.5 with 0.1 M NaOH. Demineralization with acidified gel approximates the natural carious lesion as it mimics the properties of actual dental plaques in the oral cavity. Previous studies show that this solution can produce a subsurface lesion in enamel with a sound surface layer which is characteristic of an early carious lesion[1].

As it was desired to observe the contrast between demineralized and healthy areas in a whole tooth, a treatment protocol was followed in which the interrogated surface of the sample was covered with two coatings of commercial transparent nail polish except for a rectangular or square window, henceforth referred to as the treatment window. The demineralization on the window was carried out by submerging the sample upside down in a polypropylene test tube containing 30 ml of demineralizing / artificial caries solution. After the treatment period the sample was removed from the gel, rinsed under running tap water for approximately 1 minute and dried in air for 5

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minutes. Then, the transparent nail polish was removed from the interrogated surface with acetone and the sample was again rinsed, dried, and stored in the air-tight humid box for at least 24 hours before the imaging. For consecutive demineralization, after the imaging step the sample was again covered with the transparent nail polish (except for the treatment window) and treated / demineralized for additional days in order to investigate the progression of demineralization and evolution of the artificial carious lesion with time.

Figure 5(a) shows an optical image of sample A1 before application of demineralization in the treatment window. The dashed rectangle in this figure shows the area that was imaged using the thermophotonic lock-in system while the solid rectangle depicts the location of the treatment window. The optical image shows traces of a discontinuity on the surface of enamel (feature 1). The two vertical lines on the root area show the approximate lateral position of the treatment window (solid rectangle). These lines were meant to aid the operator with sample alignment and are of no scientific importance. Figure 5(b) "F" shows the dental radiograph of the untreated sample ("before") at the same view as the optical image and figure 5(b) "S" shows the side view indicated by the arrow in the optical image (Fig. 5(a)). Based on these radiographs and visual examination sample A1 was a healthy tooth before application of artificial caries treatment and it is interesting to see that the discontinuity or crack on the enamel surface (feature 1) could not be resolved in either of the dental radiographs.

Figures 5(b-c) and 5(d) are the x-ray radiographs and the optical image, respectively, taken from sample A1 after 10 days of treatment. None of these images can show even a trace of mineral loss in the treatment window, showing the insensitivity of conventional clinical diagnostic methods to early demineralization or

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carious lesion formation. Figure 5(e) depicts the thermophotonic lock-in phase image of sample A1 taken at 10 Hz before application of any treatment. This image not only shows the enamel discontinuity observed in the optical image (feature 1) but also reveals the presence of a vertical crack (feature 2) and the cementoenamel junction (CEJ, feature 3). Neither the x-ray radiographs (Fig. 5(b)) nor the optical image (Fig. 5(a)), could resolve this vertical crack (feature 2). The reason of the high sensitivity of thermophotonic images to cracks is the fissured nature of cracks which enhances the photothermal temperature field through thermal-wave flux localization generating high contrast.

The appearance of the enamel discontinuity in the phase image (feature 1 in Fig. 5(e)) has similar physical origin to that of cracks. It was postulated that feature 1 was caused by the forces applied during the tooth extraction. The appearance of a dark band in the phase images of figure 5 (feature 3) at the CEJ level suggests the presence of a border between enamel and cementum, remnants of periodontal ligament at this position. According to the dental literature, enamel of the cervical margin of the tooth is one of the locations which favors plaque formation and is therefore prone to demineralization. It can be seen that all the thermophotonic phase images of figure 5 can detect feature 3 (the CEJ) with high sensitivity (contrast). In fact, one of the most important advantages of thermophotonic lock-in imaging compared to single point photothermal radiometric (PTR) measurements is the significant improvement in the wealth of data resulting in excellent contrast and reliability of the results in real time and in direct comparison with conventional dental radiographs. Point-by-point measurements would require much longer time spans to produce surface images, which would be impractical in clinical applications.

Figures 5(f) to 5(i) show the phase images taken at 2, 4, 8, and 10 days of

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treatment (mineral loss only within the treatment window), respectively. It should be noted that the same contrast mapping (linear, with identical thresholds) has been used in all thermophotonic lock-in images of figure 5 to ensure the validity of comparison between the images. It can be observed that as treatment time increases the treated window becomes more apparent while the other features in the images remain more or less the same. The mean phase values within the treatment window (empty rectangle in Fig. 1(e)) for the untreated, 2D, 4D, 8D, and 10D samples are found to be -7.47°, -25.22°, -31.75°, -42.07°, and -49.66°, respectively. This monotonic decrease in the phase lag is due to the progression of the lesion into the enamel. As the lesion thickness increases, the thermal-wave centroid shifts closer to the surface, thereby decreasing the phase lag between the applied optical excitation and the received infrared response. The phase lag decreases also with respect to the intact state ("before").

Feature 4 in figure 5(f) is most probably a material inhomogeneity formed as a result of incomplete removal of nail polish from the enamel surface after the second day of demineralization. The feature disappeared after the next demineralization cycle. It appears that feature 5 is stress-induced cracks that were formed during tooth extraction. The cracks become more apparent toward the later stages of demineralization (Figs 5(e) to 5(i)) due to successive nail polish penetration into them. It has been known that nail polish can penetrate tens of micrometers into dental enamel[2].

Figure 5(j) is a plot of transverse profiles of the phase images along the dashed line shown in figure 5(i). The dashed vertical lines represent the location of the treatment window (centered at 6.27 mm). It can be seen that as demineralization progresses, the absolute thermophotonic phase values increase within the treatment

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window but remain approximately the same outside the treatment window. Furthermore, examination of these phase profiles reveals that the demineralization and artificial lesion has not only propagated vertically into the enamel but has also spread out laterally. However, the extent of the lesion is always maximal within the treatment window and decreases rapidly laterally away from the treatment window. The two dips in the phase values at -3.9 mm and -8.8 mm lateral positions are related to the vertical defects at those locations (features 2 and 1, respectively).

Figure 5(k) represents the transverse micro-radiographic mineral profile vertically along the center of the treatment window. Mean lesion depth of 326.4 μm and mineral loss of 5,710 vol% μm was reported by the transverse micro-radiographic software for the lesion produced at the center of the treatment window. It can be seen that the lesion retains a relatively well-preserved surface layer with a moderate mineral loss over a large depth. It is somewhat surprising to find such a deep lesion formed after only 10 days of treatment with the artificial caries gel, but it is a well-known fact that the rate of demineralization can vary greatly among teeth[1].

Figure 6 presents the results obtained from sample A2. Unlike Sample A1, the occlusal surface was investigated for this sample. Figure 6(b) shows the thermophotonic lock-in amplitude image taken at 10 Hz. The amplitude image shows the presence of caries at several locations but the image is rather diffuse. Using this image, four regions of interest (i, f, g, and h) were identified within the imaged area of the optical image (Fig. 6(a)). The thermophotonic lock-in phase image taken at 10 Hz is shown in figure 6(c). No feature can be resolved in the blurry phase image. The reason for such poor resolution is the relatively long, diffusion-limited thermal wavelength at 10 Hz. In fact, in these images the contributions from deeper features have resulted in nuisance interferences superposed on features closer to the surface.

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Consequently, to avoid the interfering effects of deep features, it was decided to reduce the thermal wavelength by generating the images at 100 Hz in order to be able to effectively detect the areas of mineral loss in the pits and fissures of the occlusal surface and the near-subsurface regions. The resolution improvement at higher frequencies is a well-known behavior of thermal-waves[3] and is clearly visible in the amplitude and phase images obtained at 100 Hz (Figs 6(d) and 6(e)). The pits labeled/ *g*, and *h* in figure 6(e) are shown as carious spots, whereas the groove labelled *i* is shown as a healthy bright spot (similar to intact regions in images 5b to 5f). Transverse micro-radiographic profiles are shown in Figures 6i-f of the dark carious regions/ *g*, and *h* and of the groove *i*, clearly show the presence of mineral losses at points *f*, *g* and *h* while no significant mineral loss can be observed in the mineral profile obtained at *i*. The transverse micro-radiographic profiles fully validate the results of the non-contacting, non-destructive imaging method.

Example 2a: Non-destructive testing of engineering materials with subsurface absorbers and early detection of dental caries using thermophotonic radar imaging

The physical principles of light absorption/scattering and thermal-wave generation are the same for the various imaging modalities disclosed herein. The difference lies in the applied optical excitation pattern and the subsequent signal processing algorithm. As discussed above, in thermal wave radar (or thermophotonic radar) imaging a chirp excitation is used instead of a single frequency modulation. As a result, according to equation 5a, the thermal diffusion length is not fixed and the generated thermal-waves dynamically scan a series of depths. One of the problems encountered in thermophotonic lock-in imaging is the compromise one needs to make between the maximum detection depth and the depth resolution. While the low

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frequency thermal-waves can see deep into the sample, they lack the desired depth resolution; the high frequency thermal-waves, on the other hand, have the exact opposite situation due to the reduced thermal diffusion length.

In order to experimentally investigate the capabilities of the thermophotonic radar method, three samples of engineering and biological materials were designed and prepared. The first sample, B1 400 (Figure 7(a)), is a black plastic step-wedge sample (step height = 200 μm) placed inside a scattering medium (polyvinyl chloride-plastisol (PVCP) with added Titanium dioxide ($Ti0_2$) powder for scattering[6]) such that the first step is located approximately 1 mm below the phantom surface. The second sample, B2 420 (Figure 7(b)), was made using 120 μm-thick Fisher Scientific borosilicate microscope cover slips. The glass was covered by commercial green 430 (on the left) and black 440 (on the right) paints with no paint applied to the center part 450 to form a three-strip pattern. Six additional microscope cover slips were put on the painted slip to simulate 2 absorbers with different absorbing coefficients 720 μm below the surface. To show the application of the Thermophotonic Radar imaging in the dental field, the third sample, B3 460, was chosen to be an extracted human tooth that was locally demineralized using the artificial caries acidic gel within two square shape treatment windows 470, as shown in figure 7(c). The left and right windows were treated / demineralized for 10 and 20 days, respectively.

Figure 8 shows the results obtained from a comparison study on the depth resolution capabilities of thermophotonic lock-in and thermophotonic radar imaging involving sample B1 (FIG. 7(a)). Figures 8(a) and 8(d) show the thermophotonic lock-in phase image obtained at 0.01 Hz and its mean horizontal phase profile, respectively. It can be seen that due to the very large thermal diffusion length at such low modulation frequency it is impossible to resolve the 200^m-high steps from each

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other and as a result the phase image appears as a gradient of colors between the two color bar extremes.

Figure 8(b) shows the thermophotonic lock-in phase image obtained at 1 Hz. The bar plot of figure 8(e) depicts the mean phase values on each step along with their standard deviations. The error bars indicate that statistically only the first two steps can be resolved. Figures 8(a) and (b) clearly show the maximum detection depth/depth resolution trade-off of thermophotonic lock-in imaging.

Figure 8(c) is a CC amplitude image obtained from 0.01-1Hz chirps with duration of 6s (using the exact same experimental conditions as those used for Figures 8(a) and 8(b)) and figure 8(f) depicts the mean CC values on each step. It can be seen that the thermophotonic radar imaging not only resolves the steps but also detects them all. These advantages are due to the fact that the matched filtering/cross correlation process puts most energy of the signal under its main narrow peak, improving depth resolution and greatly enhancing the signal to noise ratio, which equals the time (chirp duration) - bandwidth (chirp frequency content) product, thereby improving maximum detection depth.

Figure 9 depicts the results involving sample B2 (FIG. 7(b)) to compare the three contrast parameters that can be used in thermophotonic radar imaging. Figures 9(a), 9(b), and 9(c) are the images obtained using cross correlation amplitude, peak delay time, and phase, respectively, and figures 9(d), 9(e), and 9(f) show their horizontal mean profiles. It can be seen that the amplitude channel is truly reflecting the amount of energy absorption by the two equally deep absorbers (green and black paints), yielding significantly different CC amplitude values from them. Consequently, the amplitude channel is not a true measure of the depth of the absorber while the CC peak delay time and phase values are truly linked to the depth

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of the absorbers as they maintain the same value over the two absorbers regardless of their absorption coefficient (similar to thermophotonic lock-in phase channel). However, in terms of SNR the CC amplitude channel is significantly stronger than peak delay time and phase channels and therefore it may be beneficial to use the amplitude images to complement the information obtained from the phase and peak delay time images.

Figures 10(a)-(c) show the CC amplitude, peak delay time, and phase images obtained from sample B3. In general, tooth demineralization results in more porosity and leads to more light absorption and scattering that consequently increases the amplitude of thermal-waves and shifts the thermophotonic centroid of Eq. 5b (i.e. phase shift) compared to healthy spots. As a result, the artificially created caries is clearly detectable in all CC images (FIGs 10(a)-(c)). However, due to the emissivity-normalized nature of peak delay time and phase channels, more details can be resolved in figures 10(b) and (c) compared to figure 10(a). The higher contrast of the right treatment window indicates a greater mineral loss due to the additional treatment days. On the other hand, thermophotonic lock-in phase images suffer from low depth resolution at 0.01Hz (FIG 10(d)): they cannot probe deep enough at 1Hz (FIG 10(e) and cannot show the additional mineral loss in the right treatment window). Figure 10(f) depicts the transverse micro radiography mineral profiles along points 1-3 depicted in figure 10(c) and are provided as proof of mineral loss within the treatment windows.

Additional applications to engineered automotive and aerospace materials are in detecting metal hardness case depth and case depth non-uniformities using a thermophotonic radar image of the cross-correlation peak delay times which correspond to case hardness depth[12].

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Example 2b: Non-destructive testing of engineering materials with subsurface absorbers and early detection of dental caries using binary phase code Imaging

Table 1 (shown above) includes the binary phase codes up to 16 bits. These codes are used as an envelope of a single-frequency modulated signal to yield the reference signal for binary phase code imaging.

Samples B1 and B3 (Figure 7(a) and (c)) were used to study the capabilities of binary phase code imaging. Figure 11 shows the results obtained from sample B1 using a 7-bit binary phase coding on a 1Hz carrier signal (Figures 11 (a) and (c)) as well as those of thermophotonic lock-in imaging at 1Hz (Figures 11 (b) and (d)). It can be seen that due to the advantages of matched filtering/cross-correlation the binary phase code image resolves all the steps while the thermophotonic lock-in image can statistically detect only the first two steps. That is, binary phase code imaging has a significantly better depth resolution compared to thermophotonic lock-in imaging.

Figure 12 shows a similar comparison but on an extracted tooth sample (sample B3, figure 7(c)). While the thermophotonic lock-in amplitude image appears too blurry and the thermophotonic lock-in phase image shows only traces of mineral loss within the treatment windows, the emissivity normalized binary phase code peak delay time and phase images not only detect the regions of mineral loss but also show the additional mineral loss of the right window compared to that of the left window.

Figure 13 depicts a well-known limitation and challenge of diffusion fields: resolving stacked overlapping defects. Figure 13(a) shows an exploded view of a cross-shaped sample made of two strip absorbers. The deeper strip is a black plastic

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sample completely absorbing the optical flux, while the shallower strip is a partially absorbing phantom. All other components are transparent polyvinyl chloride-plastisol.

When viewed from the top, the cross sample covers all possible combinations: absorbers at two different depths (the end sections of the absorbing strips, points 1 and 2 in Fig 13(b)) and two absorbers on top of each other (point 3 in Fig 13(b)). Figures 13(b) and 13(c) show the thermophotonic lock-in amplitude and phase images of this sample, respectively. It can be observed that the amplitude image cannot distinguish between the deeper and shallower absorbers (vertical and horizontal strip, respectively). However, the amplitude information can be used to extract and process only those pixels having a high value (i.e. a subsurface absorber). Although the thermophotonic lock-in phase image yields significantly different values over the single absorbers (points 1 and 2) it cannot detect the layered structure of point 3. The axial resolution of both amplitude and phase images is limited by the depth-integrated nature of thermal waves.

Figures 13 (d) and (e) are the binary phase code peak delay time images using the temporal data of points 1 and 2 as the matched filter, respectively. When using the temporal camera data of point 1 as the matched filter, all the diffusion waves originating at the same depth as that of point 1 will have their CC peaks located at $\tau = 0$ (correlogramic image).

A similar situation arises in figure 13(e) for diffusion waves from the shallower absorber using the temporal camera data of point 2 as the matched filter. The fact that the layered structure of point 3 shows a maximum correlation to both data of points 1 and 2 ($\tau_p = 0$) shows that matched-filter binary phase code imaging can resolve the layered structure axially.

This depth resolved phenomenon is normally a property of propagating

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hyperbolic wave-fields and not of parabolic (diffusive) fields. The implications of correlogramic imaging can open a new field of generating layer-by-layer subsurface thermal coherence tomography (TCT) using naturally incoherent diffusion waves.

Accordingly, according to some embodiments, correlographic imaging may be employed to produce images at constant delay times. Since each delay time corresponds to a given depth, by making the images at different delay times one can make slice by slice images. The example shown in Figure 13 provides experimental demonstration that this method provides depth selective (depth slice) images. Although such images may also be produced using chirped waveforms, binary phase coded waveforms generally provide superior axial resolution.

An illustration of the capabilities of this correlographic binary phase code imaging modality applied to turbid media thermophotonics (biological tissue) is its ability to detect early caries in human teeth which conventional clinical diagnostic modalities, like radiographs, cannot detect. Early caries remove mineral from areas very close to the enamel surface and create micro-pores which trap light photons and eventually promote close-to-surface light absorption/thermal-wave generation. As a result, thermal-waves from early caries travel less distance to reach the interrogated surface and yield higher amplitude and smaller phase lag/delay compared to those of intact regions.

However, an important shortcoming of dental thermophotonic lock-in imaging is its inability to detect interproximal (in between teeth) caries when inspected from the accessible buccal (front) surface. A comparison of thermophotonic lock-in and binary phase code phase images of figure 14(b) and 14(c) under identical experimental conditions, shows how the enhanced axial resolution of the binary phase code imaging can resolve deep interproximal caries. Moreover, by constructing

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images (such as amplitude or phase images) at given delay times one can perform depth-selective slicing (thermal coherence tomography) in the turbid medium to resolve the defective regions, figure 14(e), from the intact areas, figure 14(f).

Figure 15(a) shows the optical image of the interrogated surface of a goat bone along with its cross section. The optical image shows that the spongy trabecular bone is covered by the more dense cortical bone on the surface. Figure 15(b) is the phase image obtained using the binary phase code technique. The low carrier frequency of 1 Hz ensures penetration of thermal-waves into the trabecular structure, while the depth-resolved nature of phase modulated matched filtering reveals the trabecular structure that lies right below the cortical overlayer.

Figure 15 demonstrates that the depth-selective thermophotonic radar imaging methods disclosed herein are potentially suitable for the imaging of bone structure. Such imaging can be employed to support the identification of bone osteoporosis, and in particular, early bone osteoporosis. Indeed, the present example imaging methods could be employed for screening of osteoporosis. For example, the measured image may be processed according to known image processing techniques to identify abnormal bone condition, such as, by generating, based on the image, a measure of bone health, and comparing the measure to thresholds, normal ranges, or other calibration parameters. It is noted that at present, direct expenditures for treatment of osteoporotic fracture in the U.S. are estimated at $10 - $15 billion annually, and that no imaging methodology currently exists for the early diagnosis of osteoporosis.

Additional applications to engineered automotive and aerospace materials are in detecting metal hardness case depth and case depth non-uniformities using a binary phase code image of the cross-correlation peak delay times which correspond to case hardness depth[12].

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The specific embodiments described above have been shown by way of example, and it should be understood that these embodiments may be susceptible to various modifications and alternative forms. It should be further understood that the claims are not intended to be limited to the particular forms disclosed, but rather to cover all modifications, equivalents, and alternatives falling within the spirit and scope of this disclosure.

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THEREFORE WHAT IS CLAIMED IS:

1. A method of performing thermophotonic imaging, said method comprising the steps of:

providing a sample;

providing an optical source having a wavelength selected to generate photothermal radiation within said sample;

providing an imaging camera with an optical bandwidth selected for detection of said photothermal radiation;

generating a reference waveform comprising a plurality of modulation cycles;

producing a modulated optical beam by modulating an intensity of an optical beam emitted by said optical source according to said reference waveform;

illuminating said sample with said modulated optical beam;

imaging said photothermal radiation with said imaging camera;

recording a plurality of dynamically averaged image frames at time offsets corresponding to different values of said reference waveform; and

processing said dynamically averaged image frames and said reference waveform to obtain an image relating to said photothermal radiation.

2. The method according to claim 1 wherein said dynamically averaged image frames are obtained according to the following steps:

recording a plurality of image frames at times corresponding to different values of said reference waveform;

repeating, one or more times, said step of recording said image frames at times corresponding to different values of said reference waveform, and dynamically

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averaging said recorded image frames for each said different value of said reference waveform, thereby obtaining dynamically averaged image frames.

3. The method according to claim 2 wherein said step of recording said plurality of image frames at different values of said reference waveform comprises recording said plurality of image frames over a single modulation cycle/correlation period.

4. The method according to claim 2 wherein said plurality of image frames at different values of said reference waveform are obtained over more than one modulation cycle.

5. The method according to claim 4 wherein a frame acquisition rate of said imaging camera is less than a modulation frequency of said reference waveform.

6. The method according to claim 2 or 3 further comprising the step of recording, for each image frame of said plurality of image frames, a substantially instantaneous value of said reference waveform.

7. The method according to claim 6 further comprising the step of generating a quadrature waveform based on said reference waveform, and recording, for each image frame of said plurality of image frames, a substantially instantaneous value of said quadrature waveform.

8. The method according to any one of claims 1 to 7 further comprising the step of generating an integration pulse train comprising a series of pulses, wherein each

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pulse is generated at a time at which an image frame is acquired by said imaging camera, wherein said step of generating of said reference waveform is triggered according to said integration pulse train.

9. The method according to claim 8 wherein said integration pulse train is generated by said imaging camera.

10. The method according to any one of claims 1 to 9 further comprising the step of generating a flag pulse train comprising a series of pulses, wherein each pulse is generated at a commencement of a given modulation cycle/correlation period, and identifying one or both of a beginning and an end of said given modulation cycle/correlation period according to said flag pulse train.

11. The method according to any one of claims 1 to 10 wherein a modulation frequency of said reference waveform is greater than approximately 0.01 Hz.

12. The method according to any one of claims 1 to 11 wherein said reference waveform comprises a single frequency and wherein said image is obtained by lock-in processing.

13. The method according to claim 12 wherein said step of processing said dynamically averaged image frames and said reference waveform comprises, for each pixel in said image, performing the steps of:

multiplying said dynamically averaged image frames by said reference waveform to obtain in-phase product values; and

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summing said in-phase product values to obtain an in-phase sum;

generating a quadrature waveform based on said reference waveform;

multiplying said dynamically averaged image frames by said quadrature waveform to obtain phase-shifted product values; and

summing said phase-shifted product values to obtain a phase-shifted sum.

14. The method according to claim 13 wherein said image is an amplitude image, and wherein said processing further comprises calculating a magnitude of a complex quantity based on said in-phase sum and said phase-shifted sum.

15. The method according to claim 13 wherein said image is a phase image, and wherein said processing further comprises:

calculating a phase angle of a complex quantity based on said in-phase sum and said phase-shifted sum.

16. The method according to any one of claims 1 to 11 wherein said reference waveform comprises multiple frequency components.

17. The method according to claim 16 wherein said reference waveform comprises a frequency chirp.

18. The method according to claim 16 wherein said reference waveform is a binary phase coded waveform.

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19. The method according to any one of claims 16 to 18 wherein said image is a cross-correlation peak amplitude image obtained by the steps of:

obtaining a complex cross-correlation signal of said reference waveform and each pixel of said dynamically averaged image frames; and

determining, for each said pixel, a peak amplitude value of a peak in a real part of said cross-correlation signal.

20. The method according to any one of claims 16 to 18 wherein said image is a cross-correlation peak delay image obtained by the steps of:

obtaining a complex cross-correlation signal of said reference waveform and each pixel of said dynamically averaged image frames; and

determining, for each said pixel, a delay of a peak in a real part of said complex cross-correlation signal.

21. The method according to any one of claims 16 to 18 wherein said image is a cross-correlation phase image obtained by the steps of:

obtaining a first complex cross-correlation signal of said reference waveform and each pixel of said dynamically averaged image frames;

obtaining a second complex cross-correlation signal of a quadrature waveform and each pixel of said dynamically averaged image frames, wherein said quadrature waveform is based on said reference waveform;

forming a complex quantity comprising a real portion of first complex cross-correlation signal and a real portion of said second complex cross-correlation signal; and

obtaining said phase image by determining, for each pixel, a phase angle of said complex quantity at a pre-selected time delay.

22. The method according to any one of claims 1 to 21 wherein said sample is selected from the group consisting of automotive components, aerospace components, an optical material, a laser material, a biomedical material, and a biological tissue.

23. The method according to any one of claims 1 to 22 wherein said sample is a material comprising one or more of a subsurface crack and a delamination.

24. The method according to any one of claims 1 to 21 wherein said sample is an unsintered component in a green state.

25. The method according to any one of claims 1 to 24 further comprising the step of determining a case hardness depth.

26. The method according to any one of claims 1 to 21 wherein said sample is a dental sample, the method including the step of displaying the image.

27. The method according to any one of claims 1 to 21 wherein said sample is a dental or medical instrument.

28. The method according to any one of claims 1 to 21 wherein said sample includes bone, wherein the step of imaging the photothermal radiation with the imaging camera includes imaging photothermal radiation generated within the bone.

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29. The method according to claim 28 wherein the bone is covered with tissue, and wherein the optical source is configured for transmitting at least a portion of the incident optical beam through the tissue for the generation of the photothermal radiation within the bone.

30. The method according to claim 28 or 29 further wherein a modulation frequency of the modulated optical beam is selected to support penetration of the photothermal radiation within a trabecular structure of the bone.

31. The method according to any one of claims 28 to 30 further including the step of identifying an onset or presence of osteoporosis in the bone based on the image.

32. The method according to claim 26 further wherein said dental sample is a tooth sample or whole groups of teeth.

33. The method according to claim 26 wherein the dental sample is a tooth, the method further comprising the step of analyzing said image to determine one or more of a presence and a location of demineralization, erosion or dental caries in said tooth.

34. The method according to claim 26 further comprising the step of monitoring an evolution of one or more of demineralization, erosion and dental caries by comparing said image to one or more other images.

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35. The method according to claim 26 wherein the image is a first image, the method further comprising the step of obtaining additional image of the dental sample after a time delay, and comparing the first image to the additional image for monitoring changes in the dental sample.

36. The method according to claim 26 wherein the image is a first image, the method further comprising the step of applying a treatment or therapy to said dental sample, obtaining additional image, and comparing the first image to the additional image to assess an efficacy of the treatment or therapy.

37. The method according to claim 26 wherein the dental sample is a tooth surface that is prepared for prepared for placement of a direct or indirect restoration, the method including the step of confirming, based on the image, suitability of the tooth surface for placement of the restoration.

38. The method according to claim 26 wherein the dental sample includes a tooth having a dental material placed directly thereon, wherein the image includes a region around an edge of the dental material for detecting or monitoring a defect around the edge of the material.

39. The method according to claim 38 wherein the dental material is a dental sealant.

40. The method according to claim 26 wherein the dental sample includes a tooth having a dental prosthetic, wherein the image includes the dental prosthetic for detecting or monitoring a defect associated with the dental prosthetic.

41. The method according to claim 26 wherein the dental sample includes a tooth having a dental restoration attached thereto, wherein the image includes the dental restoration for detecting or monitoring the attachment of the dental restoration.

42. The method according to claim 26 wherein the dental sample includes a dental implant, wherein the image includes the dental implant for detecting or monitoring the integrity of the dental implant.

43. The method according to claim 26 wherein the image includes at least one of the pulp chamber and root canal system of the dental sample.

44. The method according to claim 26 wherein the image includes the anatomical structure of root apices or the neurovascular bundle.

45. The method according to any one of claims 1 to 44 further comprising the step of identifying a defect region in the image.

46. The method according to claim 45 further comprising the step of displaying the defect region in a colour associated with the defect region.

47. The method according to claim 46 wherein the colour is associated with a relative size of the defect region.

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48. The method according to claim 27 wherein said dental or medical instrument is selected from the group consisting of endodontic instruments, catheters and other indwelling instruments.

49. The method according to any one of claims 1 to 47 wherein said wavelength is selected to lie within a range of approximately 600 nm to 2000 nm.

50. The method according to any one of claims 1 to 47 wherein said imaging camera is selected to have a spectral response overlapping with at least a portion of the mid-infrared spectrum.

51. A system for performing thermophotonic imaging, said system comprising:

an optical source having a wavelength selected to generate photothermal radiation within a sample;

an imaging camera with an optical bandwidth selected for detection of said photothermal radiation, wherein said imaging camera is configured to acquire image frames a given frame rate and output an integration pulse train comprising a series of pulses, each pulse corresponding to a time at which an image frame is acquired by said imaging camera;

a waveform generating system for generating a reference waveform, wherein an output of said waveform generating system is connected to an input of said optical source for modulating an intensity of an optical beam emitted by said optical source;

a processor programmed to dynamically average image frames obtained by said imaging camera, and to process said dynamically averaged image frames, said

reference waveform and a quadrature waveform based on said reference waveform, to provide one or more of an amplitude image and a phase image; and

a memory for storing dynamically averaged image frames.

52. The system according to claim 51 wherein a modulation frequency of said reference waveform is greater than approximately 0.01 Hz.

53. The system according to claim 51 wherein said imaging camera comprises a frame acquisition rate that is less than a modulation frequency of said reference waveform.

54. The system according to any one of claims 51 to 53 wherein said wavelength lies within approximately 600 nm to 2000 nm.

55. The system according to any one of claims 51 to 54 wherein a spectral response of said imaging camera overlaps at least a portion of the mid-infrared spectrum.

56. A method of performing thermophotonic imaging, said method comprising the steps of:

providing a sample;

providing an optical source having a wavelength selected to generate photothermal radiation within said sample;

providing an imaging camera with an optical bandwidth selected for detection of said photothermal radiation;

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generating a reference waveform comprising a binary phase coded waveform having a plurality of modulation cycles;

producing a modulated optical beam by modulating an intensity of an optical beam emitted by said optical source according to said reference waveform;

illuminating said sample with said modulated optical beam;

imaging said photothermal radiation with said imaging camera;

recording a plurality of dynamically averaged image frames at time offsets corresponding to different values of said reference waveform; and

processing said dynamically averaged image frames and said reference waveform to obtain an image relating to said photothermal radiation.

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Mod. in 170
LASER SYSTEM
140
120
In. Ref. 160
DATA ACQUISITION SYSTEM
Quad ref. 165
Camera
Flag Pulse 175
130
IT Pulse 190
110
COMPUTING SYSTEM
Image sequence 180
100
150

Figure 1

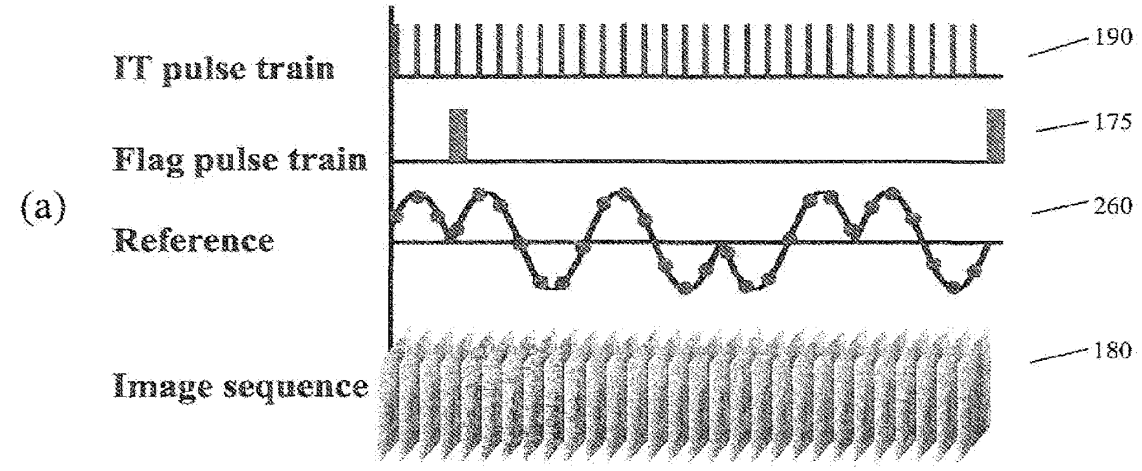
IT pulse train
190
Flag pulse train
175
In-phase Ref.
160
f(t)xsin(t)
$\sum_1$
S^0
200
Image sequence
f(t)
180
f(t)x-cos(t)
$\sum_2$
S^{90}
210
Quadrature Ref.
165

Figure 2

(a)
IT pulse train
190
Flag pulse train
175
Reference
250
Image sequence
180

(b)
Cross-correlation Signal
365
335
370
τ
300
310
325
Complex conjugate
330
Ref(t)
FFT
Z*
IFFT
Real
Imag.
350
τ_p
τ'_p
360
Phase Signal
HT
FFT
Z*
IFFT
Real
Imag.
r
θ
τ
S(t)
FFT
345
355
305
320
315
340

Figure 3


(a)
IT pulse train
Flag pulse train
Reference
Image sequence
190
175
260
180

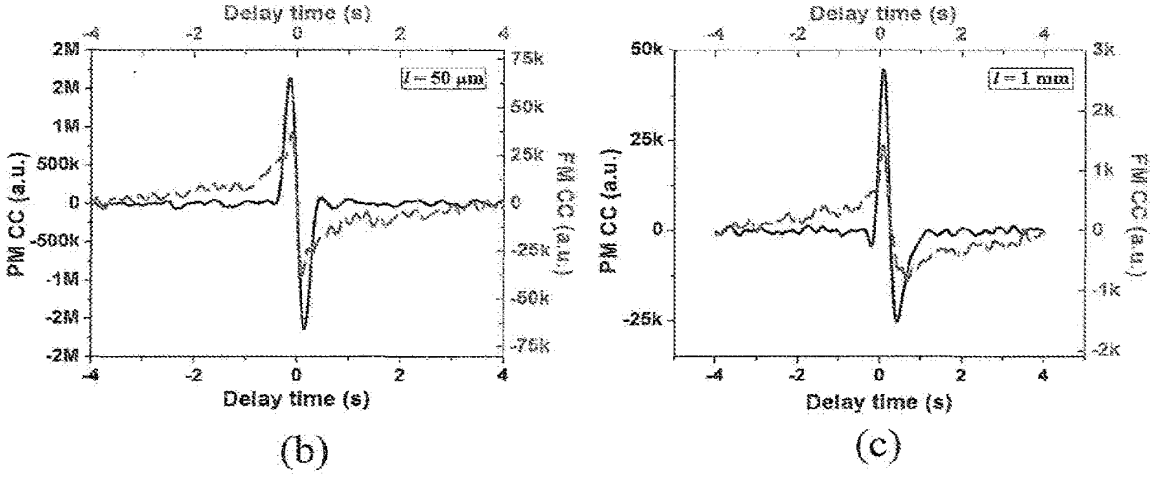

Delay time (s)
PM CC (a.u.)
l = 50 μm
(b)
Delay time (s)
PM CC (a.u.)
l = 1 mm
(c)

Figure 4

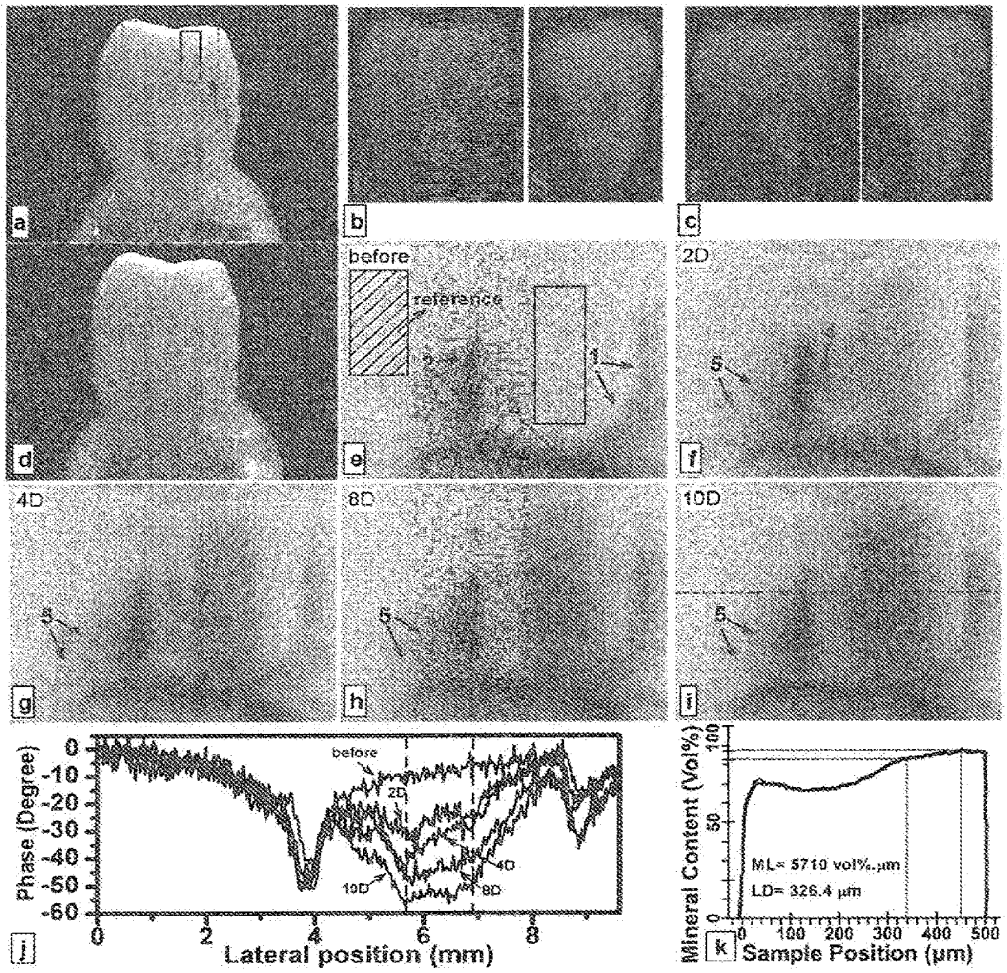

a
b
c
d
before
reference
1
e
2D
S
f
4D
S
g
8D
S
h
10D
S
i
Phase (Degree)
0
-10
-20
-30
-40
-50
-60
before
2D
4D
8D
10D
0
2
4
6
8
Lateral position (mm)
j
Mineral Content (Vol%)
100
50
0
ML= 5710 vol%.µm
LD= 326.4 µm
0
100
200
300
400
500
Sample Position (µm)
k

Figure 5

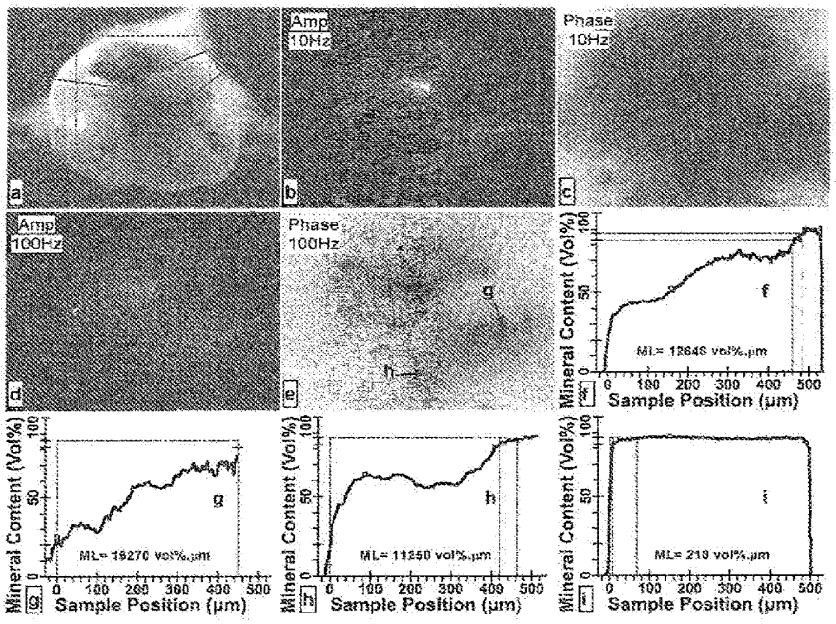


Figure 6

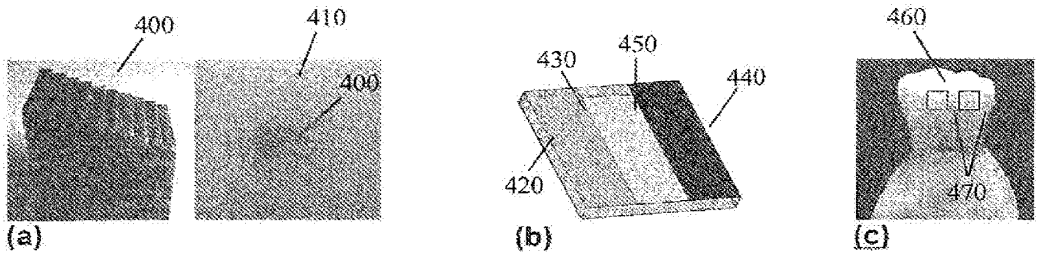


Figure 7

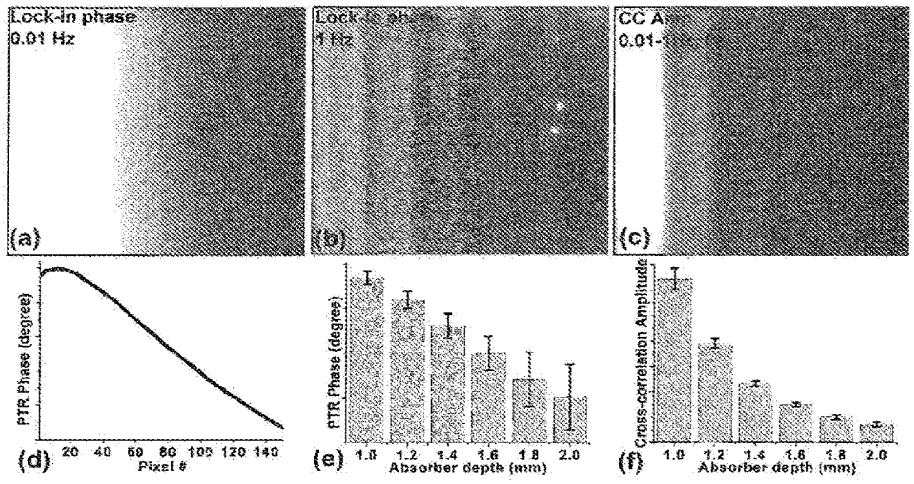


Figure 8

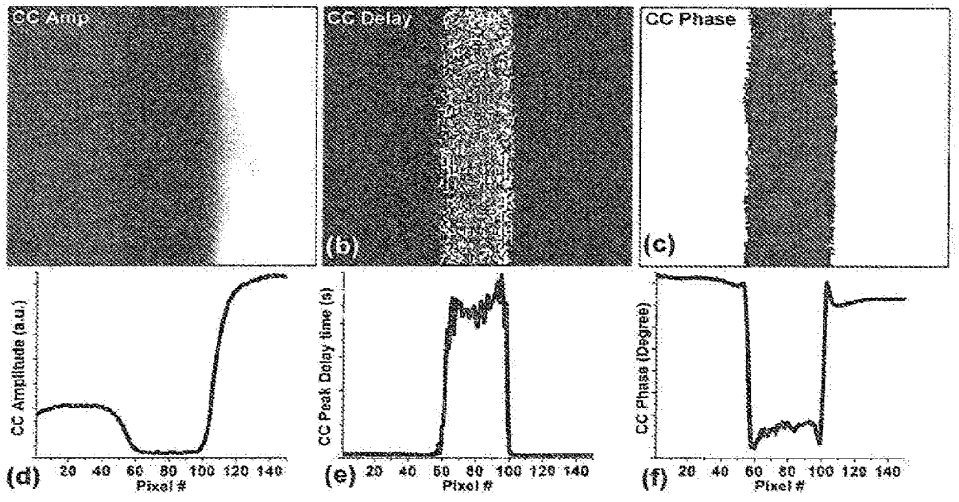


Figure 9

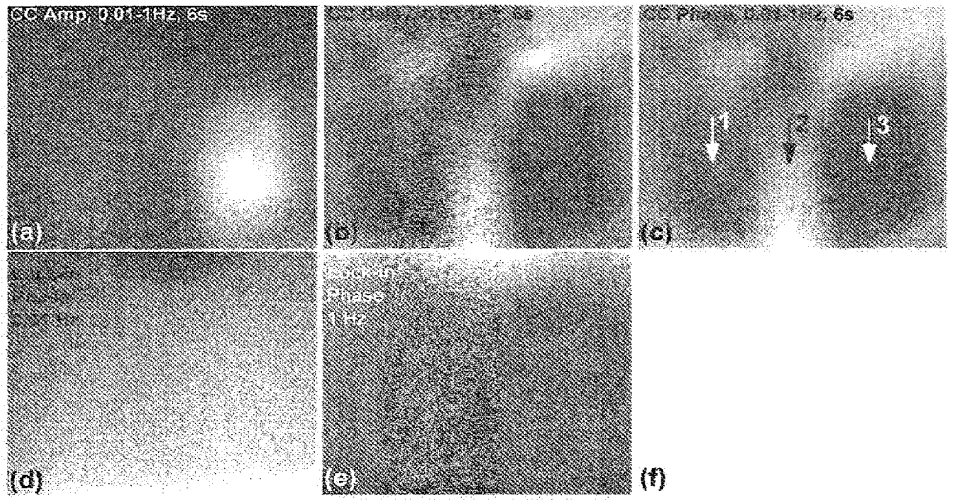


Figure 10

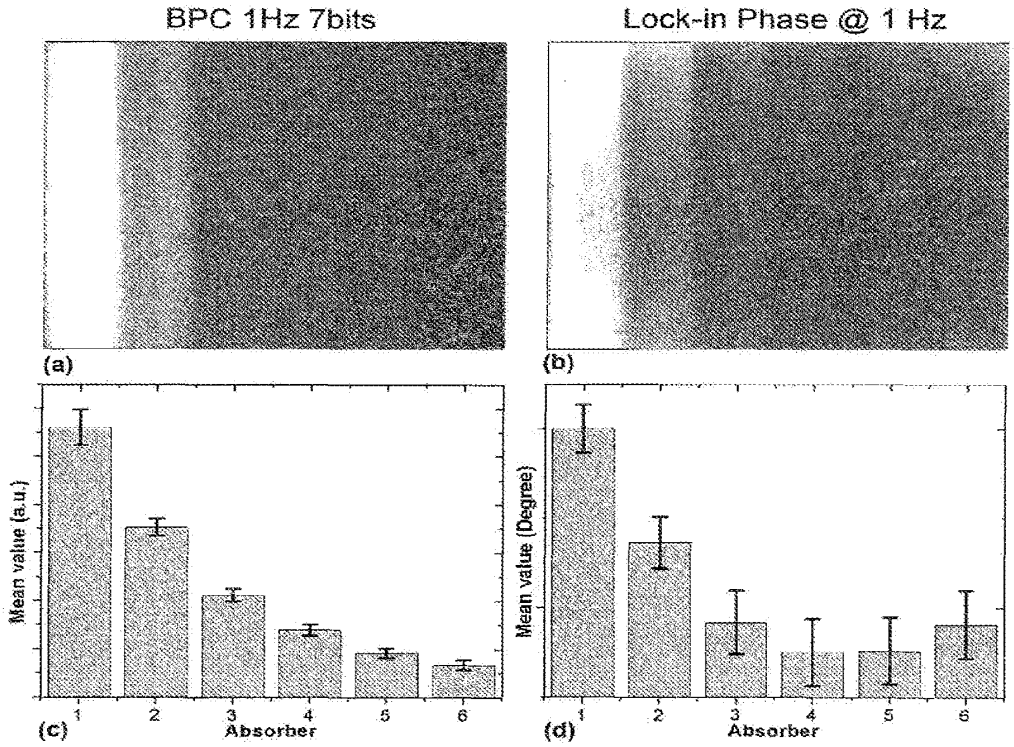

BPC 1Hz 7bits
Lock-in Phase @ 1 Hz
(a)
(b)
Mean value (a.u.)
Mean value (Degree)
1
2
3
4
5
6
Absorber
(c)
(d)

Figure 11

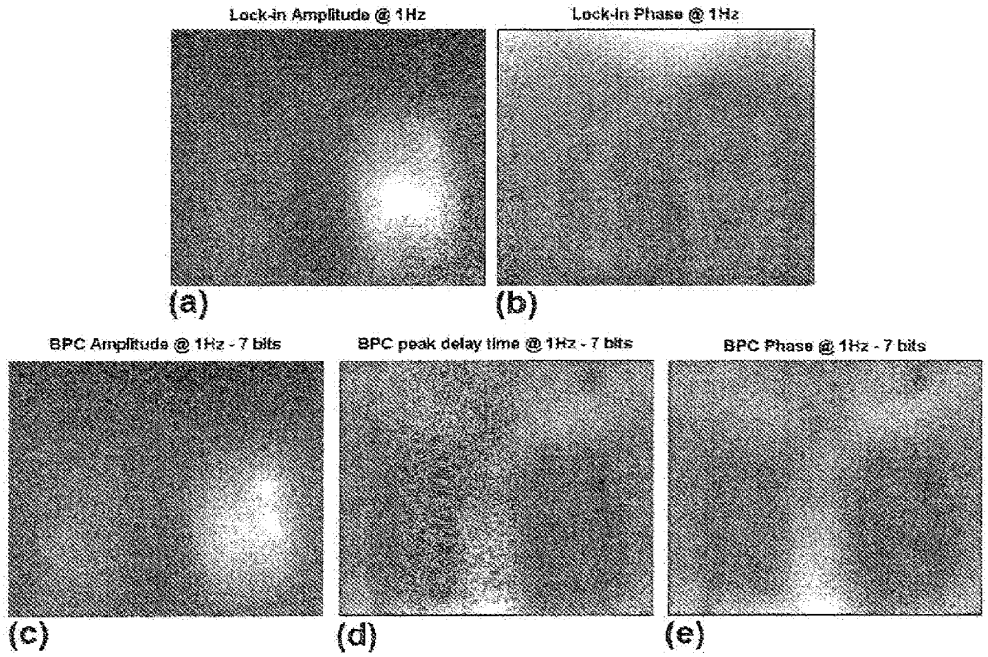

Lock-in Amplitude @ 1Hz
Lock-in Phase @ 1Hz
(a)
(b)
BPC Amplitude @ 1Hz - 7 bits
BPC peak delay time @ 1Hz - 7 bits
BPC Phase @ 1Hz - 7 bits
(c)
(d)
(e)

Figure 12

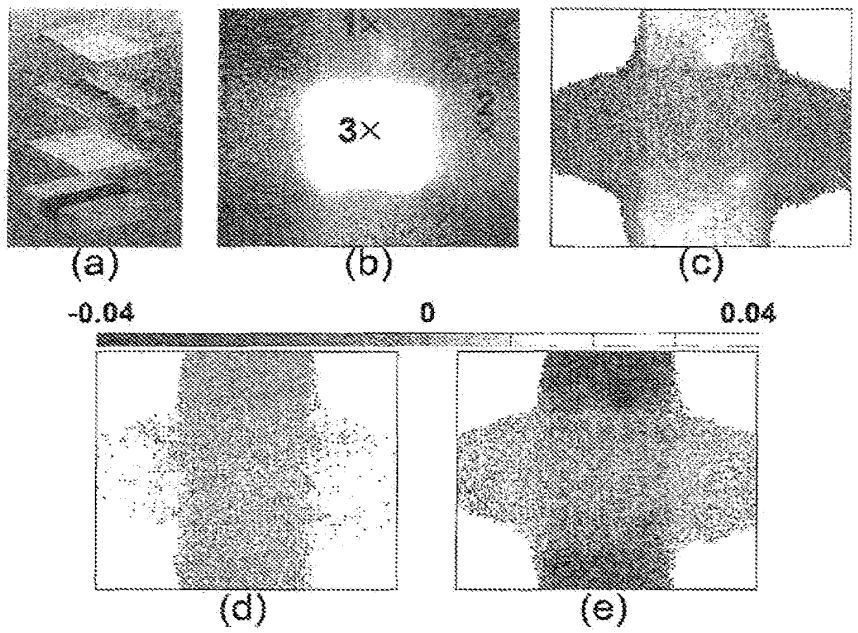


Figure 13

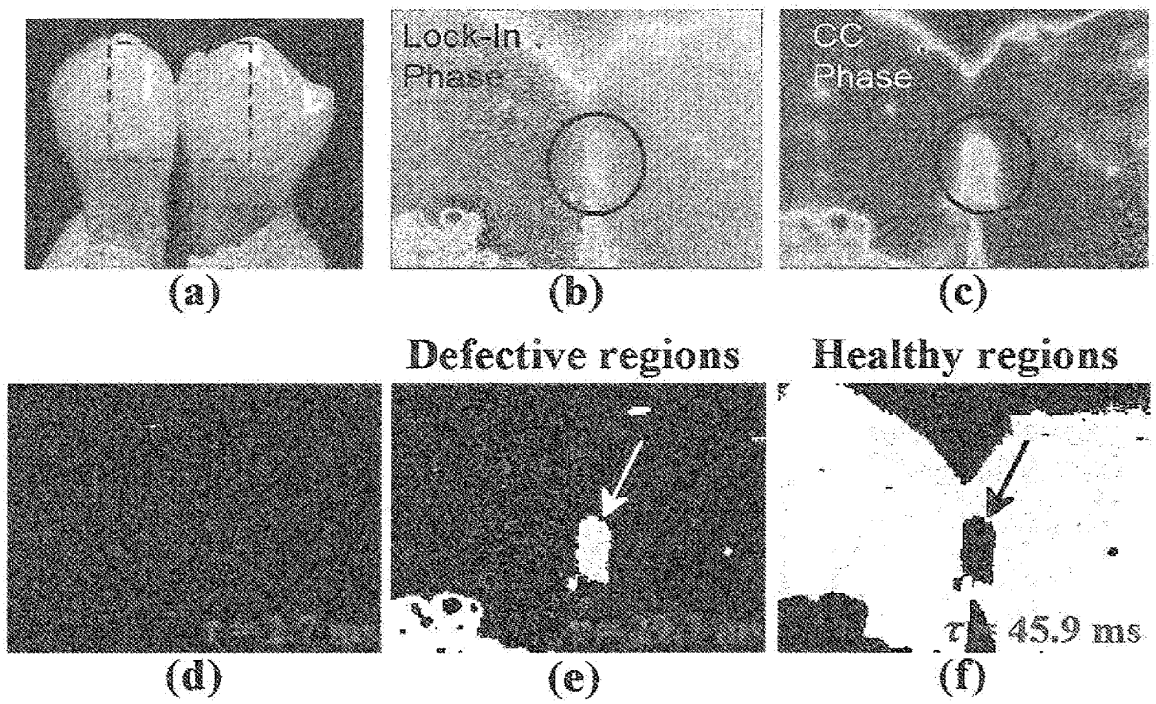

Lock-In
Phase
CC
Phase
(a)
(b)
(c)
Defective regions
Healthy regions
τ = 45.9 ms
(d)
(e)
(f)

Figure 14

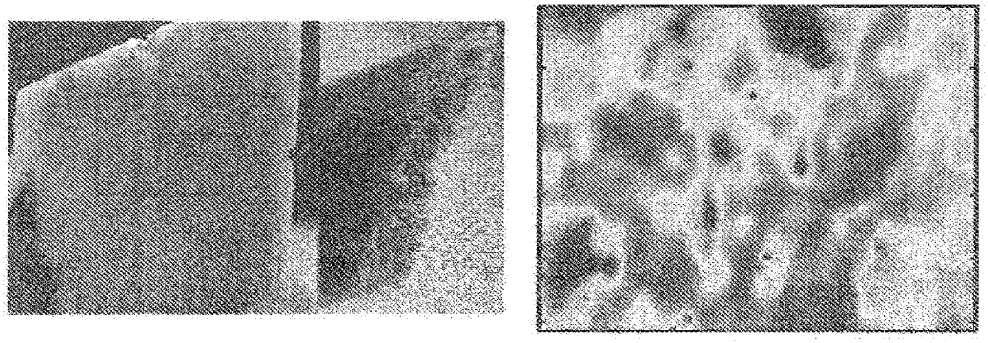


Figure 15

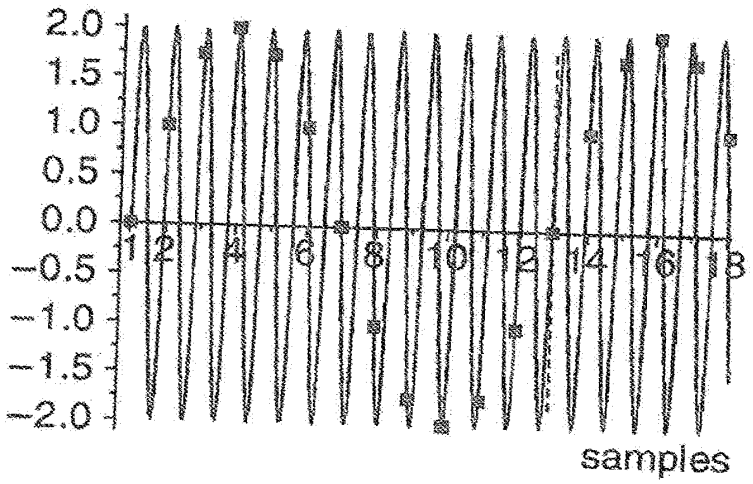


Figure 16

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CA2012/050035

A. CLASSIFICATION OF SUBJECT MATTER

IPC: ***G01N 21/63*** (2006.01) , ***A61B 6/14*** (2006.01) , ***H04N 5/33*** (2006.01)

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)

IPC: ***G01N 21/63*** (2006.01) , ***A61B 6/14*** (2006.01) , ***H04N 5/33*** (2006.01) (in combination with keloids)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic database(s) consulted during the international search (name of database(s) and, where practicable, search terms used)

Total Patent (keywords thermophotonic, thermographic, imaging, reference, waveform, dynamic averaging)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO2010065052A1, Herman et al. 10 June 2010 (10-06-2010) (See whole document)	1-35, 37-56
A	EP1258136A2, Shepard et al. 20 November 2002 (20-11-2002) (See whole document)	1-35, 37-56
A	US7551769B2, Enachescu et al. 23 June 2009 (23-06-2009) (See whole document)	1-35, 37-56
A	WO2009123799A1, Ringermacher et al.08 October 2009 (08-10-2009) (See whole document)	1-35, 37-56
A	WO2011137264A1, Walther et al. 03 November 2011 (03-11-2011) (See whole document)	1-35, 37-56

[ ] 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
13 June 2012 (13-06-2012)	14 June 2012 (14-06-2012)

Name and mailing address of the ISA/CA
Canadian Intellectual Property Office
Place du Portage I, C1 14 - 1st Floor, Box PCT
50 Victoria Street
Gatineau, Quebec K1A 0C9
Facsimile No.: 001-819-953-2476

Authorized officer

David E. Green (819) 994-82 13

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/CA2012/050035

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of the first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons :

1. [X] Claim Nos. : 36
because they relate to subject matter not required to be searched by this Authority, namely :

Claim 36 relates to a method of medical treatment

2. [ ] Claim Nos. :
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically :

3. [ ] Claim Nos. :
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows :

1. [ ] As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. [ ] As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. [ ] As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claim Nos. :

4. [ ] No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claim Nos. :

Remark on Protest

[ ] The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

[ ] The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

[ ] No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/CA2012/050035

Patent Document Cited in Search Report	Publication Date	Patent Family Member(s)	Publication Date
WO2010065052A1	10 June 2010 (10-06-2010)	US2011230942A1	22 September 2011 (22-09-2011)
EP1258136A2	20 November 2002 (20-11-2002)	AT423966T	15 March 2009 (15-03-2009)
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		DE60041661D1	09 April 2009 (09-04-2009)
		EP1258136A4	20 September 2006 (20-09-2006)
		EP1258136B1	25 February 2009 (25-02-2009)
		EP1258136B8	22 April 2009 (22-04-2009)
		JP2004530309A	30 September 2004 (30-09-2004)
		JP4467862B2	26 May 2010 (26-05-2010)
		US2002044679A1	18 April 2002 (18-04-2002)
		US6516084B2	04 February 2003 (04-02-2003)
		US2002172410A1	21 November 2002 (21-11-2002)
		US6751342B2	15 June 2004 (15-06-2004)
		US2005008215A1	13 January 2005 (13-01-2005)
		US7724925B2	25 May 2010 (25-05-2010)
		WO0141421A2	07 June 2001 (07-06-2001)
		WO0141421A3	06 December 2001 (06-12-2001)
		WO02089042A1	07 November 2002 (07-11-2002)
US7551769B2	23 June 2009 (23-06-2009)	CN1620603A	25 May 2005 (25-05-2005)
		CN100480693C	22 April 2009 (22-04-2009)
		JP2006505764A	16 February 2006 (16-02-2006)
		JP2009008687A	15 January 2009 (15-01-2009)
		US2003137318A1	24 July 2003 (24-07-2003)
		US6840666B2	11 January 2005 (11-01-2005)
		US2003222220A1	04 December 2003 (04-12-2003)
		US7149343B2	12 December 2006 (12-12-2006)
		US2007036420A1	15 February 2007 (15-02-2007)
		WO03062809A1	31 July 2003 (31-07-2003)
WO2009123799A1	08 October 2009 (08-10-2009)	CA2718762A1	08 October 2009 (08-10-2009)
		DE1 1200900634T5	10 February 2011 (10-02-2011)
		GB201016950D0	24 November 2010 (24-11-2010)
		GB2471047A	15 December 2010 (15-12-2010)
		GB2471047B	30 May 2012 (30-05-2012)
		JP2011516837A	26 May 2011 (26-05-2011)
		US2009245321A1	01 October 2009 (01-10-2009)
WO2011137264A1	03 November 2011 (03-11-2011)	None	

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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
29 October 2009 (29.10.2009)

PCT

(10) International Publication Number
WO 2009/130464 A1

(51) **International Patent Classification**:
A61B 5/00 (2006.01) *A61B 1/24* (2006.01)

(21) **International Application Number**:
PCT/GB2009/001032

(22) **International Filing Date**:
23 April 2009 (23.04.2009)

(25) **Filing Language**: English

(26) **Publication Language**: English

(30) **Priority Data**:
0807611.9 25 April 2008 (25.04.2008) GB

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(54) **Title**: DENTAL IMAGING AND APPARATUS THEREFOR

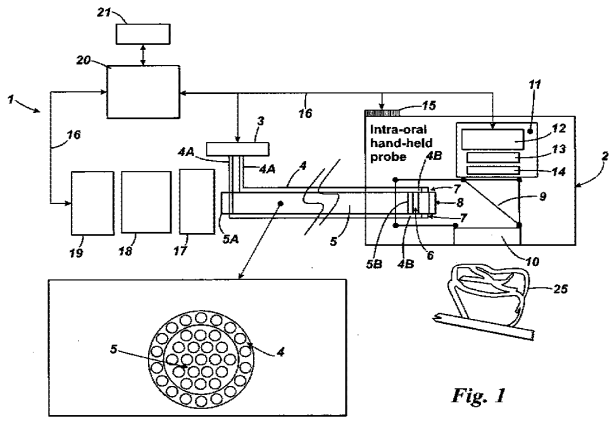


Fig. 1

(57) **Abstract**: Apparatus and method for imaging a tooth. The apparatus includes: illumination means arranged to generate first and second infra-red light; and image data acquisition means arranged for receiving infra-red light originating from the illumination means and returned from an illuminated tooth. The image data acquisition means includes infra-red pixel sensor means responsive to said returned infra-red light to generate image pixel values for a first image of the illuminated tooth using first infra-red light and for a second image of the illuminated tooth using second infra-red light. The apparatus further includes data processing means to use one or more image pixel values of the first image to calculate a first reflectance value, and to use one or more image pixel values of the second image to calculate a second reflectance value, and to determine from the first and second reflectance values a measure of the degree of enamel lesion (Se) and/or dentin lesion (Sd) present in the part.

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DENTAL IMAGING AND APPARATUS THEREFOR

The present invention relates to methods and apparatus for the imaging of teeth and particularly, though not exclusively, for imaging lesions or for processing such data.

Dental caries is a dynamic disease characterised by tooth demineralization leading to an increase in the porosity of the enamel surface. The result is commonly known as "white spots" and is due to the white appearance created by the increase of refraction index of de-mineralized enamel. Leaving these lesions untreated can potentially lead to dental cavities which may reach the dentin and pulp of the tooth, and may eventually cause tooth loss. Occlusal and approximal tooth surfaces are among the sites most susceptible to de-mineralization due the acid attack from bacterial by-products.

The use of preventive agents to inhibit, or reverse, the de-mineralization process is predicated on the detection of lesions at an early stage. However, detecting early lesions is difficult.

Non-invasive detection of white spots may employ an estimation of surface porosity or mineral loss. Although radiographic methods are suitable for approximal surface lesion detection, they offer a reduced utility for screening early caries in occlusal surfaces. In addition, radiographic methods are not ideal due to the patient exposure to x-rays and to their lack of sensitivity at very early stages of the disease. Electrical caries monitoring enables only single point measurements.

Optical methods offer non-destructive monitoring of early tooth enamel de-mineralization.

Current imaging methods are based on the observation of changes in light transport within the tooth, namely

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absorption, scattering and/or fluorescence of light. Porous media scatters more the light than uniform media and stain tends to absorb the light. Trans-illumination is a method that looks for shadows created by pumping white light from one side of the tooth, as viewed from the opposite side. Such shadows may correspond to regions where light is scattered away and/or absorbed. This technique is difficult to employ quantitatively due to an uneven light distribution inside the tooth. Quantitative light fluorescence (QLF) is an imaging method that relies on the natural fluorescence by teeth. This fluorescence acts as an internal source of light that will try to escape through the surface of the tooth. With appropriate filters, one may observe the fluorescent light and may quantify the loss of mineral by visualizing dark patches or shadows produced by scattering and/or absorption of fluorescent light. However this technique is unsuitable when trying to discriminate between white spots and stain as both produce the similar effect.

Stain is commonly observed in the occlusal sites of teeth and this obscures the true detection of caries. Stain, therefore, is one of the most confounding factors in the detection of early caries lesions.

The present invention may desirably be employed in addressing or overcoming limitations in the prior art.

At its most general, the invention proposed is spectral measurement or imaging of a tooth in infra-red light (e.g. the near infra-red (NIR) spectral region) to produce data to enable identification and/or quantification of lesions on a tooth (e.g. occlusal tooth surfaces) using the spectral signatures of water absorption and the effect of porosity or demineralisation in the scattering of light by a tooth.

Near-infrared (NIR) light has a number of advantages for use in caries detection as compared to visible light since it

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suffers a lower degree absorption by stain and may penetrate deeper into a target tooth. Infra-red light may be employed (e.g. for Hyperspectral images) having a wavelength from 1000nm to 2500nm or more. The measured effects of infra-red light scattering by porous enamel and absorption thereof by water in dentin may be used to quantify the lesion extension and generate a caries score quantifying the degree of lesion. Analysis of the reflectance spectra of a target tooth illuminated by infra-red light may identify infra-red wavelength values, or ranges, of illuminating light returned from a tooth which exhibit reflectance values characteristic of scattering by porous or demineralized enamel or absorption thereof by water in the tooth (e.g. in dentin).

Histological examination of ground target teeth, made after the spectral measurements have shown that a caries score obtained according to an aspect of the invention, correlates significantly (Pearson's correlation of 0.89, $p < 0.01$) with the corresponding histological score. Results yield a sensitivity of 75% and a specificity of 87.5% for enamel lesions and a sensitivity of 87.5% and a specificity of 100% for dentine lesions. The nature of the technique may provide a number of advantages including, desirably, the ability to spatially map the lesion distribution rather than only obtaining single-point measurements. The technique may be non-invasive, and/or non-contact and and/or stain-insensitive.

Using light in the infra-red, e.g. near infra-red, region of the electromagnetic spectrum may overcome difficulties associated with scattering and absorption. Scattering in enamel is reduced and absorption by stain is low when infra-red light is employed. In fact, the scattering by enamel tissues reduces in the form of $1/\lambda^3$ laser wavelengths, λ, of 512 nm, 632 nm and 1053 nm at least. In addition, a higher transparency for 1310nm wavelength light than for 1550nm wavelength light in sound enamel suggests that water in the enamel attenuates the light at higher wavelengths. Stimulated

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lesions in tooth samples up to 6.75mm in thickness can be resolved with a contrast ratio greater than 0.35 as between sound and demineralised enamel by using light of wavelength 1310nm.

In a first of its aspects, the invention may provide apparatus for imaging a tooth including: illumination means arranged to generate first infra-red light with a first wavelength having a value within a range of values corresponding to an infra-red spectral absorption band of water (e.g. a spectral absorption band of water within a tooth, such as within enamel and/or within dentin), to generate second infra-red light with a second wavelength having a value within a range of values corresponding to an infra-red spectral reflection band characteristic of scattering from demineralised tooth enamel, and for illuminating a tooth therewith; image data acquisition means arranged for receiving infra-red light originating from the illumination means and returned from an illuminated tooth, and including infra-red pixel sensor means responsive to said returned infra-red light to generate image pixel values for a first image of the illuminated tooth using first infra-red light and not second infra-red light and to generate image pixel values for a second image of the illuminated tooth using second infra-red light and not first infra-red light, and to provide such image pixel values for use.

In this way, a signature of enamel lesion and/or a signature of dentin lesion may be sought in the spectrally selected image data for a tooth. In generating corresponding spectrally separated images, one may ensure that corresponding parts of each image may be identified as being associated with a common part of a tooth. This avoids misalignment or movement problems common in single-point data acquisition methods.

The infra-red pixel sensor array may comprise a CCD sensor array, or an InGaAs sensor array, or a sensor array such as a

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Mercury Cadmium Telluride (MCT) sensor array. An InGaAs sensor array may have a spectral response that covers up to 1700nm whereas MCT sensor array may be responsive to infra-red wavelengths up to 2500nm.

The infra-red pixel sensor array may be preferentially responsive to near-infrared wavelengths such as wavelengths in the range 0.8 microns to 2.5 microns, or 1.0 microns to 2.5 microns. The second wavelength may have a value which also falls within a range of values corresponding to an infra-red spectral absorption band of water (e.g. water in a tooth). The illumination means may be arranged to generate infra-red light with a third wavelength (other than the first or second wavelength) having a value within a range of values corresponding to an infra-red spectral absorption band of water (e.g. water in a tooth) and/or within a range of values corresponding to an infra-red spectral reflection band characteristic of scattering from demineralised tooth enamel.

The infra-red pixel sensor means may be arranged to be responsive to returned infra-red light originating from the illumination means to generate third image pixel values for a third image of the illuminated tooth using third infra-red light and not first nor second infra-red light. The apparatus may provide such third image pixel values for use, such as for use in detecting therein a signature of enamel lesion and/or dentin lesion. Most preferably, the infra-red pixel sensor means is responsive to returned infra-red light of a reference wavelength other than the first, second or third wavelengths, and originating from the illumination means, to generate reference image pixel values or for a reference image of the illuminated tooth using the reference infra-red light, and to provide them for use. The reference image pixel values may be used by the apparatus in, for example, normalising any image pixel value of any one, some or all of first, second or third images.

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Preferably all of the first, second, third and reference infra-red wavelengths are less than 3 microns in size, e.g. within the near-IR band (e.g. from 0.8 microns to 2.5 microns). It has been found that infra-red wavelengths exceeding about 3 microns suffer significant attenuation in tooth enamel. This may reduce the intensity of illuminating infra-red light reaching dentin underneath such enamel, and may, to a varying extent, confound generation of a spectral signature in returned infra-red light characteristic of water within dentin indicative of dentin lesion.

The first wavelength may be a value chosen from the range 1410nm - 1470nm. The second wavelength may be a value chosen from the range 1580nm - 1640nm. The third wavelength may be a value chosen from the range 1880nm - 1940nm. The reference wavelength may be a value chosen from the range 1060nm - 1120nm. In each case, the wavelength may be within a narrower range being one half, or one third, or one sixth, of the size of the respective range given above, centred upon the same central wavelength as in the ranges given above.

The image data acquisition means may include optical input means via which the apparatus is arranged to receive infra-red light returned from an illuminated tooth in a direction substantially parallel with, or subtending an acute angle with respect to, a direction of illumination by the illumination means.

For example, back-scattering or back-reflection of illuminating light is preferred since the spectral signature of back-scattered light may be relatively strong in such circumstances when arising due to porosity in the tooth enamel. Also, this simplifies the arrangement and use of the apparatus and allows for a compact probe-like apparatus.

The illumination means may comprise optical output means with an optical axis along which the apparatus is arranged to

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output said infrared light to illuminate a tooth. The image data acquisition means may include optical input means comprising an optical axis along which the apparatus is arranged to receive infrared light returned from an illuminated tooth and which is substantially parallel to, or subtends an acute angle with respect to, the optical axis of the illumination means. Thus, back-scattering of infra-red light from the illumination means by an illuminated tooth, and to the optical input means may be provided. Preferably, the subtended angle is as small as is practicable, such as 5° or less, or less than 2° or less than 1°.

The image data acquisition means may include camera means including a pixel sensor array responsive to visible light returned from an illuminated tooth to form one or more image pixel values representing an image of at least a part of the tooth.

Accordingly, a "visible" image, i.e. representing what may be perceived by the human eye, may be simultaneously or contemporaneously created to permit images of the tooth formed using infra-red light to be compared with the "visible" image. The visible image may be co-registered or pixel-wise aligned with images formed using infra-red light to permit a pixel(s) selected in the "visible" image to directly identify a pixel(s) in an image of the same target formed using infra-red, by association with the same tooth part.

The apparatus may include infra-red optical filter means selectively operable in a first state to transmit infra-red light originating from the illumination means having said first wavelength and to substantially prevent transmission therethrough of infra-red light having said second wavelength, and in a second state to transmit infra-red light originating from the illumination means having said second wavelength and to substantially prevent transmission therethrough of infra-red light having said first wavelength. The infra-red optical

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filter means may be selectively operable in a third state to transmit infra-red light originating from the illumination means having said third wavelength and to substantially prevent transmission therethrough of infra-red light having any of said first wavelength and said second wavelength. The infra-red optical filter means may be selectively operable in a fourth state to transmit infra-red light originating from the illumination means having a reference (fourth) wavelength and to substantially prevent transmission therethrough of infra-red light having any of the first, second, or third wavelengths. Thus, spectrally separated and distinct first, second, third or reference infra-red image data may be acquired in this way, or otherwise. In alternatives, the illumination means may comprise means for separately (physically) generating infra-red light spectrally separated in this way for illuminating a tooth. Examples include an array of separate infra-red light sources (e.g. LEDs) each one of which is arranged to generate only one of the first, second, third and reference wavelengths. A visible light source may be provided separately in this way for use in enabling said "visible" images. In other examples, the infra-red pixel sensor means may comprise separate groups of pixel sensors in which each pixel sensor of a respective group is served by a dedicated one of a plurality of different infra-red optical filters. For example, four separate pixel sensor arrays may be provided each one of which is served by a respective one of four different infra-red optical filters arranged to transmit a respective one (only) of the first, second, third and reference infra-red wavelengths discussed above. The separate groups of pixel sensors may be arranged in a common overall pixel array (e.g. pixel sensor chip) overlaying separate individual sensor pixels of which (e.g. separately or in defined areas) are respective infra-red optical filters. In this example, the infra-red pixel sensor means may comprise an active-pixel sensor array in which individual pixels of the sensor are addressable such that pixel sensor signals from individual sensor pixels associated

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with a predetermined filter may be individually obtained and identified as such. The arrangement, in this example, may be analogous to the Bayer-type filter arrangement common in commercial digital cameras.

The infra-red optical filter means may be arranged in optical communication with the infra-red pixel sensor means to filter infra-red light directed to the infra-red pixel sensor means by the image data acquisition means.

The illumination means may include light-source means which may be operable to generate light including said first and second wavelengths and preferably said third wavelength and/or said reference wavelength (e.g. a broadband visible and near-IR source). The infra-red optical filter means may be arranged in optical communication with the light-source means to filter light generated by the light-source means for illuminating a tooth with infra-red radiation transmitted by the infra-red optical filter means.

The illumination means may comprise light-source means operable to generate light including said first and second wavelengths, (and preferably also the third and/or reference wavelength, and preferably visible wavelengths) and optical output means remotely or locally in optical communication with the light-source means via output optical waveguide means and arranged to output from the apparatus light generated by the light-source means to illuminate a tooth.

The apparatus may include optical input means remotely or locally in optical communication with the infra-red pixel sensor means via input optical means (e.g. optical waveguide means) and arranged to receive infra-red light returned from an illuminated tooth and to direct the returned infra-red light to the (local or remote) infra-red pixel sensor means for sensing thereby. The optical input means may not be remote, and may be housed within or otherwise an attachable or

integral part of a unit or probe device containing the infra-red pixel sensor means. The illumination means may be similarly so housed within or attachable to the unit or probe device.

The apparatus may include an intra-oral probe (e.g. hand held) comprising the optical input means and the optical output means. This probe may be remote from image pixel sensor means and/or the illumination means, or the probe may include the image pixel sensor means and/or the illumination means.

For example, the probe may comprise any one, some or all of: the infra-red pixel sensor means; the illumination means; the infra-red optical filter means; any optical elements intermediate the infra-red pixel sensor means and the optical input means for collecting, focussing, collimating or otherwise preparing returned infra-red light. The probe may comprise such elements in a detachable unit attachable to the rest of the probe via attachment means or adapter means to place those elements in operable and optical communication with the optical input/output means.

Thus, different detachable such units may be provided having different operating characteristics (e.g. filters, illumination means or light source, sensor array etc) as required, enabling rapid and simple alteration of the operating characteristics of the probe as a whole.

The input optical waveguide means may comprise one or more optical fibres which collectively define an aligned optical fibre bundle.

The output optical waveguide means may comprise one or more optical fibres collectively defining an aligned optical bundle.

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Optionally, at least a terminal end of the output optical waveguide means is adjacent the optical input means.

Optionally, the terminal end of the output optical waveguide comprises a bundle of optical fibres the ends of which form a ring circumscribing the output optical waveguide.

The illumination means may comprise first optical polarizer means for polarizing according to a first polarization axis infra-red radiation generated by the illumination means, and the image data acquisition means comprises second optical polarizer means for polarizing according to a second polarization axis transverse to the first polarization axis infra-red radiation received thereby from an illuminated tooth. The first and second optical polarizer means may be individually arranged to linearly polarise light, or to elliptically or circularly polarise light received thereby. Preferably, each is arranged to linearly (or optionally elliptically) polarise light, and may be such that the first and second optical polarisers define a pair of crossed polarisers. Specular reflections of light from tooth enamel tends to at least partially polarise un-polarised incident light, or put another way, specular reflections from a tooth surface preferentially select polarised light. Illuminating light returned from a tooth by a scattering process (e.g. multiple reflections) tends to de-polarise polarised incident light. Consequently, requiring returned light to pass through a polarising filter with a polarising characteristic converse to that of the filter through which illuminating light passed, to some extent removes from returned light those parts preserving the converse polarisation (e.g. specularly reflected light).

The optional use of circular polarisers to polarise light returned from an illuminated tooth has been found to enhance image contrast and definition.

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The image data acquisition means may comprise focussing means arranged to form upon the infra-red pixel sensor means a real optical image using infra-red light received by the image data acquisition means from an illuminated tooth. Alternatively, or additionally, the image data acquisition means may comprise within-probe focussing means arranged to form a focused image upon a terminal optical input end of an aligned optical fibre bundle defining the input optical waveguide means, using return illuminating infra-red light. Most preferably the input end of the input optical waveguide comprises a flat surface collectively formed by a plurality of closely-packed ends of optical fibres. In this way, the light of a focused infra-red image may be transmitted, conveyed or guided from within the probe to the infra-red pixel sensor means (optionally remote). The focussing means (intra-probe or remote) may possess a controllable "zoom" function (e.g. a variable focal length) controllable by the user of the apparatus.

The optical filter means, the focussing means and infra-red pixel sensor means may be each in mutual optical communication and locally or remotely in optical communication with the optical input means (e.g. via said input optical waveguide means when remote).

Preferably, the illumination means is arranged to deliver full-field illumination to the tooth to be imaged, in other words to illuminate the whole area of the tooth which is to be imaged, e.g. substantially the whole exposed area of the tooth. In this way, the image pixel values of the area which is to be imaged can be generated without requiring the illumination means to be scanned across the area, as might be required if the illumination means only delivered only point-like illumination. The illumination means may be arranged to deliver full-field illumination e.g. by selection of suitable light source means and/or output optical waveguide means.

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Similarly, it is also preferable for the infra-red pixel sensor means to be arranged to detect or capture a full-field image of the tooth, in other words to capture an image of the tooth without it having to be scanned across the tooth. For example, the infra-red pixel sensor means may comprise an infra-red pixel sensor array as described above. Thus, it is preferable for the apparatus to work on a full-field principle, in which the whole area which is to be imaged of the tooth is illuminated and a corresponding image captured, rather than scanning a point-like illumination across the tooth.

The apparatus may include image processing means arranged to receive said pixel image values for producing one or more of said first, second, third, reference and/or "visible-light" images therefrom.

The image processing means may be arranged to co-register a said first image and a said second image in respect of a common imaged subject, thereby to associate a given image pixel of the first image with a respective image pixel of the second image representing the same part of the imaged subject.

Such co-registration may be performed as between either or both of the first and second images and any or all of the third image and/or the reference infra-red image, and/or any visible image produced by the camera means.

The apparatus may include data processing means arranged in respect of a given part of the imaged subject to use one or more image pixel values of the first image to calculate a first reflectance value (R_1) associated with the part, and to use one or more image pixel values of the second image to calculate a second reflectance value (R_2) associated with the part, and to determine from the first and second reflectance values a measure of the degree of enamel lesion (S_e) and/or dentin lesion (S_d) present in the part. It should be clear that

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in some embodiments, the data processing means may be arranged to determine only a measure of the degree of enamel lesion (S_e) or only a measure of the degree of dentin lesion (S_d) present in the part. However, it is preferable for the data processing means to be arranged to determine both a measure of the degree of enamel lesion (S_e) and a measure of the degree of dentin lesion (S_d) present in the part.

The data processing means may be arranged, in respect of a given said part of the imaged subject, to use one or more image pixel values of the third image to calculate a third reflectance value (R_3) associated with the part, and to determine using first and/or second and/or third reflectance values, a measure of the degree of enamel lesion and/or dentin lesion.

The data processing means may be arranged to use said measure of the degree of enamel lesion (S_e) and said measure of the degree of dentin lesion (S_d) to calculate a measure ($S_{carries}$) of the degree of caries present in the part.

The spectral intensity of a pixel value may be normalised to the reflectance (R_{ref}) obtained at a reference wavelength (e.g. 1090nm) which, preferably corresponds with the highest reflectance (least extinction). The degree of enamel, S_e, and dentin, S_d, lesions may be calculated as follows:

$$S_e = S_e^{(1)} = \frac{R_2}{R_{ref}}$$

or

$$S_e = S_e^{(2)} = \frac{R_1 - R_3}{R_{ref}}$$

$$S_d = \frac{R_2 - R_1}{R_{ref}}$$

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The equation for $S_e^{(2)}$ results in a measure of lesion which has been found to be less susceptible to being influenced by, or confounded by, the effects of specular reflections at the ranges of wavelengths suggested above.

A caries score, S_{caries}, may be calculated as a combination of S_e and S_d. The combination is preferably a weighted algebraic sum of the two terms S_e and S_d, for example, with variable weight factor p:

$$S_{caries} = p\left(\frac{S_e - K_e}{N_e}\right) + (1-p)\left(1 + \frac{S_d - K_d}{N_d}\right)$$

Here, K_x and N_x are an enamel ($x : e$) and dentin ($x : d$) score calibration offset and normalisation factor, respectively. In addition, one may specify that $p = 1$ if

$$\left(1 + \frac{S_d - K_d}{N_d}\right) \prec S_{dth}$$

where S_{dth} represents a dentin lesion threshold, otherwise $p = 0$. Outliers and noise introduced into the data by specular reflections may be removed by limiting the values of the numerators in the equation for S_{caries} to the range $0 < (S_e - K_e) < M_e$ and $0 < (S_d - K_d) < M_d$; here M_e and M_d denote the upper limits. Values outside these limits may be set to zero. The computer means may be operable to perform any one, some or all of the above processing of data.

The infra-red pixel sensor means may be responsive to said returned infra-red light to generate image pixel values for a third image of the illuminated tooth using third infra-red light and not first infra-red light nor second infra-red light, and to provide such image pixel values for use.

The infra-red optical filter means may be selectively operable in a third state to transmit infra-red light originating from the illumination means having said third wavelength and to

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substantially prevent transmission therethrough of infra-red light having any of said first wavelength and said second wavelength.

The data processor means may be arranged to use one or more image pixel values of the third image to calculate a third reflectance value associated with the part, and to determine the measure of the degree of enamel lesion (S_e) and/or dentin lesion (S_d) present in the part using the third reflectance value.

The first wavelength value may be between 1300nm and 1550nm, and the second wavelength value may be between 1550nm and 1800nm. The first wavelength value may be between 1400nm and 1500nm, such as about 1440nm, and the second wavelength value may be between 1550nm and 1650nm, such as about 1610nm.

It is to be understood that the foregoing may represent a physical realisation or implementation of a corresponding method of imaging or measuring a property of a tooth, and that such corresponding methods are encompassed in by the invention.

In a second of its aspects, the invention may provide a method for imaging a tooth including: generating first infra-red light with a first wavelength having a value within a range of values corresponding to an infra-red spectral absorption band of water (e.g. a spectral absorption band of water within a tooth, such as within enamel and/or within dentin), generating second infra-red light with a second wavelength having a value within a range of values corresponding to an infra-red spectral reflection band characteristic of scattering from demineralised tooth enamel, and illuminating a tooth therewith; receiving at infra-red pixel sensor means first and second infra-red light returned from an illuminated tooth and therewith generating image pixel values for a first image of the illuminated tooth using first infra-red light and not

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second infra-red light and generating image pixel values for a second image of the illuminated tooth using second infra-red light and not first infra-red light, and providing such image pixel values for use.

The method may include receiving infra-red light returned from an illuminated tooth in a direction substantially parallel with, or subtending an acute angle with respect to, a direction of said illumination.

The method may include providing optical output means comprising an optical axis and therealong outputting said infrared light to illuminate a tooth, and providing optical input means comprising an optical axis and therealong receiving infrared light returned from an illuminated tooth for subsequent receipt at the infra-red pixel sensor means wherein the said optical axes are substantially parallel, or subtend an acute angle with respect to each other.

The method may include generating third image pixel values for a third image of the illuminated tooth using third infra-red light returned from the tooth and not first nor second infra-red light. The third image pixel values may be provided for use, such as for use in detecting therein a signature of enamel lesion and/or dentin lesion. The method may include receiving returned infra-red light of a reference wavelength other than the first, second or third wavelengths, and originating from the illumination means, and generating reference image pixel values or for a reference image of the illuminated tooth using the reference infra-red light, and to providing them for use. The reference image pixel values may be used by the apparatus in, for example, normalising any image pixel value of any one, some or all of first, second or third images.

Preferably all of the first, second, third and reference infra-red wavelengths are less than 3 microns in size, e.g.

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within the near-IR band (e.g. from 0.8 microns to 2.5 microns). The first wavelength may be a value chosen from the range 1410nm - 1470nm. The second wavelength may be a value chosen from the range 1580nm - 1640nm. The third wavelength may be a value chosen from the range 1880nm - 1940nm. The reference wavelength may be a value chosen from the range 1060nm - 1120nm. In each case, the wavelength may be within a narrower range being one half, or one third, or one sixth, of the size of the respective range given above, centred upon the same central wavelength as in the ranges given above.

The method may include forming an image representing at least a part of the illuminated tooth using visible light returned therefrom. The method may include co-registering the visible-light image or pixel-wise aligned with images formed using infra-red light to permit a pixel(s) selected in the "visible" image to directly identify a pixel(s) in an image of the same target formed using infra-red, by association with the same tooth part.

The method may include generating light for illuminating the tooth and in a first instance, filtering the light by transmitting through a filter means parts of said light having said first wavelength and substantially preventing transmission through the filter means of parts of said light having said second wavelength; and in a second instance, filtering the light by transmitting through the filter means parts of said light having said second wavelength and substantially preventing transmission through the filter means parts of said light having said first wavelength. The method may include filtering the light by transmitting infra-red light originating from the illumination means having said third wavelength and to substantially preventing transmission of infra-red light having any of said first wavelength and said second wavelength. The method may include filtering the light by transmitting infra-red light originating from the illumination means having a reference (fourth) wavelength and

to substantially preventing transmission of infra-red light having any of the first, second, or third wavelengths.

The method may include performing said filtering on light directed to the infra-red pixel sensor means.

The method may include performing said filtering on light for illuminating a tooth.

The method may include generating said light remotely from, or locally at, said tooth, guiding the generating light to the proximity of the tooth, and illuminating the tooth with the guided light.

The method may include guiding said returned infra-red light to a location local to, or remote from, the point of receipt of the returned light and generating image pixel values using said returned, guided light at said local or remote location.

The method may be performed using an intra-oral probe.

The method may include polarizing according to a first polarization axis infra-red radiation generated for illuminating a tooth, and polarizing according to a second polarization axis transverse to the first polarization axis infra-red radiation returned from the illuminated tooth. The first and second polarization may be individually linear polarization, or to elliptical or circular polarization. Preferably, each is linear (or optionally elliptical) polarization, and the first and second polarization axes may together define crossed polarization axes.

The method may include forming upon an infra-red pixel sensor means a real optical image using said infra-red light returned from an illuminated tooth.

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The method may include producing one or more of said first, second, third, reference and/or "visible-light" images from said returned light.

The method may include co-registering a said first image and a said second image in respect of a common imaged subject, thereby to associate a given image pixel of the first image with a respective image pixel of the second image representing the same part of the imaged subject. Such co-registration may be performed as between either or both of the first and second images and any or all of the third image and/or the reference infra-red image, and/or any visible image produced by the camera means.

Preferably, the method includes full-field illumination of the tooth, e.g. as described in connection with the first aspect of the invention. Preferably, the method includes detecting or capturing of a full-field image of the tooth, e.g. as described in connection with the first aspect of the invention.

The method may include, in respect of a given part of the imaged subject, calculating a first reflectance value associated with the part using one or more image pixel values of the first image, and calculating a second reflectance value associated with the part using one or more image pixel values of the second image, and determining from the first and second reflectance values a measure of the degree of enamel lesion (S_e) and/or dentin lesion (S_d) present in the part.

The method may include generating image pixel values for a third image of the illuminated tooth using third infra-red light returned from the tooth and not first infra-red light nor second infra-red light, and providing such image pixel values for use.

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The method may include generating light for illuminating the tooth and in a third instance, filtering the light by transmitting through a filter means parts of said light having said third wavelength and substantially preventing transmission through the filter means of parts of said light having any of said first wavelength and said second wavelength.

The method may include calculating a third reflectance value associated with the part using one or more image pixel values of the third image, and determining the measure of the degree of enamel lesion (S_e) and/or dentin lesion (S_d) present in the part using the third reflectance value.

The first wavelength value may be between 1300nm and 1550nm, and the second wavelength value may be between 1550nm and 1800nm. The first wavelength value may be between 1400nm and 1500nm, such as 1440nm or thereabouts, and the second wavelength value may be between 1550nm and 1650nm, such as 1610nm or thereabouts.

The method may include, in respect of a given said part of the imaged subject, using one or more image pixel values of the third image to calculate a third reflectance value (R_3) associated with the part, and determining using first and/or second and/or third reflectance values, a measure of the degree of enamel lesion and/or dentin lesion.

The method may include calculating a measure ($S_{carries}$) of the degree of caries present in the part using said measure of the degree of enamel lesion (S_e) and said measure of the degree of dentin lesion (S_d). The spectral intensity of a pixel value may be normalised to the reflectance (R_{ref}) obtained at a reference wavelength (e.g. 1090nm).

The degree of enamel, S_e, and dentin, S_d, lesions may be calculated according to the method as follows:

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$$S_e = S_e^{(1)} = \frac{R_2}{R_{ref}}$$

or

$$S_e = S_e^{(2)} = \frac{R_1 - R_3}{R_{ref}}$$

$$S_d = \frac{R_2 - R_1}{R_{ref}}$$

A caries score, S_{caries}, may be calculated as a combination of S_e and S_d. The combination is preferably a weighted algebraic sum of the two terms S_e and S_d, for example, with variable weight factor p:

$$S_{caries} = p\left(\frac{S_e - K_e}{N_e}\right) + (1-p)\left(1 + \frac{S_d - K_d}{N_d}\right)$$

Here, K_x and N_x are an enamel (x : e) and dentin (x : d) score calibration offset and normalisation factor, respectively. In addition, one may specify that p = 1 if

$$\left(1 + \frac{S_d - K_d}{N_d}\right) \prec S_{dth}$$

where S_{dth} represents a dentin lesion threshold, otherwise p = 0. Outliers and noise introduced into the data by specular reflections may be removed by limiting the values of the numerators in the equation for S_{caries} to the range $0 < (S_e - K_e) < M_e$ and $0 < (S_d - K_d) < M_d$; here M_e and M_d denote the upper limits. Values outside these limits may be set to zero.

In a third of its aspects, the invention may provide a computer programmed to implement the method of the second aspect of the invention.

In a fourth aspect, the invention may provide a computer program product comprising a computer-readable medium

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containing computer executable instructions which implement the method (in part or in full) of the invention in its second aspect when executed on a computer.

In a fifth aspect, the invention may provide a computer program containing computer executable instructions which implement the method of the second aspect when executed on a computer.

In a sixth of its aspects, the invention may provide an apparatus and/or quantitative method for dental caries detection, according to any aspect above, and may be employed to assist in determining the presence of occlusal enamel and/or dentin lesions.

The invention also includes any combination of the aspects and preferred features described except where such a combination is clearly impermissible or expressly avoided.

Preferred embodiments will now be described, by way of example only, with reference to the accompanying drawings of which:

Figure 1 schematically illustrates apparatus including a hand-held intra-oral probe and remote components;

Figure 2 illustrates a selection of spectral images. On the top left is a picture of a tooth taken using visible light. The remaining reflectance images are obtained using near infra-red (NIR) light at the wavelengths indicated;

Figure 3 illustrates NIR spectral reflectance curves from an occlusal tooth surface. The figure shows the reflectance for sound enamel (diamond symbols), an enamel lesion region (asterisks *) and a dentin lesion region (circles ∘). The inset picture shows the location of the points selected within the tooth for this example. Vertical dotted lines in the graph of Figure 3 indicate the wavelengths chosen for the NIR images of Figure 2;

Figure 4 illustrates examples of teeth with different carious lesions. Left-hand images show a picture for each

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tooth obtained in visible light. Central images show the corresponding histological section which is indicated by the straight line traversing the tooth picture, and an arrow indicates the point of view of the section. The right-hand images show the NIR caries maps, spatially scored using a numerical carries score, S_{caries}, for each tooth;

Figure 5 illustrates a correlation plot of the histological score and the average maximum NIR caries score, S_{caries} within the map region corresponding to the histological section;

Figure 6 illustrates NIR images of highly stained occlusal tooth surfaces taken using light of 1250nm wavelength. The absorption by stain is minimal;

Figure 7 illustrates apparatus including a hand-held intra-oral probe and remote computing components.

In the figures like items are assigned like reference symbols for consistency.

Figure 1 illustrates schematically an apparatus 1 for imaging a tooth.

The apparatus includes an intra-oral hand-held probe 2 dimensioned to be held in the hand of a user and at least partly inserted into the mouth of a patient immediately adjacent a target tooth.

The apparatus includes an infra-red camera 19 and an illumination light source 3 each remote from the probe 2 and each in optical communication with the probe 2 via a respective one of two aligned optical fibre bundles (4, 5). The illumination light means is arranged to generate light of a broadband spectral content covering visible light and near-infra-red light (e.g. including wavelengths in a range from 300nm to 2500nm or more, preferably inclusive of all such wavelengths), and to output generated light to an input end 4A of a first of the two aligned optical fibre bundles 4 for

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transmission therealong to an output end 4B thereof housed in the probe 2 for output from the probe in illuminating a target tooth 25.

Preferably, the illumination light source 3 and the optical fibre bundles 4,5 are arranged to deliver full-field illumination to the target tooth 25. The infra-red camera 19 is likewise arranged to detect or capture full-field images. That is, the apparatus works on a full-field principle in which a whole area of the target tooth 25 is illuminated and a corresponding image captured, rather than scanning a point-like illumination across the surface of the tooth.

The infra-red camera 19 contains an infra-red pixel sensor array (not shown) responsive to infra-red radiation incident upon in to generate one or more image pixel values, and to output the pixel value(s) for use. A second of the two aligned optical fibre bundles 5 places the probe 2 in optical communication with an infra-red camera 19, and possesses an optical input end 5B housed within the probe 2 and arranged to receive light returned from a target tooth 25, and to guide the returned light to an optical output end 5A thereof for receipt by the infra-red pixel sensor array of the infra-red camera.

Immediately adjacent the optical input end 5B of the second aligned optical fibre bundle 5, and housed within the probe, is one or more input image collecting optical element 6 (e.g. one or more lenses) arranged in optical communication with the optical input end of the second aligned optical fibre bundle. The input image collecting optical element possesses an optical axis co-linear with that of the optical input end of the second aligned optical fibre bundle, and is adapted and arranged, or controllable, to gather light received thereby and to direct the gathered light into the optical input end of the second aligned optical fibre bundle. The image-collecting optical element 6 is arranged and controllable to form a

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focused optical image upon the exposed terminal optical input end 5B of the second aligned optical fibre bundle 5 using returned infra-red light from the target tooth 25. In this way, a focused image of the target tooth 25 may be transmitted along the second aligned optical fibre bundle 5 to the infra-red camera 19. In effect, the second aligned optical fibre bundle 5 serves to optically place the infra-red pixel sensor array of the infra-red camera 19 effectively or notionally within the intra-oral hand-held probe 2, without being physically present there. That is to say, the flat surface collectively formed by the plurality of closely-packed optical fibre ends defining the optical input end 5B of the second aligned optical fibre bundle, acts as a proxy imaging surface.

Indeed, in alternative examples of the invention, such as is schematically illustrated in figure 7, the second aligned optical fibre bundle 5 may be dispensed with and a detachably attachable unit 50 may be provided containing an infra-red camera 19, and additional optical elements e.g. a filter unit 18, imaging optical element(s) 17, illumination light source 3, and aligned optical fibre bundle 4 for guiding light generated by the illumination means outwardly of the detachable unit 50. The detachable unit 50 may include an optical window 35 with which the imaging optical element(s) 17, the filter unit 18, the infra-red camera 19, the illumination light source 3 and the first aligned optical fibre bundle 4 are in optical communication to enable light from the illumination light source 3 to exit the detachable unit 50, and to allow returned light to pass into the detachable unit 50 through the optical elements, the filter unit, and to the infra-red camera therein. In this alternative example, a second optical window 30 is provided at a surface of the hand-held probe 2 positioned relative to a plurality of positioning lugs 40 arranged and dimensioned to intimately receive the detachable unit at that part thereof containing the input/output window 35 thereof. The lugs 40 may be arranged to enable a snap-fit connection or a screw-fit

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connection or any other suitable connection as may be desirable. The dimensioning of the relevant receivable part of the detachable unit 50 and the receiving lugs 40 is such as to align, in register, the input/output window 35 of a detachable unit 50 with the input/output window 30 of the hand-held probe 2. This enables optical communication between the optical elements within the detachable probe and associated optical elements within the hand-held probe. Reference numerals employed in figure 7 identify the same articles as described with reference to figure 1 herein.

Adjacent the input image collecting optical element 6, and in optical communication therewith, is an input optical linear polarising filter 8 arranged to receive light returned from an illuminated target tooth 25 and to transmit substantially only that part of the received light which is linearly polarised light according to the polarisation axis defined by the filter, for transmission through the input image collecting optical element 6 and along the second aligned optical fibre bundle 5 for receipt by the infra-red camera 19.

The first aligned optical fibre bundle 4 comprises a group of optically aligned (i.e. with parallel optical axes) optical fibres which collectively envelop the second aligned optical fibre bundle 5 thereby forming therearound, in cross-section, a ring or annulus of optical fibres.

The optical input end 4A of the first aligned optical fibre bundle adjacent the illumination light source 3, is spaced from the second aligned optical fibre bundle 5 by a diversion or bifurcation of the optical fibres of the first aligned bundle from those of the second aligned optical fibre bundle, at a location between the probe 2 and the infra-red camera 19. This permits the illumination light source 3 to be located at any convenient location separated from the optical output end 5A of the second aligned optical fibre bundle 5 and any elements of the apparatus following that (e.g. IR camera 19).

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The optical output end 4B of each optical fibre of the first aligned optical fibre bundle 4, housed within the probe 2, is in immediate optical communication with an output optical linear polarising filter 7 arranged to receive light guided from the illumination light source 3 along the first aligned fibre bundle 4, and to transmit light linearly polarised according to the linear polarisation axis of the output optical linear polarising filter for illuminating a target tooth 25.

The linear polarisation axis of the output optical linear polarising filter 7 is aligned to be perpendicular to the axis of linear polarisation of the input optical linear polarising filter 8. This reduces the content, within light returned to the probe from an illuminated tooth 25, of light resulting from specular reflection from a surface of the illuminated tooth. Polarised light transmitted by the output optical linear polarising filter, specularly reflected from a tooth surface, tends to preserve its initial state of polarisation. Consequently, such preserved polarisation prevents transmission of such light through the input optical linear polarising filter thereby at least to some extend eliminating specularly reflected light which has not undergone de-polarisation by scattering within the material (e.g. enamel) of the target tooth.

A beam-splitting mirror 9 is arranged in optical communication with both the optical output end 4B of the first aligned optical fibre bundle and the optical input end 5B of the second aligned optical fibre bundle so as to receive light output by the output linear optical polarising filter 7 and to reflect such received light through an angle (e.g. 90°) to direct the light outwardly of the probe 2 via a transparent protective window 10 of the probe. The beam-splitting mirror 9 is also arranged to receive via the protective window 10 light returned from the target tooth 25 and to reflect a

portion of the returned light towards the input optical linear polariser 8 for subsequent transmission to the infra-red camera 19. The beam-splitting mirror 9 is arranged to transmit at least a portion of the visible light (e.g. between 25% and 50%) returned from the tooth 25 such that the light transmitted thereby is received by a reference imaging camera 11 responsive thereto to form an image of the target tooth using optically visible light.

The reference imaging camera preferably comprises a colour camera including a pixel-sensor imaging array 12 responsive to visible light to generate image pixel values for use in generating an image. The reference imaging camera includes an optical filter 14 located between the beam-splitting mirror 9 and the pixel-sensor array 12 and arranged to transmit wavelengths of light corresponding to visible light for receipt by the pixel-sensor array. Located between the filter 14 and the pixel-sensor array 12 is an imaging optical element 13, or optical train, comprising lenses or the like arranged to form an image on the pixel-sensor array 12 using light transmitted thereto by the filter 14. The imaging optical element 13 is preferably adapted for forming images over the whole visible light spectrum and the pixel-sensor array 12 is preferably a colour pixel-sensor array adapted to form colour images.

A control panel 15 is arranged upon the probe and comprises one or more control buttons, or other manually operable control user-interfaces (not shown), enabling the user to control functions and operations of the probe by hand.

The control panel may be arranged to control any one or more of: the capturing of images by the reference camera 11 (e.g. act as a "shoot" button); the capturing of images by the IR camera unit 19; the intensity of illuminating light produced by the illumination light source 3; the filtering state of the filter unit 18; the focussing of the image collecting optics

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6; the optical magnification provided by (e.g. zoom) the image collecting optics 6.

A remote imaging optical element(s) 17 and a filter unit 18 are arranged in successive common optical communication with, and between, the optical output end 5A of the second aligned optical fibre bundle 5, distal the probe 2, and the infra-red imaging camera 19.

The remote imaging optical element(s) 17 comprises one or more lens elements, or the like, arranged to form from light received thereby from the second aligned optical fibre bundle 5 an image of the target tooth 25 from which the light in question was returned.

The filter unit 18 is arranged to receive light output by the remote imaging optical element(s) 17 and to transmit, according to the optical transmission characteristics of the filter unit, portions of received light to the infra-red pixel sensor array of the infra-red camera 19. The remote imaging optical element(s) 17 may be arranged or controllable for form a focused image on the infra-red pixel sensor array via the filtering optics of the filter unit 18. The filter unit may comprise a liquid-crystal variable optical filter element possessing a selectively variable optical transmission spectral characteristic and being controllable to selectively transmit optical radiation only within any one of a number of selected wavelength bandwidths (e.g. infra-red radiation). Alternatively, the filter unit 18 may comprise a filter wheel including a plurality of separate dedicated filter elements (e.g. glass filters of the like) each possessing a fixed spectral transmission characteristic and each being selectively movable into the path of light output by the imaging optics 17 thereby to filter that light for subsequent transmission to the infra-red camera 19.

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The filtering unit is arranged to selectively filter light received thereby according to any selected one of three pass-band transmission spectral characteristics with each pass-band preferably centred upon a respective desired wavelength value (e.g. a value selected from: 1090nm, 1440nm, 1610nm).

A first pass band of the filtering unit may be a pass band which extends from 1300nm to 1550nm, or from 1400nm to 1500nm, and may be centred on 1440nm. A second pass band may extend from 1550nm to 1800nm, or from 1550nm to 1650nm, and may be centred on 1610nm. A reference pass band of the filtering unit may be a pass band which extends from 1000nm to 1150nm, or from 1050nm to 1130nm, and may be centred upon 1090nm. A third pass band of the filtering unit may be a pass band which extends from 1850nm to 1970nm, or from 1880nm to 1940nm, and may be centred upon 1910nm. The pass band width of any one or more, or each, of the filter pass bands is preferably from 10nm to 15nm in extent. However, the pass band width in question may be up to 60nm in extent, or thereabouts. The pass band width in question may be any size less than 60nm and preferably wholly falls within a range of wavelengths which is 60nm in extent and is centred upon a value selected from: 1090nm, 1440nm, 1610nm.

Accordingly, operation of the filtering unit enables the infra-red camera to generate image pixel values representative of a respective one of three different images formed using light of a corresponding one of three different infra-red wavelengths. Reflectance values may be calculated from two of the three images using pixel values of the third image to normalise the reflectance values. Reflectance values may be used to calculate a measure of lesion (e.g. a carries score) a given imaged part of the tooth common to all three images.

The apparatus further includes a computer 20, such as a personal computer or the like, arranged to receive image pixel values representative of images formed upon the infra-red

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pixel sensor array of the infra-red camera 19, and to process those pixel values as discussed below.

The illumination source 3, the control panel 15 of the probe 2, and the reference imaging camera 11 of the probe 2, are each also in communication with the computer 20 via a data transmission link 16 via which control data and image data are passed between the elements of the apparatus interconnected thereby.

A control foot switch 21 is connected in operable communication with the computer 20 and is arranged to control any one or more of: the capturing of images by the reference camera 11 (e.g. act as a "shoot" button); the capturing of images by the IR camera unit 19; the intensity of illuminating light produced by the illumination light source 3; the filtering state of the filter unit 18; the focussing of the image collecting optics 6; the optical magnification provided by (e.g. zoom) the image collecting optics 6. The implementation of these functions via the control foot switch enables a user to control the operation of the probe 2 without having to manually operate elements of the control panel 15 when it is desirable not to move or shake the probe - such as when "shooting" images in use or the like.

The computer includes image processing means (e.g. implemented using software) arranged to receive pixel image values from the infra-red camera and to produce images therefrom. The image processing means is arranged to co-register separately acquired images of a common target tooth 25, each obtained using a different selected respective filter of the filter unit, thereby to associate a given image pixel of the any one co-registered image with a respective image pixel of any other co-registered image representing the same part of the imaged subject. This a reflectance spectrum or profile to be generated in respect of each such co-registered pixel value, thereby providing a hyper-spectral image data set to be

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formed. The reference image pixel values generated by the reference camera 11 are also received by the computer (via data transmission line 16) and are co-registered with images containing the same target tooth 25 via the IR camera 19 at different IR wavelengths. Thus, a "visible light" reference image may be provided representing the imaged tooth as would be perceived by the user regarding the tooth, together with two or three corresponding (and co-registered) images of the target tooth taken using one of two or three different infra-red (IR) wavelengths of light. The image processing means preferably permits the user to select upon the reference image of the tooth a pixel representing a given location on the tooth, and in response to such selection may present and one or more of: the pixel values of the corresponding IR images co-registered with the reference image corresponding to the selected location on the tooth; reflectance values of the selected location in respect of the wavelengths of light employed to generate the IR images; a measure of lesion present in the tooth at the selected region of the tooth; a carries score in respect of the selected region of the tooth.

In one example, the computer includes data processing means is arranged, in respect of a given part of the imaged tooth, to use one or more image pixel values of a first IR image (taken using a first IR wavelength or pass-band) to calculate a first reflectance value associated with the part, and to use one or more image pixel values of a second IR image (taken using a second IR wavelength or pass-band different from the first) to calculate a second reflectance value associated with the same tooth part. The data processing means of the computer determines from the first and second reflectance values a measure of the degree of enamel lesion (S_e) and/or dentin lesion (S_d) present in the common tooth part. An example is given below.

The data processing means may be arranged to use this measure of the degree of enamel lesion (S_e) and the measure of the

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degree of dentin lesion (S_d) to calculate a measure (S_{caries}) of the degree of caries present in the part. An example is given below.

Well defined signatures have been observed in reflectance (R) spectra from teeth at NIR wavelengths. Reflectance (R) above 1400nm tend to be higher for the decayed areas and in particular at 1610nm. NIR reflectance dips (i.e. NIR absorption) are pronounced by dentin lesion, and especially at 1440nm.

A first pass band of the filtering unit may be a pass band which extends from 1300nm to 1550nm, or from 1400nm to 1500nm, and may be centred on 1440nm. A second pass band may extend from 1550nm to 1800nm, or from 1550nm to 1650nm, and may be centred on 1610nm. A reference pass band of the filtering unit may be a pass band which extends from 1000nm to 1150nm, or from 1050nm to 1130nm, and may be centred upon 1090nm. A third pass band of the filtering unit may be a pass band which extends from 1850nm to 1970nm, or from 1880nm to 1940nm, and may be centred upon 1910nm. The pass band width of any one or more, or each, of the filter pass bands is preferably from 10nm to 15nm in extent. However, the pass band width in question may be up to 60nm in extent, or thereabouts. The pass band width in question may be any size less than 60nm and preferably wholly falls within a range of wavelengths which is 60nm in extent and is centred upon a value selected from: 1090nm, 1440nm, 1610nm, 1910nm.

The computer 20 is arranged to process pixel values (correlated to spectral intensity) at each IR image pixel by normalising it to (e.g. dividing it by) the corresponding (co-registered) image pixel value associated with a reference reflectance (R) e.g. obtained at the wavelength with the highest reflectance (least extinction) e.g. 1090nm. The degree of enamel, S_e, and dentin, S_d, lesions are to be calculated by the computer as follows:

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$$S_e = S_e^{(1)} = \frac{R(1610nm)}{R(1090nm)} \quad \text{or} \quad S_e = S_e^{(1)} = \frac{R(1440nm) - R(1910nm)}{R(1090nm)}$$

$$S_d = \frac{R(1610nm) - R(1440nm)}{R(1090nm)}$$

As can be seen from figure 3, a rise in reflectance occurs at around 1900nm and is associated with the scattering of infra-red light from demineralised tooth enamel. In demineralised enamel, light is scattered more than in sound enamel. Scattered intensity is typically a function of wavelength, that is to say, the amount of light scattered tends to drop in inverse proportion to wavelength increases. In a non-absorbing medium the wavelength dependence becomes apparent when comparing the reflectance intensities of two spectral regions. In such a case, demineralised enamel presents a scattering characteristic in the spectral reflectance thereof. The degree of enamel lesion $S_e^{(2)}$ is suitable for use to enhance the effect of scattering of light and to separate the influence of absorption by water. Two spectral dips occur in the spectrum of figure 3 at about 1440nm and 1910nm, and a comparison of the reflectance intensities at these wavelengths is employed. By looking at the intensity of these two dips, when scattering dominates over water absorption, the dips may become less pronounced, but the wavelength dependence introduced by scattering will become stronger. In this way, the relative rise in reflectance at 1910nm is principally due to enamel demineralisation, and the relationship between the two spectral intensities employed in the measure $S_e^{(2)}$ is used to unveil this feature.

The computer is arranged to calculate the caries score, S_{caries}, as follows:

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$$S_{caries} = p\left(\frac{S_e - K_e}{N_e}\right) + (1-p)\left(1 + \frac{S_d - K_d}{N_d}\right)$$

Here, K_x and N_x are the enamel (x : e) and dentin (x : d) score calibration offset and normalisation factor, respectively. In addition, $p = 1$ if

$$\left(1 + \frac{S_d - K_d}{N_d}\right) \prec S_{dth}$$

where S_{dth} represents the dentin lesion threshold, otherwise $p = 0$.

An example of another implementation of the invention follows using sample target teeth.

Twelve extracted human teeth (premolars and molars) with natural lesions of various degrees were acquired. Soft tissues were removed from the collected teeth and these were thoroughly cleaned. Each tooth was stored in a separate container with distilled water and 0.5% thymol to keep them hydrated and sterile and therefore free from bacteria. Note that the teeth were kept for at least 2 hours in the bottle containers before any (hyperspectral) images were taken to get the measurements closer to the natural hydration conditions. The excess of water on the occlusal surfaces was however gently wiped off using cotton.

A near-infrared (NIR) hyperspectral camera was used to capture the spectral reflectance from the samples. The instrument images a line of vision at a time and diffracts the light onto a 2-dimensional pixel-sensor array by means of a diffraction grating. A complete stack of spectral images (spectral data cube) is obtained by translating the sample at constant speed and line-imaging synchronously. The spectral analysis range was from 1000 nm to 2500 nm with a spectral resolution of 10 nm. Figure 1 shows an image of the system set-up. Note that a

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two-side illumination using halogen lamps was configured to reduce the effect of shadowing.

Acquired reflectance data, a dark current measurement associated with the data acquired (for noise subtraction), reflectance spectra of a reference object and its associated dark current measurement were used as follows to calibrate spectral reflectance data, this calculation being performed for each image pixel value:

$$R(\lambda) = \frac{R_r(\lambda) - D_r}{W_{ref}(\lambda) - D_w} W_{spec}(\lambda) \qquad \text{eq. (1)}$$

Here $R(\lambda)$, $R_r(\lambda)$ and $W_{ref}(\lambda)$ are the calibrated, raw and white reference measurements at wavelength λ, respectively. $W_{spec}(\lambda)$ corresponds to a white reference reflectance at wavelength λ. In addition, D_r and D_w are the dark current noise measurements obtained for the raw white reference reflectance data.

Histological information was obtained for all samples after obtaining the NIR hyperspectral images. The teeth were grounded along the transversal plane to their surface. Sub-millimetres grounding steps were performed and a photograph was taken after each step. The histology scoring was done for the slide showing the most representative lesion for each tooth. The score was given based on the criteria shown in Table I.

TABLE I: Histology scoring criteria.

Score	Code: Lesion depth
0	S : Sound
1	E1 : 1/3 enamel
2	E2 : 2/3 enamel
3	EDJ: enamel-dentin junction
4	D1 : 1/3 dentin
5	D2 : 2/3 dentin

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6	D3 : to the pulp

As an example, a selection of the spectral images obtained from an occlusal tooth surface is shown in Figure 2 at the wavelengths indicated. It is possible to see that the reflectance intensity drops at higher wavelengths.

A typical reflectance spectrum for sound material, white spot material (enamel lesion) and a dentin lesion material is shown in Figure 3. Well defined signatures can be observed among the three cases. For instance, reflectance above 1400nm is clearly higher for the decayed areas and in particular at 1610nm. However, the absorption dips are further pronounced for the case of dentin lesion, and specially at 1440nm.

The spectral intensity at each pixel was normalised to the reflectance obtained at 1090 nm since this the wavelength with the highest reflectance (least extinction). The degree of enamel, S_e, and dentin, S_d, lesions were therefore calculated as follows:

$$S_e = \frac{R(1610nm)}{R(1090)} \qquad \text{eq. (2)}$$

$$S_d = \frac{R(1610nm) - R(1440nm)}{R(1090)} \qquad \text{eq. (3)}$$

A caries score, S_{caries}, was calculated as a combination of S_e and S_d and was designed to account for the deepest lesion observed by the NIR spectrum as follows:

$$S_{caries} = p\left(\frac{S_e - K_e}{N_e}\right) + (1-p)\left(1 + \frac{S_d - K_d}{N_d}\right) \qquad \text{eq. (4)}$$

Here, K_x and N_x are the enamel (x : e) and dentin (x : d) score calibration offset and normalisation factor, respectively. In addition, p = 1 if

$$\left(1+\frac{S_d-K_d}{N_d}\right) \prec S_{dth}$$

where S_{dth} represents the dentin lesion threshold, otherwise p = 0.

Outliers and noise introduced by specular reflections were removed by limiting the values of the numerators in Equation 4 to the range $0 < (S_e - K_e) < M_e$ and $0 < (S_d - K_d) < M_d$; here M_e and M_d denote the upper limits. Values outside these limits were set to zero.

In order to fix the range of S_{caries} from 0 to 2, the normalization factors in Equation 4 were expressed as $N_e = M_e/S_{dth}$ and $N_d = M_d$. Therefore for values in the range of $0 < S_{caries} \leq S_{dth}$ the score indicates an enamel lesion and for $S_{caries} > S_{dth}$ the score indicates a dentin lesion. Note that sound areas have a value of $S_{caries} = 0$.

The calibration values for the equations above were obtained empirically. For our case, results were best described with $S_{dth} = 1.1$, $K_e = 0.14$, $K_d = 0.05$, $M_e = 0.35$, and $M_e = 0.15$.

Twelve teeth with different lesion degrees were imaged and processed following the method described above. As an example, coded S_{caries} maps for four teeth are shown in Figure 4. The associated pictures and the selected histological sections chosen are also shown.

Note that the extension of the lesion is not evident from the pictures in Figure 4 (which rely on visible wavelengths). It is possible to see however that the caries score maps clearly depict the lesion spatial distribution. This is due to the longer light penetration of NIR wavelengths through enamel. In addition, the depth of the lesions can be confirmed from the histological sections. The arrows pointing toward the colour pictures of Figure 4 indicate the point of view of the

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histological section, which is indicated by the straight line traversing a given picture of a tooth.

For the examples presented in Figure 4, lesions in Tooth A rest within the enamel, having $S_{caries} < 1.1$, whereas the lesions in Teeth B, C and D reach the dentin, having $S_{caries} > 1.1$. These observations can be confirmed with the histological sections which are scored as EDJ for Tooth A and D2 for Teeth B, C and D. The black points highlighted in each carries score map image (by an arrow) correspond to the maximum scores found within the region corresponding to the histological section and the average value is indicated by the arrow.

Hidden lesions, such as the one in Tooth D, are of particular interest since visual inspection does not reveal them easily and they could be left untreated increasing the risk of tooth loss. It is clear from the histology section that the damage has reached the dentin for this case and this is adequately indicated by values of $S_{caries} > 1.1$ around the decayed region.

Detection of caries in pits and fissures is of great interest among the dental practitioners since demineralisation commonly starts in these sites and the detection of them is not always obvious, especially in the presence of stain. The decay in the fissure pattern of Tooth A can be easily discriminated in the S_{caries} map; the demineralised part of the "U"-shaped fissure of this tooth is well described and confirmed with the histological section. Enamel demineralisation in the fissure pattern of the remaining teeth shown in Figure 4 are also depicted by their corresponding S_{caries} map but it is the deepest tooth lesion the one considered for our statistical analysis below.

The NIR images are to some extent affected by specular reflection, especially around the edges and the crests of the teeth where reflections are expected to be strong. These reflections act as a noise factor, especially for the

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calculation of S_e in Equation 2 above. Note that the stain and pigmentation in all teeth did not show a significant interference with the measurements.

The NIR image processing algorithm discriminates well between sound enamel, enamel lesions and dentin lesions.

A region from each of the S_{caries} maps corresponding to the selected histological section was obtained. A histogram of the values obtained across this region was calculated and the value corresponding to the highest bin with more than five pixels was extracted. This reduces or removes false maxima that could be caused by specular reflections. The average of the values within the extracted bin was used as an indication of the maximum S_{caries} score in the region and was compared to the histology score.

Figure 5 shows a correlation graph between the two scores and a Pearson correlation 0.89 significant at a level $p < 0.01$ was found. In addition, a sensitivity of 75% and a specificity of 87.5% for enamel lesions and a sensitivity of 87.5% and a specificity of 100% for dentine lesions were found using the NIR spectral imaging method.

Detecting early stages of tooth decay is advantageous as it is reversible and the progression to a stage where restorative intervention is required might therefore be avoided. Screening early lesions in occlusal pits and fissures is advantageous since these regions have a higher susceptibility to bacterial deposition and therefore deminaralisation. Visual inspection and radiography are commonly used in the clinic to perform this task; however, such methods lack the sensitivity needed to detect early stages of the disease and also the ability to quantify its progression.

Hyperspectral imaging is a powerful method used to interrogate the spectral characteristics of samples in a two-dimensional

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space. This is now found to be of particular use when studying teeth due to their inherent heterogeneous occlusal geometry and associated lesion distribution. This method may be employed according to the present invention which demonstrates the ability of NIR spectral imaging to quantify caries lesions from occlusal surfaces. A light reflectance configuration, preferably back-scattering of light, is preferably employed in the invention since uniform illumination of the tooth is easily achieved. Imaging with NIR wavelengths means that stain no longer represents a strong confounding factor when detecting tooth demineralization.

Figure 6 shows an example of the reflectance obtained at a wavelength of 1250 nm for three heavily stained teeth. It is possible to observe that the absorption of light by stain is minimal and confirms previous reported observations employing NIR wavelengths.

Note that the spectral intensity dips observed in the reflectance spectra shown in Figure 3 correspond to the absorption peaks of water. In addition, the expected raise in light scattering caused by white spot lesions can be observed in the spectra as a background intensity across all wavelengths. The results obtained for the different lesions suggest that, as the cavity reaches the dentin, the lesion size increases and the amount of water within increases too. For early enamel demineralization, the effect is rather observed as an augmented light scattered intensity at the surface due to the porous structure of the lesion. These physical effects may be used, according to the invention, as a mechanism to quantify the extension of tooth decay. Use of the reflectance at 1440 nm and 1610 nm, such as presented in Equation 4, is suitable (though other wavelengths may be considered) since these wavelengths appear to be most affected by water absorption and scattering as shown in Figure 3 for enamel and dentin lesions. Sound regions of the teeth show a reduced reflectance at wavelengths above 1450 nm; this may be

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caused by an increase in the absorption of light by hydroxyapatite and/or collagen; decayed areas have a reduced amount of mineral and/or organic material and this may explain the observed higher reflectance at such wavelengths.

Although special attention may be paid in pixel data processing algorithms discussed above, to remove the influence of specular reflections from reflectance data, measured pixel data values may still be affected by this source of noise, in particular at the edges and crests of the tooth present strong reflections are expected.

In another example, the filtering unit is arranged to selectively filter light received thereby according to any selected one of four pass-band transmission spectral characteristics with each pass-band preferably centred upon a respective desired wavelength value (e.g. a value selected from: 1090nm, 1440nm, 1610nm, 1910nm).

The above examples are intended for illustration and are not intended to be limiting. Variants and modifications to the examples, such as would be readily apparent to the skilled person, may be made without departing from the scope of the invention.

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The following statements provide general expressions of the disclosure herein.

A. Apparatus for imaging a tooth including:

illumination means arranged to generate first infra-red light with a first wavelength having a value within a range of values corresponding to an infra-red spectral absorption band of water, to generate second infra-red light with a second wavelength having a value within a range of values corresponding to an infra-red spectral reflection band characteristic of scattering from demineralised tooth enamel, and for illuminating a tooth therewith;

image data acquisition means arranged for receiving infra-red light originating from the illumination means and returned from an illuminated tooth, and including infra-red pixel sensor means responsive to said returned infra-red light to generate image pixel values for a first image of the illuminated tooth using first infra-red light and not second infra-red light and to generate image pixel values for a second image of the illuminated tooth using second infra-red light and not first infra-red light, and to provide such image pixel values for use.

B. Apparatus according to any preceding statement in which the image data acquisition means includes optical input means via which the apparatus is arranged to receive infra-red light returned from an illuminated tooth in a direction substantially parallel with, or subtending an acute angle with respect to, a direction of illumination by the illumination means.

C. Apparatus according to any preceding statement in which the illumination means comprises optical output means with an optical axis along which the apparatus is arranged to output said infrared light to illuminate a tooth, and the image data acquisition means includes optical input means comprising an optical axis along which the apparatus is arranged to receive

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infrared light returned from an illuminated tooth and which is substantially parallel to, or subtends an acute angle with respect to, the optical axis of the illumination means.

D. Apparatus according to any preceding statement in which the image data acquisition means includes camera means including a pixel sensor array responsive to visible light returned from an illuminated tooth to form one or more image pixel values representing an image of at least a part of the tooth.

E. Apparatus according to any preceding statement including infra-red optical filter means selectively operable in a first state to transmit infra-red light originating from the illumination means having said first wavelength and to substantially prevent transmission therethrough of infra-red light having said second wavelength, and in a second state to transmit infra-red light originating from the illumination means having said second wavelength and to substantially prevent transmission therethrough of infra-red light having said first wavelength.

F. Apparatus according to statement E in which the infra-red optical filter means is arranged in optical communication with the infra-red pixel sensor means to filter infra-red light directed to the infra-red pixel sensor means by the image data acquisition means.

G. Apparatus according to statement E in which the illumination means comprises light-source means operable to generate light including said first and second wavelengths, wherein the infra-red optical filter means is arranged in optical communication with the light-source means to filter light generated by the light-source means for illuminating a tooth with infra-red radiation transmitted by the infra-red optical filter means.

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H. Apparatus according to any preceding statement in which the illumination means comprises light-source means operable to generate light including said first and second wavelengths, and optical output means remotely in optical communication with the light-source means via output optical waveguide means and arranged to output from the apparatus light generated by the light-source means to illuminate a tooth.

I. Apparatus according to any preceding statement including optical input means remotely in optical communication with the infra-red pixel sensor means via input optical waveguide means and arranged to receive infra-red light returned from an illuminated tooth and to direct the returned infra-red light to the remote infra-red pixel sensor means for sensing thereby.

J. Apparatus according to statement H and statement I including a remote intra-oral probe comprising the optical input means and the optical output means.

K. Apparatus according to statement J in which the input optical waveguide means comprises one or more optical fibres which collectively define an aligned optical fibre bundle.

L. Apparatus according to statement J or K in which the output optical waveguide means comprises one or more optical fibres collectively defining an aligned optical bundle.

M. Apparatus according to statements J to L in which at least a terminal end of the output optical waveguide means is adjacent the optical input means.

N. Apparatus according to statement M in which the terminal end of the output optical waveguide comprises a bundle of optical fibres the ends of which form a ring circumscribing the output optical waveguide.

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O. Apparatus according to any preceding statement in which the illumination means comprises first optical polarizer means for polarizing according to a first polarization axis infra-red radiation generated by the illumination means, and the image data acquisition means comprises second optical polarizer means for polarizing according to a second polarization axis transverse to the first polarization axis infra-red radiation received thereby from an illuminated tooth.

P. Apparatus according to any preceding statement in which the image data acquisition means comprises focussing means arranged to form upon the infra-red pixel sensor means a real optical image using infra-red light received by the image data acquisition means from an illuminated tooth.

Q. Apparatus according to statement P when dependent upon statement E and statement I in which the optical filter means, the focussing means and infra-red pixel sensor means are each in mutual optical communication and remotely in optical communication with the optical input means via said input optical waveguide means.

R. Apparatus according to any preceding statement including image processing means arranged to receive said pixel image values for producing one or more of said first and second images therefrom.

S. Apparatus according to statement R in which the image processing means is arranged to co-register a said first image and a said second image in respect of a common imaged subject, thereby to associate a given image pixel of the first image with a respective image pixel of the second image representing the same part of the imaged subject.

T. Apparatus according to any preceding statement including data processing means arranged in respect of a given part of

the imaged subject to use one or more image pixel values of the first image to calculate a first reflectance value associated with the part, and to use one or more image pixel values of the second image to calculate a second reflectance value associated with the part, and to determine from the first and second reflectance values a measure of the degree of enamel lesion (S_e) and/or dentin lesion (S_d) present in the part.

U. Apparatus according to statement T in which the data processing means is arranged to use said measure of the degree of enamel lesion (S_e) and said measure of the degree of dentin lesion (S_d) to calculate a measure (S_{caries}) of the degree of caries present in the part.

V. Apparatus according to any preceding statement in which the infra-red pixel sensor means is responsive to said returned infra-red light to generate image pixel values for a reference image of the illuminated tooth using reference infra-red light and not first infra-red light nor second infra-red light, and to provide such image pixel values for use.

W. Apparatus according to statements E and V at least in which the infra-red optical filter means is selectively operable in a third state to transmit infra-red light originating from the illumination means having said reference wavelength and to substantially prevent transmission therethrough of infra-red light having any of said first wavelength and said second wavelength.

X. Apparatus according to statement T and statement V or statement W in which the data processor means is arranged to use one or more image pixel values of the reference image to calculate a reference reflectance value associated with the part, and to determine the measure of the degree of enamel

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lesion (S_e) and/or dentin lesion (S_d) present in the part using the reference reflectance value.

Y. Apparatus according to any preceding statement in which the first wavelength value is between 1300nm and 1550nm, and the second wavelength value is between 1550nm and 1800nm.

Z. Apparatus according to statement Y in which the first wavelength value is between 1400nm and 1500nm, such as 1440nm, and the second wavelength value is between 1550nm and 1650nm, such as 1610nm.

ZA. A method for imaging a tooth including:

generating first infra-red light with a first wavelength having a value within a range of values corresponding to an infra-red spectral absorption band of water, generating second infra-red light with a second wavelength having a value within a range of values corresponding to an infra-red spectral reflection band characteristic of scattering from demineralised tooth enamel, and illuminating a tooth therewith;

receiving at infra-red pixel sensor means first and second infra-red light returned from an illuminated tooth and therewith generating image pixel values for a first image of the illuminated tooth using first infra-red light and not second infra-red light and generating image pixel values for a second image of the illuminated tooth using second infra-red light and not first infra-red light, and providing such image pixel values for use.

ZB. A method according to statement ZA including receiving infra-red light returned from an illuminated tooth in a direction substantially parallel with, or subtending an acute angle with respect to, a direction of said illumination.

ZC. A method according to any of statements ZA to ZB including providing optical output means comprising an optical

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axis and therealong outputting said infrared light to illuminate a tooth, and providing optical input means comprising an optical axis and therealong receiving infrared light returned from an illuminated tooth for subsequent receipt at the infra-red pixel sensor means wherein the said optical axes are substantially parallel, or subtend an acute angle with respect to each other.

ZD. A method according to any of statements ZA to ZC including forming an image representing at least a part of the illuminated tooth using visible light returned therefrom.

ZE. A method according to any of statements ZA to ZD including generating light for illuminating the tooth and in a first instance, filtering the light by transmitting through a filter means parts of said light having said first wavelength and substantially preventing transmission through the filter means of parts of said light having said second wavelength; and in a second instance, filtering the light by transmitting through the filter means parts of said light having said second wavelength and substantially preventing transmission through the filter means parts of said light having said first wavelength.

ZF. A method according to statement ZE including performing said filtering on light directed to the infra-red pixel sensor means.

ZG. A method according to statement ZE including performing said filtering on light for illuminating a tooth.

ZH. A method according to any of statements ZA to ZG including generating said light remotely from said tooth, guiding the generating light to the proximity of the tooth, and illuminating the tooth with the guided light.

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ZI. A method according to any of statements ZA to ZH including guiding said returned infra-red light to a location remote from the point of receipt of the returned light and generating image pixel values using said returned, guided light at said remote location.

ZJ. A method according to any of statements ZA to ZI performed using an intra-oral probe.

ZK. A method according to any of statements ZA to ZJ including polarizing according to a first polarization axis infra-red radiation generated for illuminating a tooth, and polarizing according to a second polarization axis transverse to the first polarization axis infra-red radiation returned from the illuminated tooth.

ZL. A method according to any of statements ZA to ZK including forming upon an infra-red pixel sensor means a real optical image using said infra-red light returned from an illuminated tooth.

ZM. A method according to any of statements ZA to ZL including producing one or more of said first and second images from said returned light.

ZN. A method according to statement ZM including co-registering a said first image and a said second image in respect of a common imaged subject, thereby to associate a given image pixel of the first image with a respective image pixel of the second image representing the same part of the imaged subject.

ZO. A method according to any of statements ZA to ZN including generating image pixel values for a reference image of the illuminated tooth using reference infra-red light returned from the tooth and not first infra-red light nor

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second infra-red light, and providing such image pixel values for use.

ZP. A method according to statement ZO including, in respect of a given part of the imaged subject, calculating a first reflectance value R_1 associated with the part using one or more image pixel values of the first image, calculating a second reflectance value R_2 associated with the part using one or more image pixel values of the second image, calculating a reference reflectance value R_{ref} associated with the part using one or more image pixel values of the third image and determining from the first, second and reference reflectance values the values of the ratios R_1/R_{ref} and R_2/R_{ref} and providing the ratio values for use.

ZQ. A method according to statement ZP including calculating a value $(R_2/R_{ref}-R_1/R_{ref})$ and providing the value for use.

ZR. A method according to any of statements ZA to ZQ including generating light for illuminating the tooth and in a third instance, filtering the light by transmitting through a filter means parts of said light having said reference wavelength and substantially preventing transmission through the filter means of parts of said light having any of said first wavelength and said second wavelength.

ZS. A method according to any of statements ZA to ZR in which the first wavelength value is between 1300nm and 1550nm, and the second wavelength value is between 1550nm and 1800nm.

ZT. A method according to statement ZS in which the first wavelength value is between 1400nm and 1500nm, such as 1440nm, and the second wavelength value is between 1550nm and 1650nm, such as 1610nm.

ZU. A computer programmed to implement the method of any of statements ZM to ZQ.

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ZV. A computer program product comprising a computer-readable medium containing computer executable instructions which implement the method of any of statements ZM to ZQ when executed on a computer.

ZW. A computer program containing computer executable instructions which implement the method of any of statements ZM to ZQ when executed on a computer.

ZX. Apparatus according to any of statements A to Z including computer means programmed for use in implementing the method of any of statements ZA to ZT.

ZY. A computer program product comprising a computer-readable medium containing computer executable instructions for use in implementing the method of any of statements ZA to ZT when executed on apparatus according to statement ZX.

ZZ. A computer program containing computer executable instructions which implement the method of any of statements ZA to ZT when executed on apparatus according to statement ZX.

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CLAIMS:

1. Apparatus for imaging a tooth including:

illumination means arranged to generate first infra-red light with a first wavelength having a value within a range of values corresponding to an infra-red spectral absorption band of water, to generate second infra-red light with a second wavelength having a value within a range of values corresponding to an infra-red spectral reflection band characteristic of scattering from demineralised tooth enamel, and for illuminating a tooth therewith;

image data acquisition means arranged for receiving infra-red light originating from the illumination means and returned from an illuminated tooth, and including infra-red pixel sensor means responsive to said returned infra-red light to generate image pixel values for a first image of the illuminated tooth using first infra-red light and not second infra-red light and to generate image pixel values for a second image of the illuminated tooth using second infra-red light and not first infra-red light, and to provide such image pixel values for use; and

data processing means arranged in respect of a given part of the imaged subject to use one or more image pixel values of the first image to calculate a first reflectance value associated with the part, and to use one or more image pixel values of the second image to calculate a second reflectance value associated with the part, and to determine from the first and second reflectance values a measure of the degree of enamel lesion (S_e) and/or dentin lesion (S_d) present in the part.

2. Apparatus according to any preceding claim in which the image data acquisition means includes optical input means via which the apparatus is arranged to receive infra-red light returned from an illuminated tooth in a direction substantially parallel with, or subtending an acute angle with

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respect to, a direction of illumination by the illumination means.

3. Apparatus according to any preceding claim in which the illumination means comprises optical output means with an optical axis along which the apparatus is arranged to output said infrared light to illuminate a tooth, and the image data acquisition means includes optical input means comprising an optical axis along which the apparatus is arranged to receive infrared light returned from an illuminated tooth and which is substantially parallel to, or subtends an acute angle with respect to, the optical axis of the illumination means.

4. Apparatus according to any preceding claim in which the data processing means is arranged to use said measure of the degree of enamel lesion (S_e) and said measure of the degree of dentin lesion (S_d) to calculate a measure (S_{caries}) of the degree of caries present in the part.

5. Apparatus according to any preceding claim in which the image data acquisition means includes camera means including a pixel sensor array responsive to visible light returned from an illuminated tooth to form one or more image pixel values representing an image of at least a part of the tooth.

6. Apparatus according to any preceding claim including infra-red optical filter means selectively operable in a first state to transmit infra-red light originating from the illumination means having said first wavelength and to substantially prevent transmission therethrough of infra-red light having said second wavelength, and in a second state to transmit infra-red light originating from the illumination means having said second wavelength and to substantially prevent transmission therethrough of infra-red light having said first wavelength.

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7. Apparatus according to claim 6 in which the infra-red optical filter means is arranged in optical communication with the infra-red pixel sensor means to filter infra-red light directed to the infra-red pixel sensor means by the image data acquisition means.

8. Apparatus according to claim 7 in which the illumination means comprises light-source means operable to generate light including said first and second wavelengths, wherein the infra-red optical filter means is arranged in optical communication with the light-source means to filter light generated by the light-source means for illuminating a tooth with infra-red radiation transmitted by the infra-red optical filter means.

9. Apparatus according to any preceding claim in which the illumination means comprises light-source means operable to generate light including said first and second wavelengths, and optical output means remotely in optical communication with the light-source means via output optical waveguide means and arranged to output from the apparatus light generated by the light-source means to illuminate a tooth.

10. Apparatus according to any preceding claim including optical input means remotely in optical communication with the infra-red pixel sensor means via input optical waveguide means and arranged to receive infra-red light returned from an illuminated tooth and to direct the returned infra-red light to the remote infra-red pixel sensor means for sensing thereby.

11. Apparatus according to claim 9 and claim 10 including a remote intra-oral probe comprising the optical input means and the optical output means.

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12. Apparatus according to claim 11 in which the input optical waveguide means comprises one or more optical fibres which collectively define an aligned optical fibre bundle.

13. Apparatus according to claim 11 or 12 in which the output optical waveguide means comprises one or more optical fibres collectively defining an aligned optical bundle.

14. Apparatus according to claims 11 to 13 in which at least a terminal end of the output optical waveguide means is adjacent the optical input means.

15. Apparatus according to claim 14 in which the terminal end of the output optical waveguide comprises a bundle of optical fibres the ends of which form a ring circumscribing the output optical waveguide.

16. Apparatus according to any preceding claim in which the illumination means comprises first optical polarizer means for polarizing according to a first polarization axis infra-red radiation generated by the illumination means, and the image data acquisition means comprises second optical polarizer means for polarizing according to a second polarization axis transverse to the first polarization axis infra-red radiation received thereby from an illuminated tooth.

17. Apparatus according to any preceding claim in which the image data acquisition means comprises focussing means arranged to form upon the infra-red pixel sensor means a real optical image using infra-red light received by the image data acquisition means from an illuminated tooth.

18. Apparatus according to claim 17 when dependent upon claim 6 and claim 10 in which the optical filter means, the focussing means and infra-red pixel sensor means are each in mutual optical communication and remotely in optical

communication with the optical input means via said input optical waveguide means.

19. Apparatus according to any preceding claim including image processing means arranged to receive said pixel image values for producing one or more of said first and second images therefrom.

20. Apparatus according to claim 19 in which the image processing means is arranged to co-register a said first image and a said second image in respect of a common imaged subject, thereby to associate a given image pixel of the first image with a respective image pixel of the second image representing the same part of the imaged subject.

21. Apparatus according to any preceding claim in which the infra-red pixel sensor means is responsive to said returned infra-red light to generate image pixel values for a reference image of the illuminated tooth using reference infra-red light and not first infra-red light nor second infra-red light, and to provide such image pixel values for use.

22. Apparatus according to claims 6 and 21 at least in which the infra-red optical filter means is selectively operable in a third state to transmit infra-red light originating from the illumination means having said reference wavelength and to substantially prevent transmission therethrough of infra-red light having any of said first wavelength and said second wavelength.

23. Apparatus according to claim 21 or claim 22 in which the data processor means is arranged to use one or more image pixel values of the reference image to calculate a reference reflectance value associated with the part, and to determine the measure of the degree of enamel lesion (S_e) and/or dentin lesion (S_d) present in the part using the reference reflectance value.

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24. Apparatus according to any preceding claim in which the first wavelength value is between 1300nm and 1550nm, and the second wavelength value is between 1550nm and 1800nm.

25. Apparatus according to claim 24 in which the first wavelength value is between 1400nm and 1500nm, such as 1440nm, and the second wavelength value is between 1550nm and 1650nm, such as 1610nm.

26. A method for imaging a tooth including:

generating first infra-red light with a first wavelength having a value within a range of values corresponding to an infra-red spectral absorption band of water, generating second infra-red light with a second wavelength having a value within a range of values corresponding to an infra-red spectral reflection band characteristic of scattering from demineralised tooth enamel, and illuminating a tooth therewith;

receiving at infra-red pixel sensor means first and second infra-red light returned from an illuminated tooth and therewith generating image pixel values for a first image of the illuminated tooth using first infra-red light and not second infra-red light and generating image pixel values for a second image of the illuminated tooth using second infra-red light and not first infra-red light, and providing such image pixel values for use; and

in respect of a given part of the imaged subject, calculating a first reflectance value associated with the part using one or more image pixel values of the first image, and calculating a second reflectance value associated with the part using one or more image pixel values of the second image, and determining from the first and second reflectance values a measure of the degree of enamel lesion (S_e) and/or dentin lesion (S_d) present in the part.

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27. A method according to claim 26 including receiving infra-red light returned from an illuminated tooth in a direction substantially parallel with, or subtending an acute angle with respect to, a direction of said illumination.

28. A method according to any of claims 26 to 27 including providing optical output means comprising an optical axis and therealong outputting said infrared light to illuminate a tooth, and providing optical input means comprising an optical axis and therealong receiving infrared light returned from an illuminated tooth for subsequent receipt at the infra-red pixel sensor means wherein the said optical axes are substantially parallel, or subtend an acute angle with respect to each other.

29. A method according to any of claims 26 to 28 including forming an image representing at least a part of the illuminated tooth using visible light returned therefrom.

30. A method according to any of claims 26 to 29 including generating light for illuminating the tooth and in a first instance, filtering the light by transmitting through a filter means parts of said light having said first wavelength and substantially preventing transmission through the filter means of parts of said light having said second wavelength; and in a second instance, filtering the light by transmitting through the filter means parts of said light having said second wavelength and substantially preventing transmission through the filter means parts of said light having said first wavelength.

31. A method according to claim 30 including performing said filtering on light directed to the infra-red pixel sensor means.

32. A method according to claim 30 including performing said filtering on light for illuminating a tooth.

33. A method according to any of claims 26 to 32 including generating said light remotely from said tooth, guiding the generating light to the proximity of the tooth, and illuminating the tooth with the guided light.

34. A method according to any of claims 26 to 33 including guiding said returned infra-red light to a location remote from the point of receipt of the returned light and generating image pixel values using said returned, guided light at said remote location.

35. A method according to any of claims 26 to 34 performed using an intra-oral probe.

36. A method according to any of claims 26 to 35 including polarizing according to a first polarization axis infra-red radiation generated for illuminating a tooth, and polarizing according to a second polarization axis transverse to the first polarization axis infra-red radiation returned from the illuminated tooth.

37. A method according to any of claims 26 to 36 including forming upon an infra-red pixel sensor means a real optical image using said infra-red light returned from an illuminated tooth.

38. A method according to any of claims 26 to 37 including producing one or more of said first and second images from said returned light.

39. A method according to claim 38 including co-registering a said first image and a said second image in respect of a common imaged subject, thereby to associate a given image pixel of the first image with a respective image pixel of the second image representing the same part of the imaged subject.

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40. A method according to any of claims 26 to 39 including generating image pixel values for a reference image of the illuminated tooth using reference infra-red light returned from the tooth and not first infra-red light nor second infra-red light, and providing such image pixel values for use.

41. A method according to claim 40 including, in respect of the given part of the imaged subject, calculating a first reflectance value R_1 associated with the part using one or more image pixel values of the first image, calculating a second reflectance value R_2 associated with the part using one or more image pixel values of the second image, calculating a reference reflectance value R_{ref} associated with the part using one or more image pixel values of the third image and determining from the first, second and reference reflectance values the values of the ratios R_1/R_{ref} and R_2/R_{ref} and providing the ratio values for use.

42. A method according to claim 41 including calculating a value $(R_2/R_{ref}-R_1/R_{ref})$ and providing the value for use.

43. A method according to any of claims 26 to 42 including generating light for illuminating the tooth and in a third instance, filtering the light by transmitting through a filter means parts of said light having said reference wavelength and substantially preventing transmission through the filter means of parts of said light having any of said first wavelength and said second wavelength.

44. A method according to any of claims 26 to 43 in which the first wavelength value is between 1300nm and 1550nm, and the second wavelength value is between 1550nm and 1800nm.

45. A method according to claim 44 in which the first wavelength value is between 1400nm and 1500nm, such as 1440nm, and the second wavelength value is between 1550nm and 1650nm, such as 1610nm.

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46. A method according to any of claims 26 to 45 including calculating a measure ($S_{carries}$) of the degree of caries present in the part using said measure of the degree of enamel lesion (S_e) and said measure of the degree of dentin lesion (S_d).

47. A computer programmed to implement the method of any of claims 26 to 46.

48. A computer program product comprising a computer-readable medium containing computer executable instructions which implement the method of any of claims 26 to 46 when executed on a computer.

49. A computer program containing computer executable instructions which implement the method of any of claims 26 to 46 when executed on a computer.

50. Apparatus according to any of claims 1 to 25 including computer means programmed for use in implementing the method of any of claims 26 to 46.

51. A computer program product comprising a computer-readable medium containing computer executable instructions for use in implementing the method of any of claims 26 to 46 when executed on apparatus according to claim 50.

52. A computer program containing computer executable instructions which implement the method of any of claims 26 to 46 when executed on apparatus according to claim 50.

53. A method substantially as described in any one embodiment hereinbefore with reference to, or substantially as illustrated in, any of the accompanying drawings.

54. Apparatus substantially as described in any one embodiment hereinbefore with reference to, or substantially as illustrated in, any of the accompanying drawings.

IPR2025-01254 Page 00797

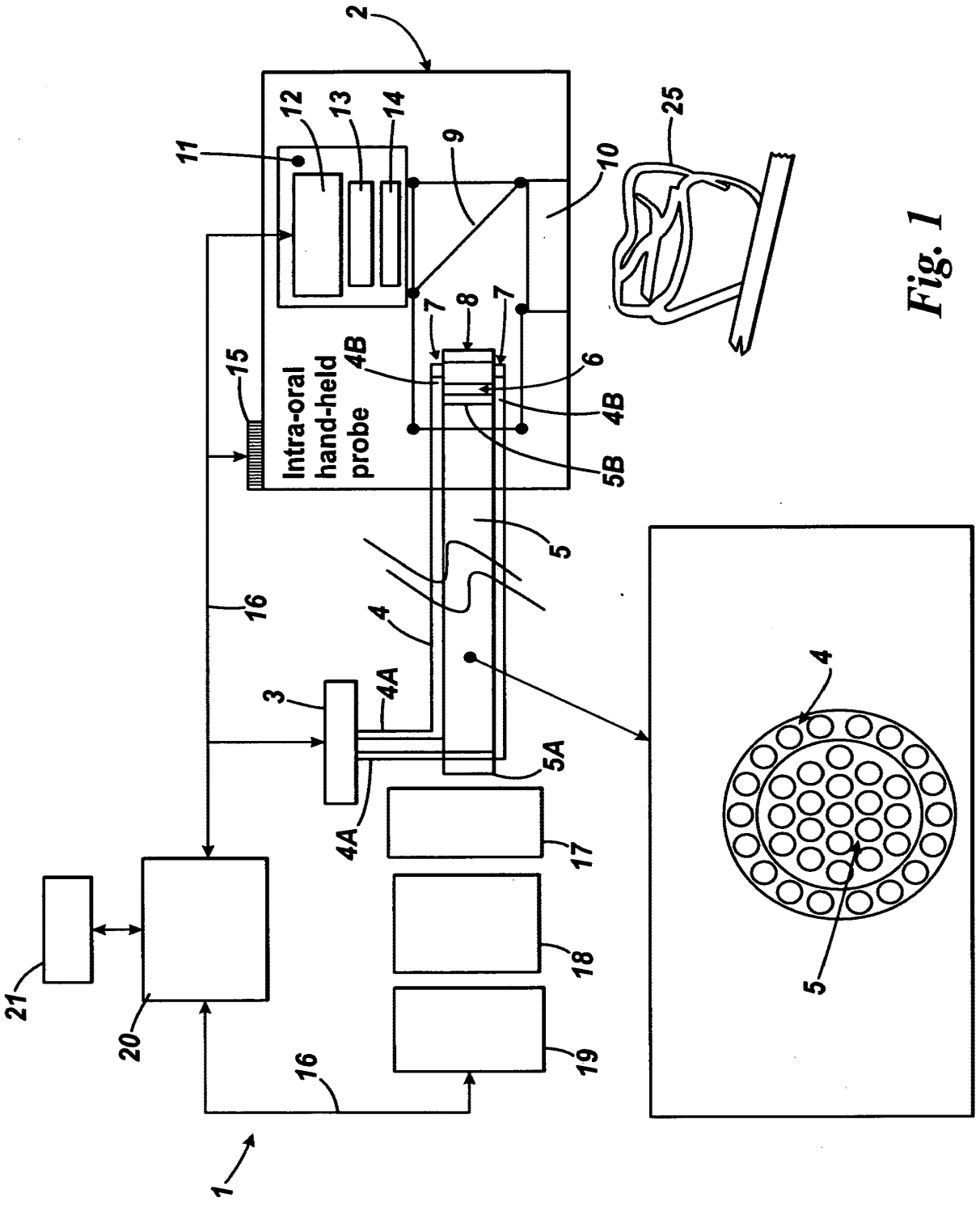

2
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7
15
4B
6
Intra-oral
hand-held
probe
4B
5B
5
16
4
3
4A
5A
4A
17
18
19
21
20
16
1
4
5

Fig. 1

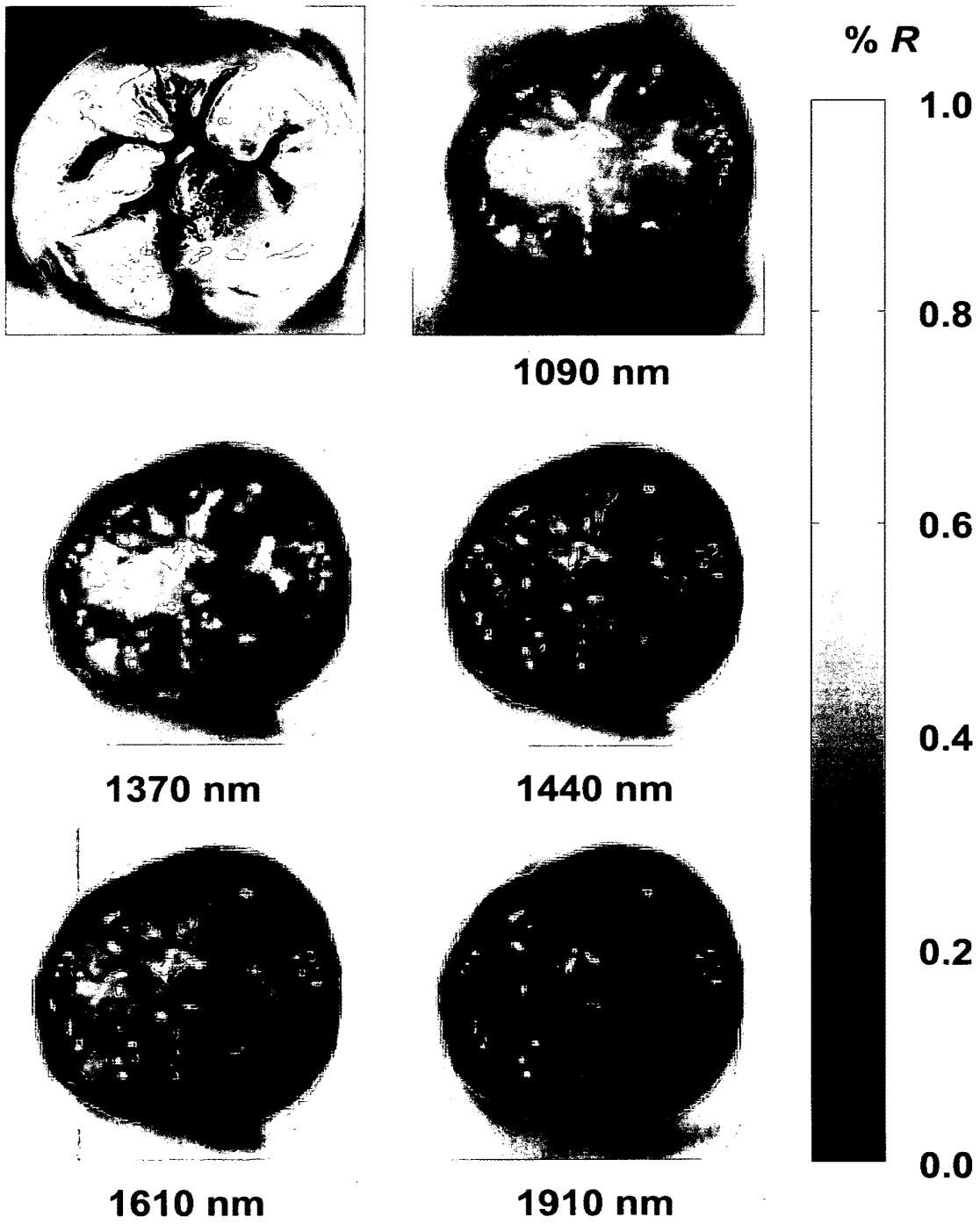


Fig. 2

SUBSTITUTE SHEET (RULE 26)

Fig. 3

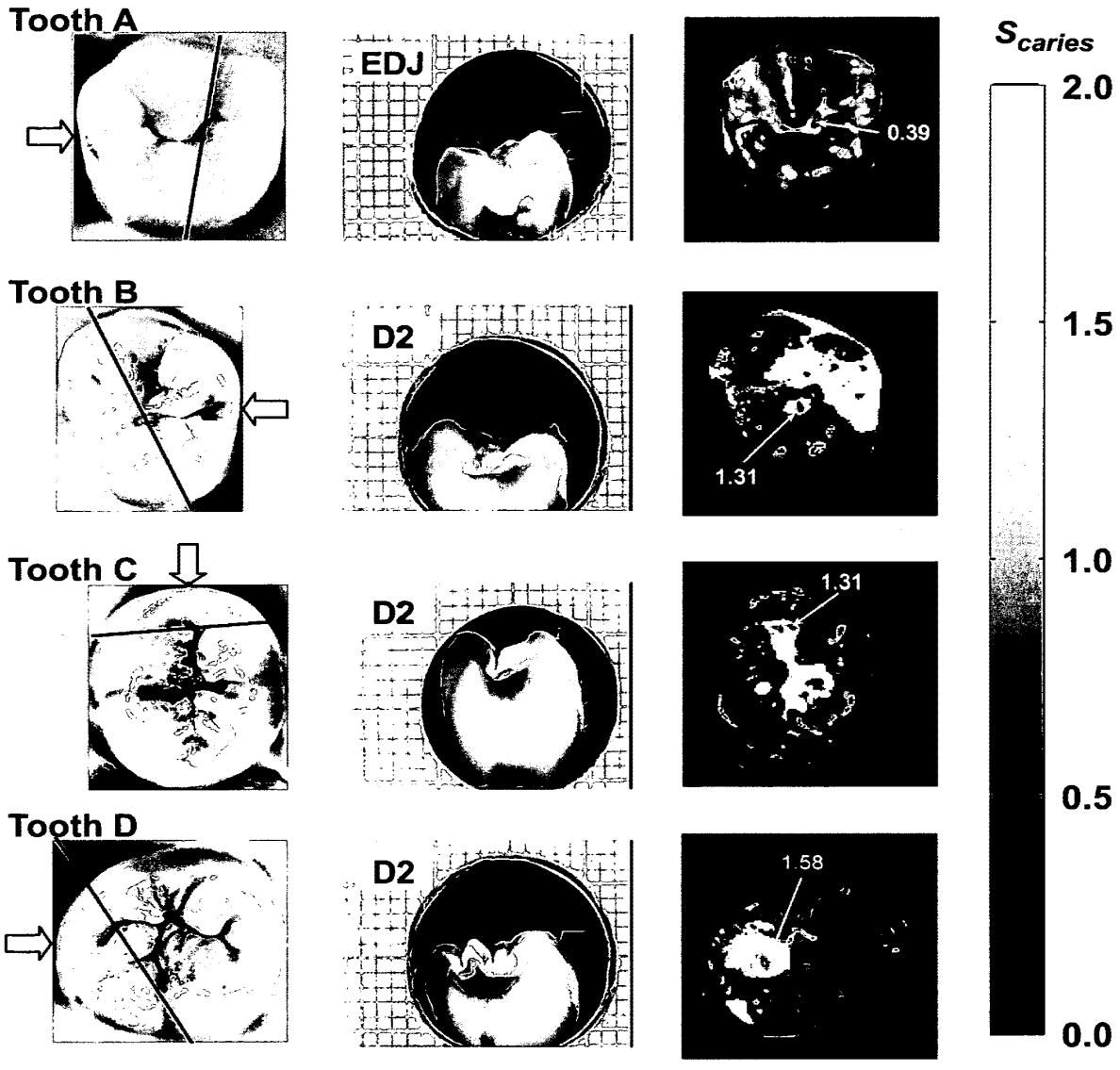

Tooth A
EDJ
0.39
Tooth B
D2
1.31
Tooth C
D2
1.31
Tooth D
D2
1.58
S_{caries}
2.0
1.5
1.0
0.5
0.0

Fig. 4

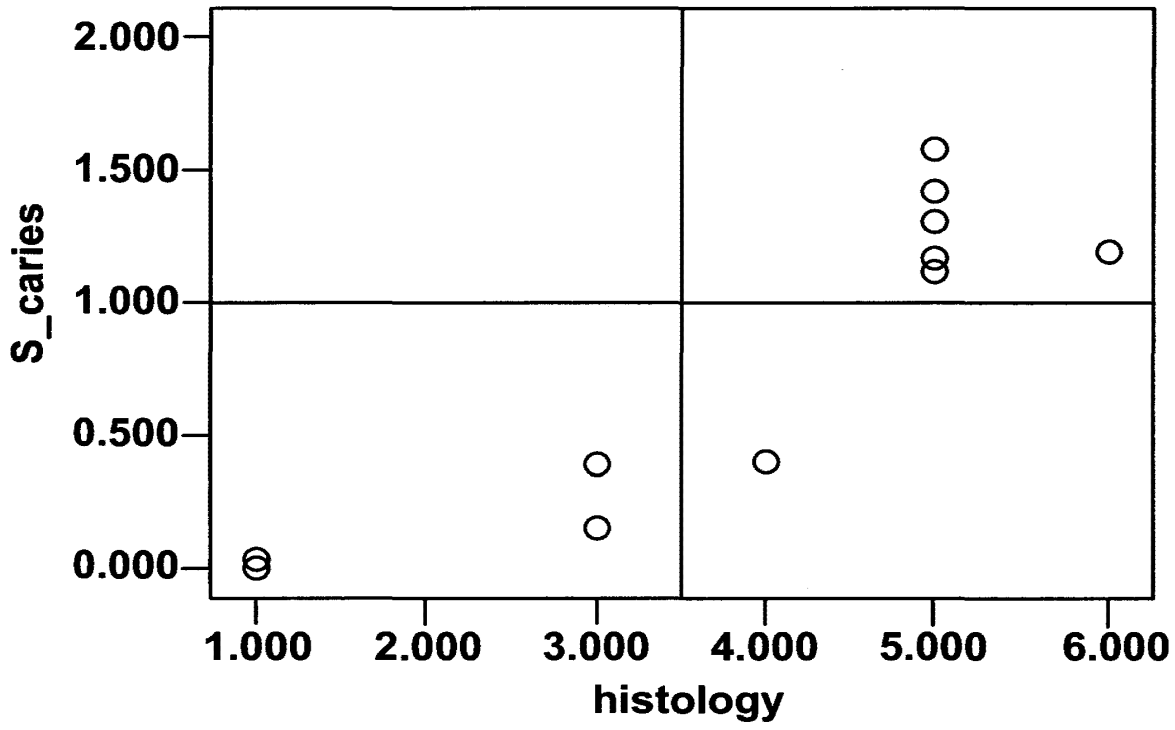
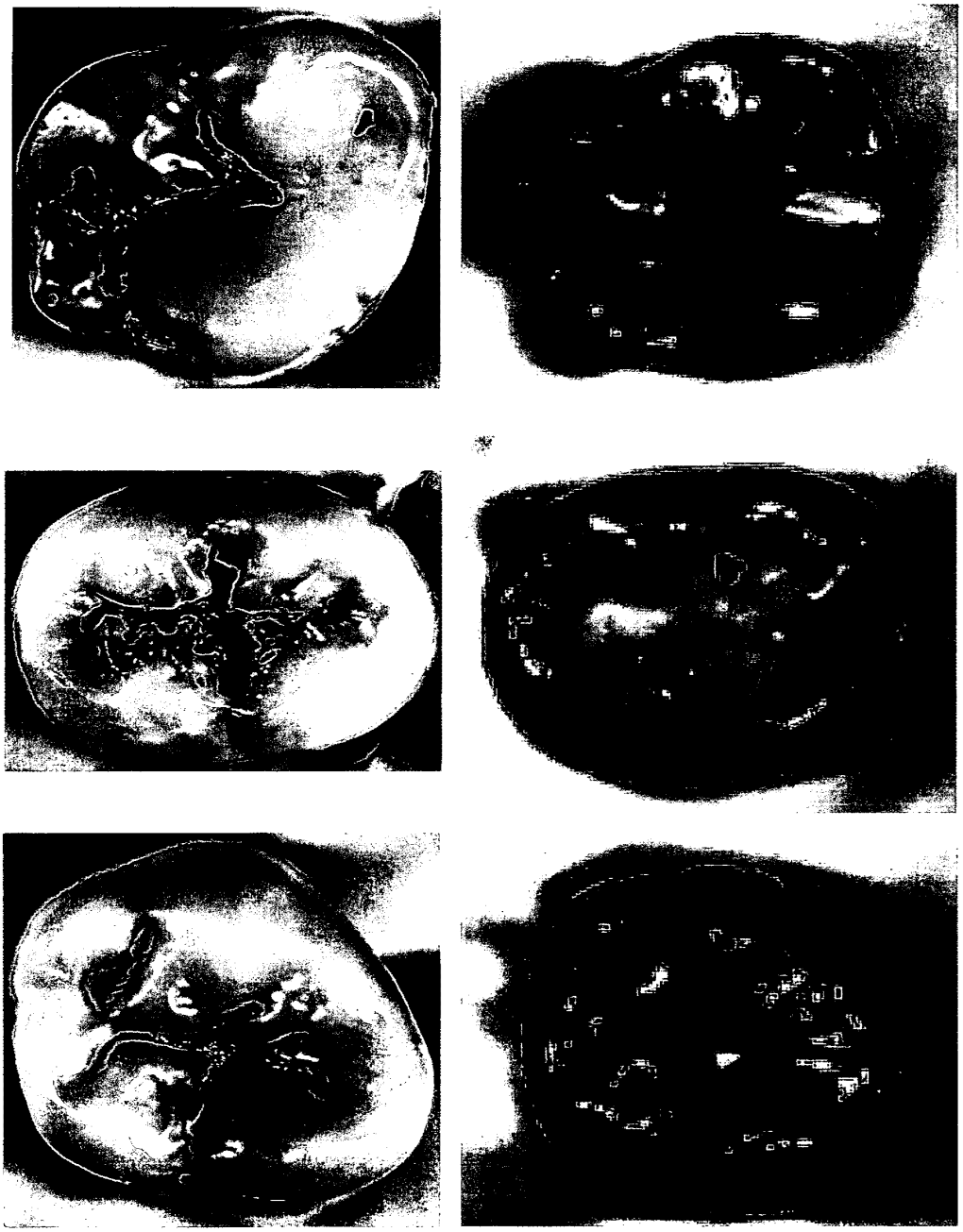

2.000
1.500
1.000
0.500
0.000
S_caries
1.000
2.000
3.000
4.000
5.000
6.000
histology

Fig. 5

Fig. 6



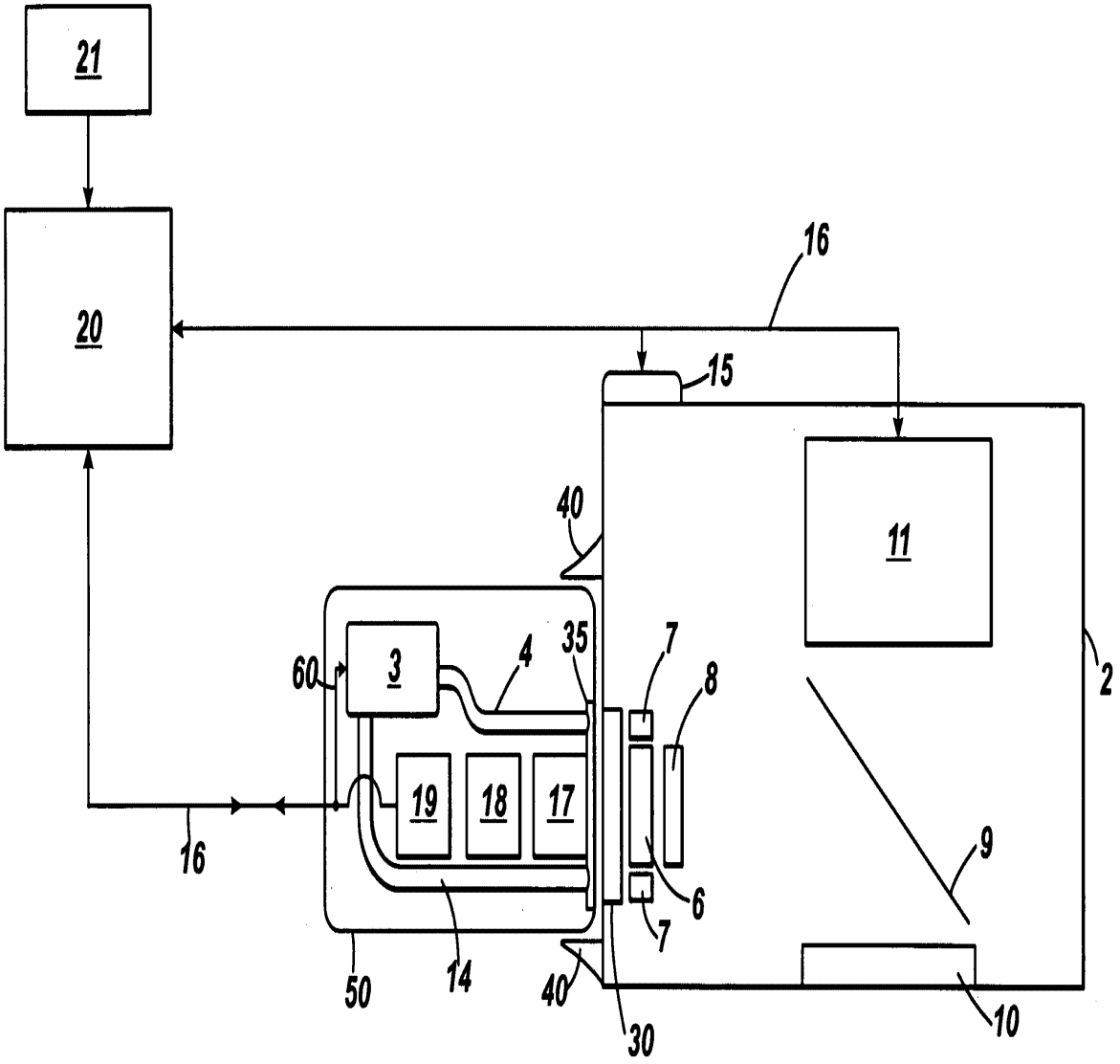


Fig. 7

SUBSTITUTE SHEET (RULE 26)

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2009/001032

A. CLASSIFICATION OF SUBJECT MATTER
INV. A61B5/00
ADD. A61B1/24

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2007/134615 A1 (LOVELY PETER S [US]) 14 June 2007 (2007-06-14) paragraphs [0044], [0048], [0055], [0066], [0075], [0079] - [0086], [0090]; figures 8,10,11	1-52
Y	US 2005/181333 A1 (KARAZIVAN NAIM [CA] ET AL) 18 August 2005 (2005-08-18) paragraphs [0030] - [0036], [0038], [0043], [0046], [0068]	1-52
A	WO 98/52460 A (MEDICAL LASER TECHNOLOGIES LIM [GB]; COLLES MICHAEL JOHN [GB]) 26 November 1998 (1998-11-26) page 3, line 9 - page 4, line 14 page 6, lines 27-32 page 7, line 16 - page 10, line 11 page 10, line 35 - page 11, line 3	1,26

-/--

[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
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"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
27 July 2009	04/08/2009

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	Kronberger, Raphael

Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2009/001032

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,X	EP 2 042 085 A (DEGUDENT GMBH [DE]) 1 April 2009 (2009-04-01) paragraphs [0004], [0006], [0007], [0012] - [0016], [0027], [0041], [0051]	1,26
A	HSIAO-CHUAN WANG ET AL: "Selection of an appropriate laser wavelength for launching surface acoustic waves on tooth enamel" OPTICAL FIBRE TECHNOLOGY/AUSTRALIAN OPTICAL SOCIETY, 2006. ACOFT/AOS 2006. AUSTRALIAN CONFERENCE ON, IEEE, PISCATAWAY, NJ, USA, 10 July 2006 (2006-07-10), pages 99-101, XP031252053 ISBN: 978-0-9775657-1-9 Section IV. Conclusionfigures 2,3	24,25, 44,45
A	US 5 570 182 A (NATHEL HOWARD [US] ET AL) 29 October 1996 (1996-10-29) column 1, lines 47-64 column 4, lines 25-53 column 7, lines 44-64	1,26
A	US 2004/236232 A1 (JONUSAUSKAS GEDIMINAS [FR] ET AL) 25 November 2004 (2004-11-25) paragraphs [0002], [0014], [0015], [0017] - [0022], [0040] - [0043], [0051] - [0056]; figures 3,4	1,26

Form PCT/ISA/210 (continuation of second sheet) (April 2005)

IPR2025-01254 Page 00806

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

Continuation of Box II.2

Claims Nos.: 53,54

Claims 53,54 are not in compliance with the provisions of clarity of Article 6 PCT, as it is not possible for a skilled person to establish the exact subject-matter for which protection is sought. The non-compliance with the substantive provisions is to such an extent, that no search was performed for these claims.

The applicant's attention is drawn to the fact that claims relating to inventions in respect of which no international search report has been established need not be the subject of an international preliminary examination (Rule 66.1(e) PCT). The applicant is advised that the EPO policy when acting as an International Preliminary Examining Authority is normally not to carry out a preliminary examination on matter which has not been searched. This is the case irrespective of whether or not the claims are amended following receipt of the search report or during any Chapter II procedure. If the application proceeds into the regional phase before the EPO, the applicant is reminded that a search may be carried out during examination before the EPO (see EPO Guideline C-VI, 8.2), should the problems which led to the Article 17(2)PCT declaration be overcome.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/GB2009/001032

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☒ Claims Nos.: 53,54
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
see FURTHER INFORMATION sheet PCT/ISA/210

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers allsearchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search reportcovers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/GB2009/001032

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2007134615 A1	14-06-2007	NONE	
US 2005181333 A1	18-08-2005	AU 2003229419 A1	11-11-2003
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		JP 2004526550 T	02-09-2004

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PATENT AND TRADEMARK OFFICE

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ELECTRONIC ACKNOWLEDGEMENT RECEIPT

APPLICATION #	RECEIPT DATE / TIME	ATTORNEY DOCKET #
18/927,698	**12/12/2024 03:54:49 PM Z ET**	**OMNI0101PUSA13**

Title of Invention

WEARABLE DEVICE FOR DIFFERENTIAL MEASUREMENT ON PULSE RATE AND BLOOD FLOW

Application Information

APPLICATION TYPE	Utility - Nonprovisional Application under 35 USC 111(a)	PATENT #	-
CONFIRMATION #	9133	FILED BY	Sharon Kaiser
PATENT CENTER #	68348664	FILING DATE	10/25/2024
CUSTOMER #	109543	FIRST NAMED INVENTOR	Mohammed N. ISLAM
CORRESPONDENCE ADDRESS	-	AUTHORIZED BY	Kevin Heinl

Documents

TOTAL DOCUMENTS: 16

DOCUMENT	PAGES	DESCRIPTION	SIZE (KB)
OMNI0101PUSA13_IDS_2_US_pubs_foreign.pdf	12	Information Disclosure Statement (IDS) Form (SB08)	1020 KB
JP2005270544.pdf	17	Foreign Reference	627 KB
DE102010012987.pdf	17	Foreign Reference	970 KB
WO2002028123.pdf	57	Foreign Reference	2929 KB
WO2009130464.pdf	76	Foreign Reference	3381 KB
WO2007061772.pdf	16	Foreign Reference	4867 KB
WO2001089362.pdf	137	Foreign Reference	5429 KB
WO2015084376.pdf	35	Foreign Reference	12840 KB
WO2013012938.pdf	35	Foreign Reference	14267 KB

WO2001050959.pdf	34	Foreign Reference	1413 KB
WO2005013843.pdf	38	Foreign Reference	12741 KB
WO1997015240.pdf	92	Foreign Reference	3080 KB
EP1148666.pdf	14	Foreign Reference	4889 KB
WO1997049340.pdf	18	Foreign Reference	5482 KB
WO2002027640.pdf	49	Foreign Reference	16845 KB
WO2012135952A1.pdf	85	Foreign Reference	25192 KB

Digest

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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.

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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.

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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
11 June 2015 (11.06.2015)

WIPO | PCT

(10) International Publication Number
WO 2015/084376 A1

(51) International Patent Classification:
A61B 5/024 (2006.01) *A61B 5/00* (2006.01)

(21) International Application Number:
PCT/US2013/073405

(22) International Filing Date:
5 December 2013 (05.12.2013)

(25) Filing Language: English

(26) Publication Language: English

(71) Applicant: **APPLE INC.** [US/US]; 1 Infinite Loop, Cupertino, California 95014 (US).

(72) Inventors: **HAN, Chin San**; c/o Apple Inc., 1 Infinite Loop, MS 83-T, Cupertino, California 95014 (US). **WANG, Albert**; c/o Apple Inc., 1 Infinite Loop, MS 83-D, Cupertino, California 95014 (US).

(74) Agents: **JONES, Stephen, C.** et al.; Morrison & Foerster LLP, 707 Wilshire Boulevard, Los Angeles, CA 90017 (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, LT, 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, 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).

Published:

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

(54) Title: WEARABLE MULTI-MODAL PHYSIOLOGICAL SENSING SYSEM

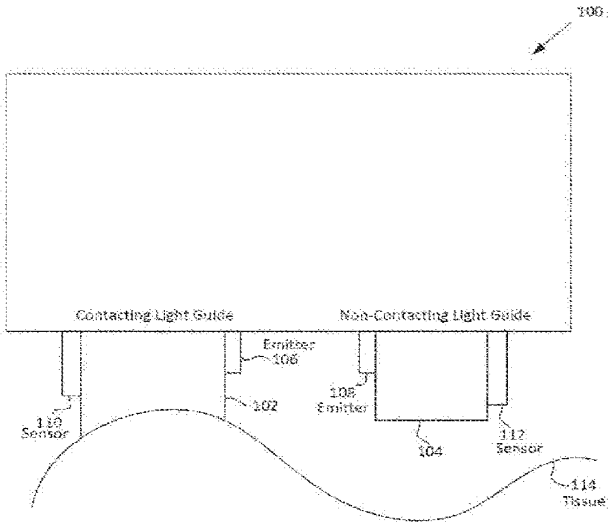


FIG. 1

(57) Abstract: A PPG signal may be obtained from a pulse oximeter, which employs a light emitter and a light sensor to measure the perfusion of blood to the skin of a user. However, the signal may be compromised by noise due to motion artifacts. To address the presence of motion artifacts, examples of the present disclosure can receive light information from each of two light guides, one in contact with the tissue of the user and one not in contact with the tissue of the user. First light information can be obtained from the first light guide, and second light information can be obtained from the second light guide. A heart rate signal can then be computed from the first and second light information, for example, by using blind source separation and/or cross-correlation.

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WEARABLE MULTI-MODAL PHYSIOLOGICAL SENSING SYSTEM

Field of the Disclosure

[0001] This relates generally to reducing motion artifacts from a physiological signal.

Background of the Disclosure

[0002] A photoplethysmogram (PPG) signal may be obtained from a pulse oximeter, which employs a light emitter and a light sensor to measure the perfusion of blood to the skin of a user. However, the signal may be compromised by noise due to motion artifacts. That is, movement of the body of a user may cause the skin and vasculature to expand and contract, introducing noise to the signal. Further, the device itself may move with respect to the body of the user, introducing further noise. To address the presence of motion artifacts, examples of the present disclosure can receive light information from each of two light guides, one in contact with the tissue of the user and one not in contact with the tissue of the user. First light information can be obtained from the first light guide, and second light information can be obtained from the second light guide. A heart rate signal can then be computed from the first and second light information, for example, by using blind source separation and/or cross-correlation.

Summary of the Disclosure

[0003] A photoplethysmogram (PPG) signal may be obtained from a pulse oximeter, which employs a light emitter and a light sensor to measure the perfusion of blood to the skin of a user. However, the signal may be compromised by noise due to motion artifacts. That is, movement of the body of a user may cause the skin and vasculature to expand and contract, introducing noise to the signal. Further, the device itself may move with respect to the body of the user, introducing further noise. To address the presence of motion artifacts, examples of the present disclosure can receive light information from each of two light guides, one in contact with the tissue of the user

and one not in contact with the tissue of the user. First light information can be obtained from the first light guide, and second light information can be obtained from the second light guide. A heart rate signal can then be computed from the first and second light information, for example, by using blind source separation and/or cross-correlation.

Brief Description of the Drawings

[0004] FIG. 1 illustrates an electronic device having light sensors for determining a heart rate signal according to examples of the disclosure.

[0005] FIG. 2 illustrates a method of computing a heart rate signal according to examples of the disclosure.

[0006] FIG. 3 illustrates a method of computing a heart rate signal according to examples of the disclosure.

[0007] FIG. 4 is a block diagram illustrating an exemplary API architecture, which may be used in some examples of the disclosure.

[0008] FIG. 5 illustrates an exemplary software stack of an API according to examples of the disclosure.

[0009] FIG. 6 is a block diagram illustrating exemplary interactions between the touch screen and other components of the device according to examples of the disclosure.

[0010] FIG. 7 is a block diagram illustrating an example of a system architecture that may be embodied within any portable or non-portable device according to examples of the disclosure.

Detailed Description

[0011] In the following description of examples, reference is made to the accompanying drawings which form a part hereof, and in which it is shown by way of illustration specific examples that can be practiced. It is to be understood that other examples can be used and structural changes can be made without departing from the scope of the disclosed examples.

[0012] A photoplethysmogram (PPG) signal may be obtained from a pulse oximeter, which employs a light emitter and a light sensor to measure the perfusion of

blood to the skin of a user. However, the signal may be compromised by noise due to motion artifacts. That is, movement of the body of a user may cause the skin and vasculature to expand and contract, introducing noise to the signal. Further, the device itself may move with respect to the body of the user, introducing further noise. To address the presence of motion artifacts, examples of the present disclosure can receive light information from each of two light guides, one in contact with the tissue of the user and one not in contact with the tissue of the user. First light information can be obtained from the first light guide, and second light information can be obtained from the second light guide. A heart rate signal can then be computed from the first and second light information, for example, by using blind source separation and/or cross-correlation.

[0013] Although examples disclosed herein may be described and illustrated herein primarily in terms of two sensors, emitters, and light guides, it should be understood that the examples are not so limited, but are additionally applicable to devices including any number and configuration of sensors, emitters, and light guides.

[0014] Examples of the disclosure are directed to a system for sensing and measurement of physiological signals that enables a signal decomposition approach to physiological measurements. That is, multiple signals may be obtained, and each signal may contain a physiological signal of interest (e.g., a heart rate signal)—each signal may also contain different noise components, and thus signal decomposition methods may be used to filter the noise and compute the signal of interest. Multiple sensing modalities optimized for the signal decomposition approach may provide robustness against non-signal artifacts commonly induced in wearable sensors, such as motion- or biologically-induced artifacts. Sensing modalities may include detection of physiological signals from optical sensors, force and pressure sensors, temperature sensors, accelerometers, proximity detectors, and/or impedance sensors, among other possibilities. In some examples, sensing modalities may include optical sensors including light guides in contact and not in contact with tissue of a user. Because the signal of interest may be compromised by noise due to motion of the device with respect to the tissue and also by noise due to motion of the tissue itself (e.g., the expansion and contraction of tissue and vasculature), different noise may be captured by sensors corresponding to each of contacting and non-contacting light guides, and signal decomposition methods (e.g., blind source separation) may be employed to separate the signal of interest from the noise.

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[0015] FIG. 1 illustrates an electronic device 100 having light sensors for determining a heart rate signal according to examples of the disclosure. A first light sensor 110 may be co-located with a contacting light guide 102 and a first light emitter 106. The contacting light guide 102 may be configured so as to be in contact with tissue 114 of a user, such as skin. For example, the contacting light guide 102 may be curved such that the surface is configured to contact tissue 114 of the user. In some examples, the contacting light guide 102 may jut out from the body of the electronic device 100 such that it is configured to contact tissue 114 of the user. A second light sensor 112 may be co-located with a non-contacting light guide 104 and a second light emitter 108. The non-contacting light guide 104 may be configured so as to not be in contact with tissue 114 of the user. In some examples, the non-contacting light guide 104 may be recessed with respect to the body of the electronic device 100 such that it is configured not to contact tissue 114 of the user.

[0016] The electronic device 100 may be situated such that the sensors 110 and 112, the emitters 106 and 108, and the light guides 102 and 104 are proximate the tissue 114 of the user, so that light from a light emitter may be directed through a light guide and be incident on the tissue. For example, the electronic device 100 may be held in a user's hand or strapped to a user's wrist, among other possibilities. A portion of the light from a light emitter may be absorbed by the skin, vasculature, and/or blood, among other possibilities, and a portion may be reflected back to a light sensor co-located with the light emitter. In some examples, light guides may direct light to tissue and/or back to a light sensor, and some emitters and sensors may direct light to and from tissue without a light guide.

[0017] FIG. 2 illustrates a method of computing a heart rate signal. Light may be emitted from a first light emitter through a contacting light guide (200). First light information may be received at a first light sensor through the contacting light guide (202). Similarly, light may be emitted from a second light emitter through a non-contacting light guide (204), and second light information may be received at a second light sensor through the non-contacting light guide (206). In some examples, a light emitter may emit light, the light may travel to the tissue of a user, and a portion of the light may reflect to a co-located light sensor, and some or all of the travel of the light may be directed by a light guide. Accordingly, the first light information may indicate an

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amount of light from a first light emitter that has been reflected by the skin, blood, and/or vasculature of the user, among other possibilities. In some examples, the first light information may indicate an amount of light from the first light emitter that has been absorbed by the skin, blood, and/or vasculature of the user.

[0018] The light emitters may produce light in ranges corresponding to infrared (IR), green, amber, blue, and/or red light, among other possibilities. Additionally, the light sensors may be configured to sense light having certain wavelengths more easily than light having other wavelengths. For example, if the first light emitter emits light having a wavelength in the IR range, then the first light sensor may be configured to sense light in the IR range more powerfully than light in the green range. That is, the incidence of light in the IR range may produce a stronger response in the first light sensor than the incidence of light in the green range. In this way, the first light sensor can be configured so as to sense the light produced by the first light emitter more powerfully than the light produced by the second light emitter, for example. In some examples, each light emitter may produce light in the same wavelength.

[0019] In some examples, a light emitter may be a light emitting diode (LED) and a light sensor may be a photodiode. The light information may include information produced by the photodiode. For example, the light information may include a voltage reading that corresponds to light absorbed by the photodiode. In some examples, the light information may include some transformation of raw signal produced by the photodiode, such as through filtering, scaling, or other signal processing.

[0020] Based on the first and second light information, a heart rate signal may be computed (206). For example, the first and second light information may be processed through blind source separation and/or cross-correlation methods. For example, the first and second light information may be processed with principal component analysis (one example method of blind source separation), to separate out a plurality of linearly uncorrelated component signals. Those components may then be further processed with a cross-correlation method, serving as a second filter, to compute a heart rate signal. In some examples, the first light information may include light information of red, green, and blue wavelengths, and the second light information may also include light information of red, green, and blue wavelengths, although any number and combination of wavelengths is possible. In some examples, the computed heart rate signal may

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include one or more additional signals, such as residual noise and/or a signal corresponding to a respiratory rate of a user, among other possibilities.

[0021] FIG. 3 illustrates a method of computing a heart rate signal based on multiple wavelengths of contacting and non-contacting light information. Red, green, and blue contacting light information (300) may be processed with blind source separation (e.g., principal component analysis, among other possibilities) (304). Further, red, green, and blue non-contacting light information (302) may be processed with blind source separation (306). The results of the contacting and non-contacting blind source separation processes may be cross-correlated (308), and the result may be a heart rate signal with reduced noise (310).

[0022] The examples discussed above can be implemented in one or more Application Programming Interfaces (APIs). An API is an interface implemented by a program code component or hardware component (hereinafter "API-implementing component") that allows a different program code component or hardware component (hereinafter "API-calling component") to access and use one or more functions, methods, procedures, data structures, classes, and/or other services provided by the API-implementing component. An API can define one or more parameters that are passed between the API-calling component and the API-implementing component.

[0023] The above-described features can be implemented as part of an application program interface (API) that can allow it to be incorporated into different applications (*e.g.*, spreadsheet apps) utilizing touch input as an input mechanism. An API can allow a developer of an API-calling component (which may be a third party developer) to leverage specified features, such as those described above, provided by an API-implementing component. There may be one API-calling component or there may be more than one such component. An API can be a source code interface that a computer system or program library provides in order to support requests for services from an application. An operating system (OS) can have multiple APIs to allow applications running on the OS to call one or more of those APIs, and a service (such as a program library) can have multiple APIs to allow an application that uses the service to call one or more of those APIs. An API can be specified in terms of a programming language that can be interpreted or compiled when an application is built.

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[0024] In some examples, the API-implementing component may provide more than one API, each providing a different view of the functionality implemented by the API-implementing component, or with different aspects that access different aspects of the functionality implemented by the API-implementing component. For example, one API of an API-implementing component can provide a first set of functions and can be exposed to third party developers, and another API of the API-implementing component can be hidden (not exposed) and provide a subset of the first set of functions and also provide another set of functions, such as testing or debugging functions which are not in the first set of functions. In other examples the API-implementing component may itself call one or more other components via an underlying API and thus be both an API-calling component and an API-implementing component.

[0025] An API defines the language and parameters that API-calling components use when accessing and using specified features of the API-implementing component. For example, an API-calling component accesses the specified features of the API-implementing component through one or more API calls or invocations (embodied for example by function or method calls) exposed by the API and passes data and control information using parameters via the API calls or invocations. The API-implementing component may return a value through the API in response to an API call from an API-calling component. While the API defines the syntax and result of an API call (e.g., how to invoke the API call and what the API call does), the API may not reveal how the API call accomplishes the function specified by the API call. Various API calls are transferred via the one or more application programming interfaces between the calling (API-calling component) and an API-implementing component. Transferring the API calls may include issuing, initiating, invoking, calling, receiving, returning, or responding to the function calls or messages; in other words, transferring can describe actions by either of the API-calling component or the API-implementing component. The function calls or other invocations of the API may send or receive one or more parameters through a parameter list or other structure. A parameter can be a constant, key, data structure, object, object class, variable, data type, pointer, array, list or a pointer to a function or method or another way to reference a data or other item to be passed via the API.

[0026] Furthermore, data types or classes may be provided by the API and implemented by the API-implementing component. Thus, the API-calling component

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may declare variables, use pointers to, use or instantiate constant values of such types or classes by using definitions provided in the API.

[0027] Generally, an API can be used to access a service or data provided by the API-implementing component or to initiate performance of an operation or computation provided by the API-implementing component. By way of example, the API-implementing component and the API-calling component may each be any one of an operating system, a library, a device driver, an API, an application program, or other module (it should be understood that the API-implementing component and the API-calling component may be the same or different type of module from each other). API-implementing components may in some cases be embodied at least in part in firmware, microcode, or other hardware logic. In some examples, an API may allow a client program to use the services provided by a Software Development Kit (SDK) library. In other examples an application or other client program may use an API provided by an Application Framework. In these examples the application or client program may incorporate calls to functions or methods provided by the SDK and provided by the API or use data types or objects defined in the SDK and provided by the API. An Application Framework may in these examples provide a main event loop for a program that responds to various events defined by the Framework. The API allows the application to specify the events and the responses to the events using the Application Framework. In some implementations, an API call can report to an application the capabilities or state of a hardware device, including those related to aspects such as input capabilities and state, output capabilities and state, processing capability, power state, storage capacity and state, communications capability, etc., and the API may be implemented in part by firmware, microcode, or other low level logic that executes in part on the hardware component.

[0028] The API-calling component may be a local component (i.e., on the same data processing system as the API-implementing component) or a remote component (i.e., on a different data processing system from the API-implementing component) that communicates with the API-implementing component through the API over a network. It should be understood that an API-implementing component may also act as an API-calling component (i.e., it may make API calls to an API exposed by a different API-implementing component) and an API-calling component may also act as an API-

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implementing component by implementing an API that is exposed to a different API-calling component.

[0029] The API may allow multiple API-calling components written in different programming languages to communicate with the API-implementing component (thus the API may include features for translating calls and returns between the API-implementing component and the API-calling component); however the API may be implemented in terms of a specific programming language. An API-calling component can, in one example, call APIs from different providers such as a set of APIs from an OS provider and another set of APIs from a plug-in provider and another set of APIs from another provider (e.g. the provider of a software library) or creator of the another set of APIs.

[0030] FIG. 4 is a block diagram illustrating an exemplary API architecture, which may be used in some examples of the disclosure. As shown in FIG. 4, the API architecture 600 includes the API-implementing component 610 (e.g., an operating system, a library, a device driver, an API, an application program, software or other module) that implements the API 620. The API 620 specifies one or more functions, methods, classes, objects, protocols, data structures, formats and/or other features of the API-implementing component that may be used by the API-calling component 630. The API 620 can specify at least one calling convention that specifies how a function in the API-implementing component receives parameters from the API-calling component and how the function returns a result to the API-calling component. The API-calling component 630 (e.g., an operating system, a library, a device driver, an API, an application program, software or other module), makes API calls through the API 620 to access and use the features of the API-implementing component 610 that are specified by the API 620. The API-implementing component 610 may return a value through the API 620 to the API-calling component 630 in response to an API call.

[0031] It will be appreciated that the API-implementing component 610 may include additional functions, methods, classes, data structures, and/or other features that are not specified through the API 620 and are not available to the API-calling component 630. It should be understood that the API-calling component 630 may be on the same system as the API-implementing component 610 or may be located remotely and accesses the API-implementing component 610 using the API 620 over a network. While FIG. 4 illustrates a single API-calling component 630 interacting with the API 620, it should be

understood that other API-calling components, which may be written in different languages (or the same language) than the API-calling component 630, may use the API 620.

[0032] The API-implementing component 610, the API 620, and the API-calling component 630 may be stored in a non-transitory machine-readable storage medium, which includes any mechanism for storing information in a form readable by a machine (e.g., a computer or other data processing system). For example, a machine-readable medium includes magnetic disks, optical disks, random access memory; read only memory, flash memory devices, etc.

[0033] In the exemplary software stack shown in FIG. 5, applications can make calls to Services A or B using several Service APIs and to Operating System (OS) using several OS APIs. Services A and B can make calls to OS using several OS APIs.

[0034] Note that the Service 2 has two APIs, one of which (Service 2 API 1) receives calls from and returns values to Application 1 and the other (Service 2 API 2) receives calls from and returns values to Application 2. Service 1 (which can be, for example, a software library) makes calls to and receives returned values from OS API 1, and Service 2 (which can be, for example, a software library) makes calls to and receives returned values from both OS API 1 and OS API 2. Application 2 makes calls to and receives returned values from OS API 2.

[0035] FIG. 6 is a block diagram illustrating exemplary interactions between the touch screen and the other components of the device. Described examples may include touch I/O device 1001 that can receive touch input for interacting with computing system 1003 via wired or wireless communication channel 1002. Touch I/O device 1001 may be used to provide user input to computing system 1003 in lieu of or in combination with other input devices such as a keyboard, mouse, etc. One or more touch I/O devices 1001 may be used for providing user input to computing system 1003. Touch I/O device 1001 may be an integral part of computing system 1003 (e.g., touch screen on a smartphone or a tablet PC) or may be separate from computing system 1003.

[0036] Touch I/O device 1001 may include a touch sensing panel which is wholly or partially transparent, semitransparent, non-transparent, opaque or any combination thereof. Touch I/O device 1001 may be embodied as a touch screen, touch pad, a touch

screen functioning as a touch pad (e.g., a touch screen replacing the touchpad of a laptop), a touch screen or touchpad combined or incorporated with any other input device (e.g., a touch screen or touchpad disposed on a keyboard) or any multi-dimensional object having a touch sensing surface for receiving touch input.

[0037] In one example, touch I/O device 1001 embodied as a touch screen may include a transparent and/or semitransparent touch sensing panel partially or wholly positioned over at least a portion of a display. According to this example, touch I/O device 1001 functions to display graphical data transmitted from computing system 1003 (and/or another source) and also functions to receive user input. In other examples, touch I/O device 1001 may be embodied as an integrated touch screen where touch sensing components/devices are integral with display components/devices. In still other examples a touch screen may be used as a supplemental or additional display screen for displaying supplemental or the same graphical data as a primary display and to receive touch input.

[0038] Touch I/O device 1001 may be configured to detect the location of one or more touches or near touches on device 1001 based on capacitive, resistive, optical, acoustic, inductive, mechanical, chemical measurements, or any phenomena that can be measured with respect to the occurrences of the one or more touches or near touches in proximity to device 1001. Software, hardware, firmware or any combination thereof may be used to process the measurements of the detected touches to identify and track one or more gestures. A gesture may correspond to stationary or non-stationary, single or multiple, touches or near touches on touch I/O device 1001. A gesture may be performed by moving one or more fingers or other objects in a particular manner on touch I/O device 1001 such as tapping, pressing, rocking, scrubbing, twisting, changing orientation, pressing with varying pressure and the like at essentially the same time, contiguously, or consecutively. A gesture may be characterized by, but is not limited to a pinching, sliding, swiping, rotating, flexing, dragging, or tapping motion between or with any other finger or fingers. A single gesture may be performed with one or more hands, by one or more users, or any combination thereof.

[0039] Computing system 1003 may drive a display with graphical data to display a graphical user interface (GUI). The GUI may be configured to receive touch input via touch I/O device 1001. Embodied as a touch screen, touch I/O device 1001 may display the GUI. Alternatively, the GUI may be displayed on a display separate from touch I/O

device 1001. The GUI may include graphical elements displayed at particular locations within the interface. Graphical elements may include but are not limited to a variety of displayed virtual input devices including virtual scroll wheels, a virtual keyboard, virtual knobs, virtual buttons, any virtual UI, and the like. A user may perform gestures at one or more particular locations on touch I/O device 1001 which may be associated with the graphical elements of the GUI. In other examples, the user may perform gestures at one or more locations that are independent of the locations of graphical elements of the GUI. Gestures performed on touch I/O device 1001 may directly or indirectly manipulate, control, modify, move, actuate, initiate or generally affect graphical elements such as cursors, icons, media files, lists, text, all or portions of images, or the like within the GUI. For instance, in the case of a touch screen, a user may directly interact with a graphical element by performing a gesture over the graphical element on the touch screen. Alternatively, a touch pad generally provides indirect interaction. Gestures may also affect non-displayed GUI elements (e.g., causing user interfaces to appear) or may affect other actions within computing system 1003 (e.g., affect a state or mode of a GUI, application, or operating system). Gestures may or may not be performed on touch I/O device 1001 in conjunction with a displayed cursor. For instance, in the case in which gestures are performed on a touchpad, a cursor (or pointer) may be displayed on a display screen or touch screen and the cursor may be controlled via touch input on the touchpad to interact with graphical objects on the display screen. In other examples in which gestures are performed directly on a touch screen, a user may interact directly with objects on the touch screen, with or without a cursor or pointer being displayed on the touch screen.

[0040] Feedback may be provided to the user via communication channel 1002 in response to or based on the touch or near touches on touch I/O device 1001. Feedback may be transmitted optically, mechanically, electrically, olfactory, acoustically, or the like or any combination thereof and in a variable or non-variable manner.

[0041] Attention is now directed towards examples of a system architecture that may be embodied within any portable or non-portable device including but not limited to a communication device (e.g. mobile phone, smart phone), a multi-media device (e.g., MP3 player, TV, radio), a portable or handheld computer (e.g., tablet, netbook, laptop), a desktop computer, an All-In-One desktop, a peripheral device, or any other system or

device adaptable to the inclusion of system architecture 2000, including combinations of two or more of these types of devices. FIG. 7 is a block diagram of one example of system 2000 that generally includes one or more computer-readable mediums 2001, processing system 2004, I/O subsystem 2006, radio frequency (RF) circuitry 2008, audio circuitry 2010, and sensors circuitry 2011. These components may be coupled by one or more communication buses or signal lines 2003.

[0042] It should be apparent that the architecture shown in FIG. 7 is only one example architecture of system 2000, and that system 2000 could have more or fewer components than shown, or a different configuration of components. The various components shown in FIG. 7 can be implemented in hardware, software, firmware or any combination thereof, including one or more signal processing and/or application specific integrated circuits.

[0043] RF circuitry 2008 can be used to send and receive information over a wireless link or network to one or more other devices and includes well-known circuitry for performing this function. RF circuitry 2008 and audio circuitry 2010 can be coupled to processing system 2004 via peripherals interface 2016. Interface 2016 can include various known components for establishing and maintaining communication between peripherals and processing system 2004. Audio circuitry 2010 can be coupled to audio speaker 2050 and microphone 2052 and can include known circuitry for processing voice signals received from interface 2016 to enable a user to communicate in real-time with other users. In some examples, audio circuitry 2010 can include a headphone jack (not shown). Sensors circuitry 2011 can be coupled to various sensors including, but not limited to, one or more Light Emitting Diodes (LEDs) or other light emitters, one or more photodiodes or other light sensors, one or more photothermal sensors, a magnetometer, an accelerometer, a gyroscope, a barometer, a compass, a proximity sensor, a camera, an ambient light sensor, a thermometer, a GPS sensor, and various system sensors which can sense remaining battery life, power consumption, processor speed, CPU load, and the like.

[0044] Peripherals interface 2016 can couple the input and output peripherals of the system to processor 2018 and computer-readable medium 2001. One or more processors 2018 communicate with one or more computer-readable mediums 2001 via controller 2020. Computer-readable medium 2001 can be any device or medium that can

store code and/or data for use by one or more processors 2018. In some examples, medium 2001 can be a non-transitory computer-readable storage medium. Medium 2001 can include a memory hierarchy, including but not limited to cache, main memory and secondary memory. The memory hierarchy can be implemented using any combination of RAM (*e.g.*, SRAM, DRAM, DDRAM), ROM, FLASH, magnetic and/or optical storage devices, such as disk drives, magnetic tape, CDs (compact disks) and DVDs (digital video discs). Medium 2001 may also include a transmission medium for carrying information-bearing signals indicative of computer instructions or data (with or without a carrier wave upon which the signals are modulated). For example, the transmission medium may include a communications network, including but not limited to the Internet (also referred to as the World Wide Web), intranet(s), Local Area Networks (LANs), Wide Local Area Networks (WLANs), Storage Area Networks (SANs), Metropolitan Area Networks (MAN) and the like.

[0045] One or more processors 2018 can run various software components stored in medium 2001 to perform various functions for system 2000. In some examples, the software components can include operating system 2022, communication module (or set of instructions) 2024, touch processing module (or set of instructions) 2026, graphics module (or set of instructions) 2028, and one or more applications (or set of instructions) 2030. Each of these modules and above noted applications can correspond to a set of instructions for performing one or more functions described above and the methods described in this application (e.g., the computer-implemented methods and other information processing methods described herein). These modules (i.e., sets of instructions) need not be implemented as separate software programs, procedures or modules, and thus various subsets of these modules may be combined or otherwise re-arranged in various examples. In some examples, medium 2001 may store a subset of the modules and data structures identified above. Furthermore, medium 2001 may store additional modules and data structures not described above.

[0046] Operating system 2022 can include various procedures, sets of instructions, software components and/or drivers for controlling and managing general system tasks (*e.g.*, memory management, storage device control, power management, *etc.*) and facilitates communication between various hardware and software components.

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[0047] Communication module 2024 can facilitate communication with other devices over one or more external ports 2036 or via RF circuitry 2008 and can include various software components for handling data received from RF circuitry 2008 and/or external port 2036.

[0048] Graphics module 2028 can include various known software components for rendering, animating and displaying graphical objects on a display surface. In examples in which touch I/O device 2012 is a touch sensing display (e.g., touch screen), graphics module 2028 can include components for rendering, displaying, and animating objects on the touch sensing display.

[0049] One or more applications 2030 can include any applications installed on system 2000, including without limitation, a browser, address book, contact list, email, instant messaging, word processing, keyboard emulation, widgets, JAVA-enabled applications, encryption, digital rights management, voice recognition, voice replication, location determination capability (such as that provided by the global positioning system (GPS)), a music player, *etc.*

[0050] Touch processing module 2026 can include various software components for performing various tasks associated with touch I/O device 2012 including but not limited to receiving and processing touch input received from I/O device 2012 via touch I/O device controller 2032.

[0051] I/O subsystem 2006 can be coupled to touch I/O device 2012 and one or more other I/O devices 2014 for controlling or performing various functions. Touch I/O device 2012 can communicate with processing system 2004 via touch I/O device controller 2032, which can include various components for processing user touch input (*e.g.*, scanning hardware). One or more other input controllers 2034 can receive/send electrical signals from/to other I/O devices 2014. Other I/O devices 2014 may include physical buttons, dials, slider switches, sticks, keyboards, touch pads, additional display screens, or any combination thereof.

[0052] If embodied as a touch screen, touch I/O device 2012 can display visual output to the user in a GUI. The visual output may include text, graphics, video, and any combination thereof. Some or all of the visual output may correspond to user-interface objects. Touch I/O device 2012 can form a touch sensing surface that accepts touch input

from the user. Touch I/O device 2012 and touch screen controller 2032 (along with any associated modules and/or sets of instructions in medium 2001) can detect and track touches or near touches (and any movement or release of the touch) on touch I/O device 2012 and can convert the detected touch input into interaction with graphical objects, such as one or more user-interface objects. In the case in which device 2012 is embodied as a touch screen, the user can directly interact with graphical objects that are displayed on the touch screen. Alternatively, in the case in which device 2012 is embodied as a touch device other than a touch screen (e.g., a touch pad), the user may indirectly interact with graphical objects that are displayed on a separate display screen embodied as I/O device 2014.

[0053] Touch I/O device 2012 may be analogous to the multi-touch sensing surface described in the following U.S. Patents: 6,323,846 (Westerman et al.), 6,570,557 (Westerman et al.), and/or 6,677,932 (Westerman), and/or U.S. Patent Publication 2002/0015024A1, each of which is hereby incorporated by reference.

[0054] In examples for which touch I/O device 2012 is a touch screen, the touch screen may use LCD (liquid crystal display) technology, LPD (light emitting polymer display) technology, OLED (organic LED), or OEL (organic electro luminescence), although other display technologies may be used in other examples.

[0055] Feedback may be provided by touch I/O device 2012 based on the user's touch input as well as a state or states of what is being displayed and/or of the computing system. Feedback may be transmitted optically (e.g., light signal or displayed image), mechanically (e.g., haptic feedback, touch feedback, force feedback, or the like), electrically (e.g., electrical stimulation), olfactory, acoustically (e.g., beep or the like), or the like or any combination thereof and in a variable or non-variable manner.

[0056] System 2000 can also include power system 2044 for powering the various hardware components and may include a power management system, one or more power sources, a recharging system, a power failure detection circuit, a power converter or inverter, a power status indicator and any other components typically associated with the generation, management and distribution of power in portable devices.

[0057] In some examples, peripherals interface 2016, one or more processors 2018, and memory controller 2020 may be implemented on a single chip, such as

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processing system 2004. In some other examples, they may be implemented on separate chips.

[0058] Examples of the disclosure can be advantageous in allowing for an electronic device to obtain a heart rate signal with reduced noise due to motion artifacts, making for a more accurate reading of heart rate.

[0059] In some examples, a method of an electronic device including a plurality of light emitters, a plurality of light sensors, and a plurality of light guides is disclosed. The method may include: emitting light from each of the plurality of light emitters through respective light guides, wherein a contacting light guide may be configured to contact tissue of a user and a non-contacting light may be configured not to contact tissue of the user; receiving first light information from the contacting light guide; receiving second light information from the non-contacting light guide; and computing a heart rate signal based on the first and second light information. Additionally or alternatively to one or more of the above examples, a surface of the contacting light guide may be curved such that the surface is configured to contact tissue of the user. Additionally or alternatively to one or more of the above examples, the non-contacting light guide may be recessed with respect to the electronic device such that the non-contacting light guide may be configured not to contact tissue of the user. Additionally or alternatively to one or more of the above examples, computing the heart rate signal based on the first and second light information may include performing blind source separation on the first and second light information. Additionally or alternatively to one or more of the above examples, computing the heart rate signal based on the first and second light information may include performing cross-correlation on the first and second light information. Additionally or alternatively to one or more of the above examples, emitting light through the contacting light guide may include emitting light of a plurality of wavelengths through the contacting light guide; and wherein computing the heart rate signal may include performing blind source separation on light information of the plurality of wavelengths. Additionally or alternatively to one or more of the above examples, the plurality of wavelengths may include wavelengths of red, green, and blue light. Additionally or alternatively to one or more of the above examples, one or more of the plurality of light sensors may be in contact with respective light guides through which

light is sensed, and one or more of the plurality of light sensors may be not in contact with respective light guides through which light is sensed.

[0060] In some examples, a non-transitory computer readable medium is disclosed. The non-transitory computer readable medium may contain instructions that, when executed, perform a method of an electronic device including a plurality of light emitters, a plurality of light sensors, and a plurality of light guides. The method may include: emitting light from each of the plurality of light emitters through respective light guides, wherein a contacting light guide may be configured to contact tissue of a user and a non-contacting light may be configured not to contact tissue of the user; receiving first light information from the contacting light guide; receiving second light information from the non-contacting light guide; and computing a heart rate signal based on the first and second light information. Additionally or alternatively to one or more of the above examples, a surface of the contacting light guide may be curved such that the surface is configured to contact tissue of the user. Additionally or alternatively to one or more of the above examples, the non-contacting light guide may be recessed with respect to the electronic device such that the non-contacting light guide may be configured not to contact tissue of the user. Additionally or alternatively to one or more of the above examples, computing the heart rate signal based on the first and second light information may include performing blind source separation on the first and second light information. Additionally or alternatively to one or more of the above examples, computing the heart rate signal based on the first and second light information may include performing cross-correlation on the first and second light information. Additionally or alternatively to one or more of the above examples, emitting light through the contacting light guide may include emitting light of a plurality of wavelengths through the contacting light guide; and wherein computing the heart rate signal may include performing blind source separation on light information of the plurality of wavelengths. Additionally or alternatively to one or more of the above examples, the plurality of wavelengths may include wavelengths of red, green, and blue light. Additionally or alternatively to one or more of the above examples, one or more of the plurality of light sensors may be in contact with respective light guides through which light is sensed, and one or more of the plurality of light sensors may be not in contact with respective light guides through which light is sensed.

[0061] In some examples, an electronic device is disclosed. The electronic device may include: a processor to execute instructions; a plurality of light emitters; a plurality of light sensors; a plurality of light guides; and a memory coupled with the processor to store instructions, which when executed by the processor, may cause the processor to perform operations to generate an application programming interface (API) that allows an API-calling component to perform a method. The method may include: emitting light from each of the plurality of light emitters through respective light guides, wherein a contacting light guide may be configured to contact tissue of a user and a non-contacting light may be configured not to contact tissue of the user; receiving first light information from the contacting light guide; receiving second light information from the non-contacting light guide; and computing a heart rate signal based on the first and second light information. Additionally or alternatively to one or more of the above examples, a surface of the contacting light guide may be curved such that the surface is configured to contact tissue of the user. Additionally or alternatively to one or more of the above examples, the non-contacting light guide may be recessed with respect to the electronic device such that the non-contacting light guide may be configured not to contact tissue of the user. Additionally or alternatively to one or more of the above examples, computing the heart rate signal based on the first and second light information may include performing blind source separation on the first and second light information. Additionally or alternatively to one or more of the above examples, computing the heart rate signal based on the first and second light information may include performing cross-correlation on the first and second light information. Additionally or alternatively to one or more of the above examples, emitting light through the contacting light guide may include emitting light of a plurality of wavelengths through the contacting light guide; and wherein computing the heart rate signal may include performing blind source separation on light information of the plurality of wavelengths. Additionally or alternatively to one or more of the above examples, the plurality of wavelengths may include wavelengths of red, green, and blue light. Additionally or alternatively to one or more of the above examples, one or more of the plurality of light sensors may be in contact with respective light guides through which light is sensed, and one or more of the plurality of light sensors may be not in contact with respective light guides through which light is sensed.

[0062] Although the disclosed examples have been fully described with reference to the accompanying drawings, it is to be noted that various changes and modifications will become apparent to those skilled in the art. Such changes and modifications are to be understood as being included within the scope of the disclosed examples as defined by the appended claims.

WHAT IS CLAIMED IS:

1. A method of an electronic device including a plurality of light emitters, a plurality of light sensors, and a plurality of light guides, the method comprising:

emitting light from each of the plurality of light emitters through respective light guides, wherein a contacting light guide is configured to contact tissue of a user and a non-contacting light is configured not to contact tissue of the user;

receiving first light information from the contacting light guide;

receiving second light information from the non-contacting light guide; and

computing a heart rate signal based on the first and second light information.

2. The method of claim 1, wherein a surface of the contacting light guide is curved such that the surface is configured to contact tissue of the user.

3. The method of claim 1, wherein the non-contacting light guide is recessed with respect to the electronic device such that the non-contacting light guide is configured not to contact tissue of the user.

4. The method of claim 1, wherein computing the heart rate signal based on the first and second light information includes performing blind source separation on the first and second light information.

5. The method of claim 1, wherein computing the heart rate signal based on the first and second light information includes performing cross-correlation on the first and second light information.

6. The method of claim 1, wherein emitting light through the contacting light guide includes emitting light of a plurality of wavelengths through the contacting light guide; and

wherein computing the heart rate signal includes performing blind source separation on light information of the plurality of wavelengths.

7. The method of claim 6, wherein the plurality of wavelengths include wavelengths of red, green, and blue light.

8. The method of claim 1, wherein one or more of the plurality of light sensors are in contact with respective light guides through which light is sensed, and one or more of the plurality of light sensors are not in contact with respective light guides through which light is sensed.

9. A non-transitory computer readable medium, the computer readable medium containing instructions that, when executed, perform a method of an electronic device including a plurality of light emitters, a plurality of light sensors, and a plurality of light guides, the method comprising:

emitting light from each of the plurality of light emitters through respective light guides, wherein a contacting light guide is configured to contact tissue of a user and a non-contacting light is configured not to contact tissue of the user;

receiving first light information from the contacting light guide;

receiving second light information from the non-contacting light guide; and

computing a heart rate signal based on the first and second light information.

10. The non-transitory computer readable medium of claim 9, wherein a surface of the contacting light guide is curved such that the surface is configured to contact tissue of the user.

11. The non-transitory computer readable medium of claim 9, wherein the non-contacting light guide is recessed with respect to the electronic device such that the non-contacting light guide is configured not to contact tissue of the user.

12. The non-transitory computer readable medium of claim 9, wherein computing the heart rate signal based on the first and second light information includes performing blind source separation on the first and second light information.

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