

## Wearable approach for continuous ECG – and Activity Patient-Monitoring

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**Abstract**---The paper describes an approach to monitor a person's ECG and activity continuously with functional clothing. A belt with integrated electronics has been developed and has proven long-term robustness of all electrical components. A low-power module measures the ECG signal as well as the acceleration (2-axis) and stores data continuously up to two days. A user test has been performed to evaluate the belt according to system performance at different daily-life activities like sleeping, walking and so on. System parameters are ECG-signal quality, system up-time, and ECG-signal coverage during a day.

**Keywords**---personal health care, wearable technology, continuous monitoring, dry electrodes

### I. Introduction

In all developed countries, cardio-vascular diseases like myocardial infarction and congestive heart failure have an increasing impact in societies on mortality and morbidity [1]. There is an increasing demand for long term continuous monitoring of a patient's ECG and activity, which offers the opportunity to evaluate the performance of the cardio-vascular system. The ECG signal is a parameter that is easily accessible in theory by placing electrodes on the patient's body. However, the state of the art devices for cardiac monitoring are clumsy and too uncomfortable for long-term use and most of them were designed to sell to clinical professionals, losing the end-user viewpoint.

An ideal monitoring system should measure relevant medical parameters with almost no impact on quality of life. Realizing this idea it is a natural approach to use items of clothing with integrated sensors. Clothing is a daily part of our life and in close contact to the signal source. For measuring ECG signals classical medical electrodes have excellent electrical properties but they are normally fixed to the skin by an adhesive, which can cause irritation and is incompatible with a wearable textile approach. Therefore, dry electrodes, which have sufficient electrical properties and can be easily integrated into textiles, had to be developed and characterized. For this, opposing technologies had to be brought together: "soft" textile and "hard" electronic circuits. Additionally, besides classical criteria for a textile like comfort and fashion the designer also has to also ensure the new functionality in the design process. The complex design aspects, which can be seen in figure 1, are e.g. the placement of electrodes on the body with an appropriate contact pressure, the integration of electrical components like cables and connectors and finding a suitable position of the electronic components, which is comfortable in most daily life situations. The system

performance (signal quality, system up time, etc.) has to be evaluated to show the suitability of the wearable approach.

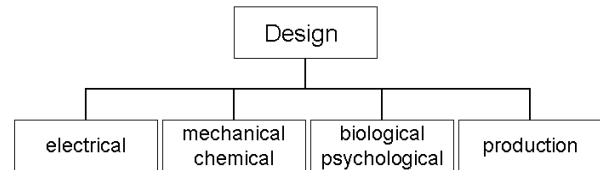


Fig. 1. Complexity of design criteria of functional clothes with sensor functionalities

### II. Technologies and Measurement set-up

The measurement set-up consists of:

- A wearable device (belt) with three integrated dry electrodes, shielded cables, connector to the module PCB.
- Module with ECG-amplifier, 2 axis acceleration sensor and storage capacity of 64MB, RS232 connection to transfer data from module to a PC.
- Data evaluation and visualization software based on Matlab; three variants of QRS – detectors (peak detector, modified filter bank [2] and modified wavelet approach [3]).
- Annotation of user activities by dictaphones

#### A. Wearable design

A belt has been developed with three integrated dry electrodes (Figure 2). The electrodes, which are based on carbon-loaded rubber, are fixed into a garment using a thermal moulding process. To transmit the ECG signal from the body surface to the module PCB a very thin and flexible shielded cable is anchored in the rubber of each electrode. To remove the module from the belt a specially designed connector is integrated, which is very flat, robust and easy to operate.

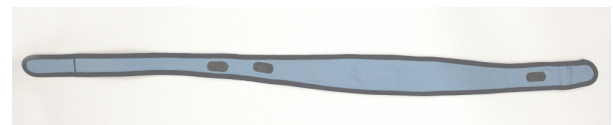


Fig. 2. wearable belt approach with three integrated dry electrodes for monitoring patient's ECG and activity

All system parts of the belt have proven sufficient robustness (more than 30 washing cycles at 40°C, washing machine, drying in air).

## B. Module PCB

The PCB has a one-lead ECG – amplifier unit with a driven right leg circuit (third electrode) and a 2-axis acceleration sensor (Analog Devices ADXL 202, 4g, dynamic and static). The digital part of the PCB performs a 12bit AD-conversion of the sensor signals (ECG: 100Hz sampling frequency, acceleration: 10Hz sampling frequency) and stores the data in 64 MB flash memory. In total the electronic is in size: 28 mm x 75 mm x 3 mm. The battery capacity allows measuring for at least 7 days continuously in a typical operation mode. Data is transmitted to a PC via the RS232 interface.

## C. Belt positions on the body

The picture (3) shows a person wearing the belt. The position can be chosen around and below the chest. The electrodes are located at the hips, which guarantees a sufficient contact pressure most of the time. The module is positioned at the back inside the textile accessible by a zip. The two axes of the acceleration sensor are shown in figure (3).

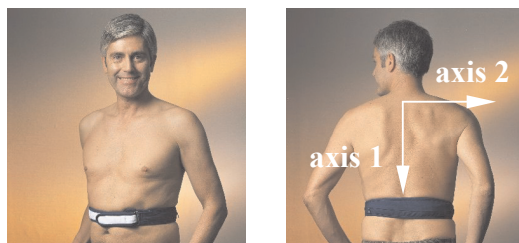


Fig. 3. Patient wearing the monitoring belt, the electronics package is placed on the back. In the right picture the direction of the two axes for measuring the acceleration are shown

## D. Data evaluation

Software has been developed to visualize and evaluate the data in a Matlab environment. Heart rate was calculated using the output of three different QRS-detectors based on peak-detection, a modified filter bank of [2] and a modified wavelet approach of [3]. The performance of two detectors was verified with the annotated MIT-BIH-Arrhythmia-database. Results are given in table 1:

|                  | Sensitivity [%] | Positive Predictivity [%] |
|------------------|-----------------|---------------------------|
| Filter bank      | 97.09           | 99.55                     |
| Wavelet approach | 99.13           | 99.30                     |

Table. 1. Performance parameter (sensitivity, positive predictivity) of three different algorithms detecting the QRS – complex (MIT database)

We say the signal quality was “good” if the detected heart rate could be detected and fell within the “normal range” between 40...190 beats per minute with a heart rate variability of <20%. A noisy signal would result in higher measured heart rate variability. Due to the nature of the algorithm used, this is a rather pessimistic measure, as the

detector discarded 5 beats in a row if any single above condition was met.

The mean activity level of a subject was calculated with a full wave rectifier approach.

## E. Design of User test

12 volunteers (11 male, 1 female) were assigned to wear the belt continuously for 2 days including practically all activities. They were allowed to remove the belt for showering only. The position could be chosen between waist and chest according to personal comfort preferences. The subjects were advised to annotate their activities with a dictaphone in order to obtain synchronous logging of ECG and acceleration data as well as subject activities (example categories were: sitting, standing, walking, driving, fitness, sleeping).

After the test was finished subjects were ask to evaluate the belt design for comfort, usability and design.

## III. Results and Discussion

### F. ECG – detection with dry rubber electrodes

After the belt had been placed on the body it typically took about 3min...15min to get an ECG signal with sufficient signal-to-noise ratio depending on the subject (skin type) and previous activity level (sweating). This delay at the beginning is given by the time in which the electrical properties of the skin-electrode contact changes due to the sweat glands filling, reducing the skin-electrode impedance. In equilibrium the skin-electrode impedance range at 1 Hz is about 50...300 kΩ. After the equilibrium is reached, slight repositioning of the electrodes results only in minor impedance variation due to a “sweat memory” with a shorter recovery time. Increasing the input impedance of the circuit may shorten the initial dead time of the system.

Figure (4) shows the ECG signal (left: chest, right: waist) of a test subject at rest.

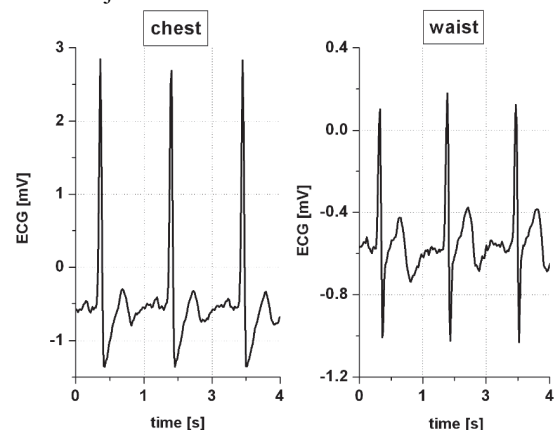


Fig. 4. ECG traces of a person at rest measured with the wearable system; left figure: chest V=3mV; right figure: V=1mV; The typical QRS-signal structure as well as the T-wave can be seen.

All typical signal parameters like the QRS-complex and T-wave can be seen even in the waist signal with its decreased signal amplitude (max-min) by a factor of 3...10 compared to the chest. Because the belt position is not fixed to the body by any constraints there is no constant ECG-projection, causing slight morphological variations. Additionally, ECG signal strength as well as the shape changes if lying on the back or front, left and right side, and standing due to movement of the heart in the gravity field. The noise level increases with increasing skin-electrode impedance, which is prominent especially for patients with strong hair growth. Still, for all subjects the signal quality was sufficient to detect heart rate from the waist. This proves the feasibility of a belt-type wearable monitoring system, which can be worn comfortably around the waist.

Typical traces of ECG and acceleration signals measured during a day with normal subject activity are shown in the middle and lower part in figure (5).

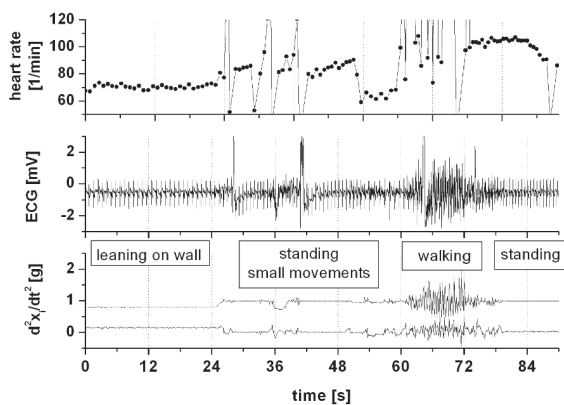


Fig. 5. Typical ECG-trace (middle diagram) and acceleration signals (lower diagram) of a patient wearing the belt on the waist; The heart rate in the upper diagram was calculated using the peak detector. Movement artefact on the ECG signal is apparent.

The subject wore the belt on the waist. The electrode positions were at the hips. From 0...26s the patient was leaning against a wall. This shows in the acceleration signals, the projection of the 1g gravity vector onto both axes. The heart rate is about  $73\text{min}^{-1}$ , calculated by the peak detector.

In the second state the patient was standing (full projection of 1g on one axis) with small movements. This caused artefact in the ECG signal in some cases and clearly gave a few wrong heart rate results. During the third state the patient did a short fast walk in the room. The movements cause strong movements artefacts in the ECG, which make it impossible to calculate the heart rate during this period. In the last phase the patient was again standing at rest and the heart rate was about  $112\text{min}^{-1}$ . After 84 s heart rate decreases due to the recovery of the cardio-vascular system, which is well visible in the plot.

As shown, the dry electrodes induce motion artefacts in the ECG-signal. Attempts to compensate motion artefacts using the acceleration data failed in most cases probably due to the

different position of acceleration sensor and electrodes and additional noise sources like the electromyogram (EMG). Movement artefacts can be strongly decreased by an increased contact pressure of the dry electrodes to the body by a stronger fastening of the belt, but this is also limited due to the comfort aspects.

### G. Activity level

In figure (6) the lower diagram shows the acceleration measured at the back of a subject while walking slowly, normally and quickly. The results of the activity detection algorithm can be seen in the upper part. Depending on the level of activity (slow, normal, fast) an activity measure can be calculated. The states "at rest" and "active" were discriminated by defining a threshold value a).

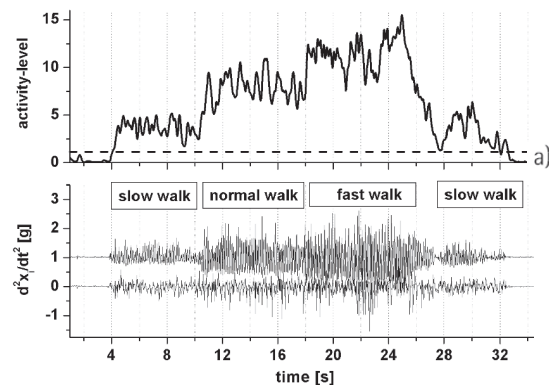


Fig. 6. Lower diagram: acceleration measured during slow, normal and fast walk; upper diagram: calculated activity level; threshold a) discriminates states of rest and activity

### H. System performance

A user test was conducted with 12 subjects. They wore the device for at least two days. Objectives were to evaluate the belt design and system performance in normal life including sleeping and fitness activities. No subjects had complaints about skin irritation and all preferred the belt position on the waist versus the chest.

**Robustness:** No belt showed changes in electrical properties of the electrode/cable/connector construction. Each belt was washed with the pcb removed at least 30 times at  $40^{\circ}\text{C}$  in a standard home washing machine with standard detergent and was dried in free air. Washing has no significant effect on the ECG signal quality.

#### Signal coverage:

The performance of the system was evaluated by measuring the time in which the heart rate was detected as "good" as defined in section D. The ratio of the duration of detected good heart rate and total measurement time (called "good signal" coverage) gives a measure of the system performance.

Figure (7) shows the “good”-signal coverage (average of all subjects) getting a detectable ECG signal for three different heart rate detectors. These measures were also modified in a way that if positive activity was detected, this period could also be counted as “good” because the source of error was clearly known. Therefore, the coverage rose around 5%, the typical value of detectable activity over a day.

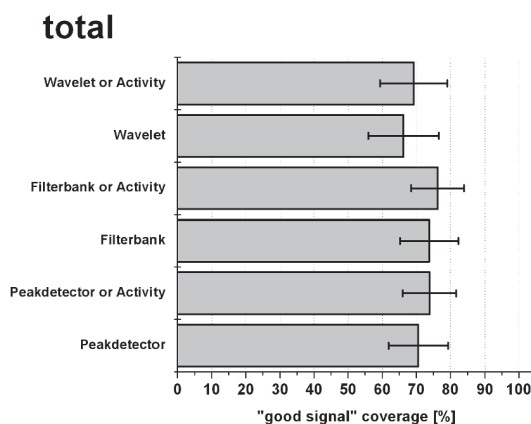


Fig. 7. Average value of good signal coverage [%] during a 24h-day; three heart rate detectors; detecting heart rate or activity shows only a mirror increase

On average about 70% of a full 24h-day (16.8h) was covered by the monitoring system analysing only the ECG-signal (peak detector:  $70 \pm 10$  %, filter bank:  $72 \pm 9$  %, wavelet:  $70 \pm 10$  %). There is no significant difference in the performance of the ECG-detectors.

One contribution of the signal loss is from little movements during the day (stand up, sit down, short walk, etc.) of the subject, which typically yield to ECG-signal loss of about 5...10s a time. In general there are 10...40 events per hour, which sum up to 1min...8min per hour. This means during 16 hours of an active day there is an amount of about 10 % of bad signal time (2 hours) due to little movements.

Additionally, the time ratio in which either the heart rate or a person's activity could be detected was calculated. The coverage increased by the average time of detected activity (peak detector:  $74 \pm 10$  %, filter bank:  $76 \pm 9$  %, wavelet:  $74 \pm 10$  %). About 30 % of a day is thus not covered by the system. Most of this loss is due to larger periods of signal loss during sleep, as illustrated in the following.

Figure (8) shows the results for good signal coverage during sleep. On average the portion of “good signal” is  $60 \pm 22$  %. Because there are almost no movements during night there is no additional increase of signal-coverage if gated with detected activity. Analysing the ECG-signals while sleeping shows that the electrodes often get displaced from the skin due to deformation of the body. This indicates that the belt design apparently does not ensure a sufficient contact pressure at night.

## sleep

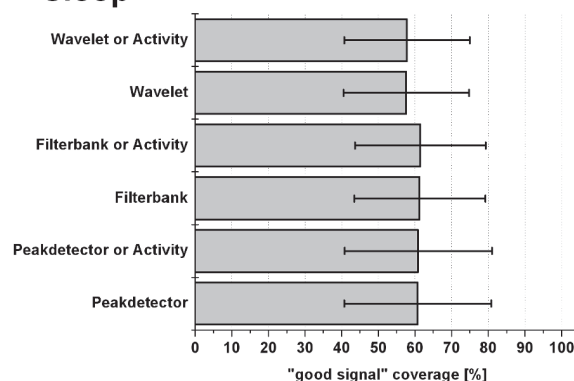


Fig. 8. Average value of good signal coverage [%] during sleep, which is a subset of the data used for the total validation figures. Interestingly, values are lower during night. This has to do with suboptimal belt design.

## IV. Conclusion

A wearable electronics approach for monitoring applications has been realized and evaluated. It is suited to monitor a person's ECG and activity during normal life. The textile can be used and handled like normal clothing, including washing. Dry electrodes have been developed which can be integrated into textiles. They need no additional electrode paste for operation. It is possible getting a sufficient signal quality with these electrodes especially at rest, but they are susceptible for motion artifacts that limit the system performance.

In general, the textile design is highly accepted by subjects but there are some points for improvements. Coverage of ECG-signal detection (70 % of a day, 60 % during sleep) should be increased especially at night. Also, more elaborate activity detection and classification should be possible after further investigations. This is subject to continuing research.

[1] American Heart Association, *Heart and Stroke statistical update*, 2004

[2] Afonso, V. X.; Topkins, W. J.; Nguyen, T. Q.; Luo, S.: *ECG Beat Detection using Filter Banks In: IEEE Transactions on Biomedical Engineering, Jg. 1999, S. 192-202*

[3] C. Li, C. Zheng, C. Tai, *Detection of ECG Characteristics Points Using Wavelet Transforms*, IEEE Transactions on Biomedical Engineering, Vol. 42, No. 1, January 1995, 21-28