Electrode Comparison for Textile-Integrated Electrocardiogram and Impedance Pneumography Measurement

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Abstract— **Wearable electronics is a quickly broadening category in sports, wellbeing and entertainment products. Also, fully textile-integrated electronics is used increasingly to improve user experience. Medical industry is interested in exploiting, especially the latter sub-category of wearable electronics in long-term home care. In this study, we report a textile-integrated electrocardiography (ECG) and impedance pneumography (IP) measurement system. The performance of the system is evaluated by comparing the measurement accuracy for heart rate and respiration rate obtained with different electrode types and different measurement methods. Three electrode types: disposable, textile, and printed electrodes, are investigated and both, bipolar and tetrapolar measurement methods are compared by using a modified commercial evaluation board. Disposable electrodes provide the least noisy signal and the most stable results. However, the skin irritation caused by these electrodes prevents their use in long-term monitoring. The textile and printed electrodes did not seem to cause similar skin irritation. From the two measuring techniques, tetrapolar measuring method had higher noise levels, but heart rate and breathing were estimated with better accuracy compared to bipolar measuring method.**

Keywords— **medical analog front-end, electrocardiogram, impedance pneumography, textile-integrated electronics**

I. Introduction

The number and the proportion of elderly has been increasing in the human population. Due to this progress, also chronic diseases are becoming more common [1]. This leads to an increase in the public health expenditure [2]. To reverse this development, a shift from expensive institutional care to home-care is promoted and numerous miniaturized telehealth/mHealth/eHealth systems have been introduced.

Meaningful health-related parameters for elderly patients are for example heart rate, respiratory rate, temperature and activity. Cardiovascular diseases are among the most common chronic diseases [3]. The respiratory rate (RR) is an important indicator of the worsening state of the patient's health [4-6]. A rising temperature is a common sign of an infection and a decreasing activity level might be a sign of disease progression. The activity level also clarifies whether the increased heartbeat is caused by an illness or just by movements of the patient.

In this study, we introduce medical textile-integrated electronics for easy long-term monitoring of the elderly. The system measures the ECG, the breathing, and the activity of the patient. The idea of the textile-integrated electronics is that the measurement device is a part of clothing, and there are no loose wires or external devices to limit the mobility of the subject. The system consists of integrated electronic modules, i.e. measurement modules (ECG, IP, and activity), microcontroller and communication (Bluetooth low-energy, BLE) units, electrodes, battery, and data receiving device, as presented in Fig. 1. Electrodes are integrated on sides of the measurement shirt. The battery-powered ECG-IP-module processes the measurement data and sends the extracted information to the mobile phone via the BLE connection. Finally, the gathered health data is stored to the cloud and will be available for suitable parties such as the patient, the relatives or the hospital personnel.

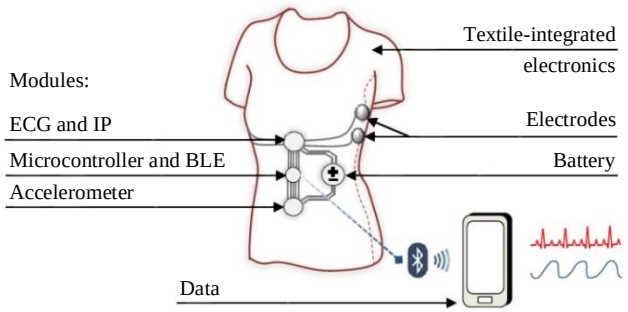

Fig. 1 Textile-integrated wireless monitoring system for heart rate, respiratory rate, and activity.

II. Materials and Methods

A. Measurement electronics

Many electronics companies nowadays provide medical Analog Front-End (AFE) modules for the ECG and IP monitoring. Despite of the relative wide range of alternatives, our requirement for the tetrapolar measurement of the IP signal was the main limiting factor in the AFE selection. Tetrapolar measurement was the special focus in this study because of its many advantages over the bipolar IP measurement. The tetrapolar method reduces the impedance of the electrode-tissue-interface and avoids the polarization of the electrodes [7]. The use of four electrodes also enables a more detailed analysis of tidal breathing and the respiratory flow measurement [8]. In addition, an advantage of the tetrapolar system lays in the improved controllability of the sensitivity field of the measurement S, which can be focused to particular regions, like upper airways [9].

Texas Instruments has the required AFE, but the evaluation board is offered just for the bipolar system [10]. However, it was noticed that this evaluation board can be manually modified to suit the tetrapolar measurement as well.

In the design of the measurement module, a small size and avoidance of any extra leads were the main goals. The number of external connections to the module should be as small as possible. In the final design, there were 32 external components. The number of leads from and to the measurement module were minimized, and due to this, for example the right leg drive was discarded from the design. At the end, there were altogether eleven leads left: power supply and ground (2), serial peripheral interface (SPI) (4), data ready (DRDY) interface (1), and electrode leads (4).

B. Electrode materials

Suitability of three different types of electrodes were tested for the measurement application. These electrodes were disposable Ag/AgCl gel electrodes, textile electrodes, and printed electrodes as shown in Fig. 2a-c. The disposable electrodes, Ambu Blue Sensor M-00-S' (13.2 mm^2), were used as a reference to compare the performance of the other two electrodes. The textile electrodes (20 x 25 mm) were added and the dry printable electrodes (20 x 25 mm) were laminated on the separate elastic textiles. The ink of the printed electrodes was stretchable ECM CI-1036 [11]. Textile electrodes were silver coated medical grade nylon knit fabric with a surface resistance smaller than 3 Ω/□. For the first prototype, both the textile and the printed electrodes were attached to a T-shirt with Velcro straps and electrical connections were made with silicon covered multi strand copper wires. In the final prototype, all wires were replaced with printed interconnections. Fig. 2.d. presents fully textile-integrated electrodes and interconnections from the reversed side of the shirt. The interconnections continue on the front side where also the electronics modules are placed.

Fig. 2 a. Reference electrode, b. Textile electrode, c. Printed electrode, and d. Printed electrodes and interconnections integrated on the textile

C. Test setup

All the measurements of this study were performed on one healthy 25 years old female. Tests were done in random order 2 – 5 hours at a time, between 7:30 am and 9:00 pm, during three months. The skin was prepared equally for wet and dry electrodes before the measurements. Dead skin cells were scraped off with a rough sponge around the electrode area and cleaned with cleaning liquid.

Each electrode type was tested 5 – 9 times for different setups. The duration of each recording was 131 seconds and the first 10 seconds were removed as setting time. Tests were made while posing for daily activities such as sitting, standing or laying down. There were also two categories for each activity: normal breathing and forced breathing. Forced breathing was included to evaluate the capability of the prototype to record irregular breathing patterns where the respiratory rate is too low or too high. The forced breathing part included five 12 seconds lasting deep breaths, eight 2-seconds lasting short breaths, 15-seconds long breath holding, and finally 31 seconds of uncontrolled normal tidal breathing.

The performance of the electrodes was examined by manually observing the amplitude of the noise (μV) in the signals. The average noise ratio for each electrode type in laying, sitting and standing positions, and in both breathing categories was determined by calculating an average of the three least noisy results separately for the ECG and the IP signals.

III. Results and discussion

A. The choice of the suitable electrode type

One of the main goals in this research was to compare how disposable, textile and printed electrodes perform in this kind of combined IP and ECG measurement. Another equally important goal was to determinate if the minimum requirement, the RR and heart rate (HR) detection, would be successful during movements in everyday life. In addition, the detection of the RR was also tested with the forced breathing pattern.

Table 1 lists average noise levels for each electrode type in both breathing categories and with both measurement techniques. Results are presented in sitting position. It can be easily pointed out that for the ECG measurement, the disposable electrodes produced the least noise. Between the textile and printed electrodes, there was no noticeable difference. For the IP noise levels, there is not a clear best electrode type although the textile electrodes give evenly good values in tetrapolar measurements.

Table 1 Noise levels of electrode type

Bipolar, IP [μV]	Normal breathing	Forced breathing
Disposable electrodes (Ambu)	61	57
Textile electrodes	88	64
Printed electrodes	320	343
Bipolar, ECG [μV]		
Disposable electrodes (Ambu)	950	289
Textile electrodes	2160	1240
Printed electrodes	1260	1470
Tetrapolar, IP [μV]		
Disposable electrodes (Ambu)	224	241
Textile electrodes	57	58
Printed electrodes	252	430
Tetrapolar, ECG [μV]		
Disposable electrodes (Ambu)	266	1050
Textile electrodes	2600	2670
Printed electrodes	1810	3350

There was no significant difference between the three electrode types to detect the HR. The disposable electrodes were able to display clear R-peaks of the ECG in a filtered signal with 96 % accuracy. Both the textile and the printed electrodes displayed R-peaks with 98 % accuracy. For the RR detection, breathing peaks were detected with disposable electrodes 98 % of the time. For the textile electrodes, this value was as good as 92 %, while for the printed electrodes only 56 %. The IP signal was generally the noisiest when measured with the printed electrodes.

B. Bipolar and tetrapolar methods

One advantage of the bipolar measurement has been said to be the smaller amount of skin irritation due to only two electrodes instead of four. However, skin irritation after around five hours of use was remarkable only for the disposable electrodes. The printed and textile electrodes did not leave any significant signs on the skin. It can be said that when the printed or the textile electrodes are used, skin irritation is not a valid justification to prefer the bipolar measurement over the tetrapolar measurement.

The noise level of the measurement signals seemed to be smaller when the bipolar method was used. The noise levels of the tetrapolar signals were higher in 83% of the cases compared to the bipolar measurement. Despite that, the tetrapolar method seems to deliver a more accurate RR and HR detection. From the bipolar measurements results, the RR could be recognized with 76 % and the HR with 97 % accuracy. For the tetrapolar measurements the corresponding values were 82 % for the RR and 99 % for the HR. Based on the measurements in this study, the tetrapolar measurement method can be considered a better alternative for the detection of the RR and HR.

IV. CONCLUSIONS

In this study, we compared bipolar and tetrapolar measurement techniques for the IP and the ECG monitoring. The implementation of the measurement device was made using a medical analog front-end circuit, ADS1292R, by Texas Instruments. The evaluation board ADS1x9xECG-FE was used in order to study the difference between the bipolar and the tetrapolar measurement techniques and to study, which of the three electrode alternatives would work the best in this kind of application, and if the RR and the HR can be detected during the everyday activities.

From the evaluated electrodes, the disposable Ag/AgCl electrodes were the most reliable, stable, and gave good test results. Because this application is for long-term monitoring, the skin irritation caused by these electrodes was however intolerable. Despite the fact that the performance results of the textile electrodes was in many cases even better than for the

disposable electrodes, there was occasional serious performance problems with them.

The RR and the HR were better detected from the tetrapolar measurements than from the bipolar measurements. However, the tetrapolar measurement included a higher noise level, and may not offer the ECG signal clear enough for other diagnostics purposes.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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