EVALUATION OF THREE MATTRESS DESIGNS FOR CAPACITIVE ECG MEASUREMENT FROM CONDUCTIVE TEXTILES ON BED

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ABSTRACT
In this paper, we developed three designs depending on the shape of electrode array for unconstrained electrocardiogram (ECG) measurement and tested the systems in practical and numerical terms. Conductive textiles and polyurethane form were used to make electrodes for comfortable ECG measurement. A total of three experiments were conducted to compare each design with a conventional ECG system by error rates of heart rate variability parameters, and to test the effects of capacitive ECG measurement depending on the thickness of cotton cloth inserted between a subject and textile electrodes, in cases of textiles with laminating or without laminating process. The overall results showed that the general type of horizontal array had the best performance in numerical side even though other designs were modified for reflection of heart axis or better contact in practical aspect. The maximum possible thickness for ECG measurement was about 2 mm on conductive textile and about 1.5 mm on the textile laminated by non-conductive material. Therefore, in terms of durability, the system is possible to apply enough in real life and we can use this system for algorithm of arrhythmias detection, OSA detection and sleep stages.

KEY WORDS
Capacitive ECG Measurement, Conductive Textile, Heart Rate Variability (HRV), Maximum Possible Thickness.

1. Introduction
As the world is rapidly becoming an aging society, the number of people who want to achieve a healthy life is increasing. For this reason, various home-based healthcare systems that are unconstrained and unconscious physiological signal monitoring systems at home have been developed. However, it is difficult to apply the non-contact sensors in our daily life because most of them are vulnerable to motion artifacts. Therefore, when the facts that we spend about one-third of our lives on a bed and movements are little during sleep are considered, it is suitable to unconstrainedly monitor and analyze bio-signals on the bed during sleep.

Measuring electrocardiogram (ECG) that is a basic signal among many physiological signals can provide early diagnosis of cardiac diseases by analyses of heart rate variability (HRV) calculated from ECG. For example, it is used to monitor sudden cardiac death and arrhythmias that are closely related to autonomic nervous system (ANS) since many studies have reported that HRV reflects the activities between sympathetic and parasympathetic nervous systems [1]-[3]. Moreover, many researches have also shown that detection of obstructive sleep apnea (OSA) and analysis of sleep stages from HRV have high accuracies [4]-[5].

Therefore, there are several teams that have developed ECG measurement systems in bed. Among them, the papers that used conductive textiles as electrodes have been recently published. Sandrine et al. [6] developed a textile ECG recording system that consisted of pillow and a foot mat electrode. In other words, two components were needed for ECG measurement. In addition, the system was not a non-contact or capacitive measurement method since skin of foot and neck was directly contacted to electrodes. Akinori et al. [7] proposed a bed-sheet electrode system that measured ECG capacitively. But, electrodes were exposed to the outside and a subject wearing underwear lay on the bedsheets that the textiles were put on. Kin fai et al. [8] also designed textile bedsheet sensors. They tested the system after covering a cotton bedcover on the sensor. However, if a subject lay on the edge of bed, ECG could not be measured because the width of the sensor was 50 cm and the sensor was placed on the middle of the bed. So, it is necessary to develop a system that is comprised of one component, single mattress size, and a proper design for ECG measurement during sleep.

In this paper, we introduced three designs of unconstrained ECG measurement system made of conductive textiles. Each design was evaluated in practical and numerical terms. For the numerical analysis, error rates of HRV parameters between the textile ECG system and conventional ECG system (Ag/AgCl electrodes) were calculated for 4 sleep postures. In addition, we tested the effects of capacitive ECG measurement depending on the thickness of the inserted cloth between a subject and textile electrodes with or without laminating.
2. Materials and Methods

2.1 Three Designs of Electrode Array

Conductive textile that is harmless to human was used to make ECG measurement systems (Kolon, Korea). To offer comfortable feeling and avoid not contacting body surface with the textile like waist on supine posture or sides on lateral posture due to hollow body line, the textiles were attached and fixed on polyurethane foam (5mm).

As shown in Figure 1, capacitive ECG was measured by two sensing electrodes and three ground electrodes. Two methods were used to increase the effect of common mode noise reduction. Firstly, the lowest ground textile that was put under the lower part of body was designed as large size to contact with the body as much as possible. Secondly, another textile connected to active shield was glued at the back area of the polyurethane form that covered the upper part of body.

Figure 1 shows three types of electrode array designs. First design was a basic and general type [8], second one was a modified type having a slope of approximately 20 degrees, and last one was another modified type of the first design as changing the height of electrodes. Each pre-amp module was placed near each sensing electrode to improve the signal-to-noise ratio.

The whole size of system is 100 x 120 cm whose width is almost same size as individual electrical pad and each specific textile size was described in Figure 1. The system was put between bed mattress and bedcover.

Figure 2 shows a block diagram of the analog modules.

2.2 Experiments

Subjects wore cotton T-shirt and pajama pants and lay on a cotton bedcover. They posed with one of 4 sleep postures; supine, prone, right, and left posture. They also changed their posture every 5 minutes. Ag/AgCl electrodes were attached on both wrists for reference ECG measurement. Three experiments were conducted in same condition as much as possible.

Biopac systems (MP150 module and ECG 100C amplifier, USA) were used for data acquisition. Sampling rate was 500 Hz.

2.2.1 Experiment 1

Three male subjects (age range 24 to 30) participated in experiment 1 that is to compare the performance between horizontal array and diagonal array. The diagonal angle was about 20 degrees and it was smaller than the real electrical axis of heart. If our design had same angle to axis of heart, the size of whole textile system could be longer because the cosine value is increased as the degree is larger. So, we selected the proper degree angle (20 degrees) considering the whole size of the system.

2.2.2 Experiment 2

Two male subjects (age range 28 to 29) participated in the experiment 2. This experiment was conducted to see the effects depending on changing the height of electrodes. Therefore, the height of upper two sensing electrodes was modified from 10 cm to 15 cm to increase the probability of contacting with the electrodes. And ground electrodes were decreased from 10 cm to 5 to remain the total size of upper electrodes.

2.2.3 Experiment 3

The signal quality of the textile electrodes could be changed by the thickness between the textile and a subject. So, experiment 3 was to check the possibility of ECG measurement as the layer of cotton cloth between them was increased. In addition, we also examined the same method on conductive textiles that was laminated with non-conductive material.

2.3 Data Analysis

Offline analyses were done with MATLAB 2012a (Mathworks, USA). R-peaks of ECG were detected by self-developed algorithm and HRV parameters in time
Table 1
The average HRV error rates of experiment 1 in horizontal array and diagonal array for 4 sleep postures.
SDNN: The standard deviation of the RR-intervals. RMSSD: The root mean square successive differences of RR-intervals.
pNN50: The percentage of the successive RR-intervals differing more than 50 ms. Mean HR: mean of heart rate. LF: Power in low frequency range. HF: Power in high frequency domain. nLF: LF power in normalised units. nHF: HF power in normalised units. LF/HF: Ratio LF/HF [9].

<table>
<thead>
<tr>
<th>HRV parameters</th>
<th>horizontal array</th>
<th>diagonal array</th>
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<tbody>
<tr>
<td></td>
<td>supine</td>
<td>prone</td>
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<td><strong>Error rates in time domain (mean, %)</strong></td>
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<tr>
<td><strong>Error rates in frequency domain (mean, %)</strong></td>
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<tr>
<td>LF</td>
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<td>HF</td>
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<td>LF/HF</td>
<td>0.38</td>
<td>0.47</td>
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Table 2
The average HRV error rates of experiment 2 in horizontal array and modified horizontal array for 4 sleep postures.

<table>
<thead>
<tr>
<th>HRV parameters</th>
<th>horizontal array</th>
<th>modified horizontal array</th>
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<tbody>
<tr>
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<tr>
<td><strong>Error rates in time domain (mean, %)</strong></td>
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<tr>
<td>Mean HR</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td><strong>Error rates in frequency domain (mean, %)</strong></td>
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<tr>
<td>LF</td>
<td>3.97</td>
<td>0.15</td>
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<tr>
<td>HF</td>
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<tr>
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<td>nHF</td>
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<tr>
<td>LF/HF</td>
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<td>1.14</td>
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and frequency domains were calculated using RR-intervals. HRV parameters from reference ECG and from our ECG system were compared by calculating error rate as follow:

\[
\text{error rate (\%)} = \left( \frac{r\text{-parameter} - t\text{-parameter}}{r\text{-parameter}} \right) \times 100 \tag{1}
\]

where r-parameter is HRV parameter of reference ECG and t-parameter is that of textile ECG.

The possible thickness for ECG measurement was evaluated by the mean amplitude of QRS complex, which is the amplitude difference from R-peak to S-peak.

3. Results

3.1 The Performances of Experiment 1

The average HRV error rates in both domains of experiment 1 were summarized in Table 1. HRV parameters except pNN50 in time domain had error rates less than 1% in both arrays. Especially, the error rates of mean HR were almost 0%. pNN50 parameter had the high error rate on supine posture in diagonal array. HRV parameters in frequency domain mostly showed less error values in horizontal array than those in diagonal array. The differences were big in LF, HF, and LF/HF on supine and left lateral postures.
increased. Depending on the thickness in Figure 3, the amplitude value of QRS complex was decreased as the layer of the cloth was depending on the thickness in Figure 3, the amplitude value could be measured by 1090um thickness on the laminated textile cotton pajama, about 440um. On the other hand, ECG could be measured up to approximately 1530um except the subject thickness between textile electrodes and a subject was about 5mm. Although the purpose of experiment 2 was to increase the contact probability for a short person by increasing the height of sensing electrodes, the effects were poor. This was probably since the effect of surrounding noise was larger as the area of the sensing electrode was bigger. Consequently, the noise could affect time index of R-peak and RR-intervals. Furthermore, the reason that pNN50 parameter showed relatively big error values was due to relatively small frequency. For example, pNN50 from conventional ECG system was 1 but that from the design of modified horizontal array was 2 on right posture. In this case, the error rate of pNN50 was 100%.

Figure 3. ECG waveforms and RS amplitudes depending on different cotton cloth thickness between a subject and textile electrodes with laminating process

3.2 The Performances of Experiment 2

The average performances of experiment 2 were shown in Table 2. Most cases had lower error rates in horizontal array than in modified horizontal array for all postures. Moreover, except pNN50, the error rates of HRV parameters in frequency domain were higher than those in time domain about both arrays.

3.3 The Performances of Experiment 3

In case of use of textile without laminating process, the thickness between textile electrodes and a subject was allowed up to approximately 1530um except the subject’s cotton pajama, about 440um. On the other hand, ECG could be measured by 1090um thickness on the laminated textile electrodes. Although it was difficult to find the difference depending on the thickness in Figure 3, the amplitude value of QRS complex was decreased as the layer of the cloth was increased.

4. Discussion

The focus of this study was on the comparisons of three types of textile array designs in terms of practical and numerical sides for unconstrained ECG measurement. HRV parameters were used for numerical analysis. The overall results showed that there were almost no differences between the traditional ECG system and our developed systems by HRV parameters. Unlike hard-type rigid electrodes, subjects just felt soft and comfortable during the experiments because the form (thickness, 5mm) was attached to the back of the textile. Moreover, we confirmed that ECG could be measured to about six layers of cotton cloth between a subject wearing cotton pajama and electrodes.

Through the results of the experiment 1, even though the diagonal array was the modified type to reflect the electrical axis of heart, the average error results were higher than those of horizontal array, because the angle of cardiac axis is not the same for everybody and the slope direction of diagonal design probably followed only the heart vector of right and prone posture. So, HRV parameters in both domains had low error rates on right and prone posture.

In addition, the horizontal array design showed better contact between the body and two sensing electrodes for any posture since the lower sensing electrode in the diagonal array was relatively located below as shown in Figure 1 (b). So, sometimes the lower sensing electrode was contacted with pelvis or hip that is thick part by underwear or waist rubber band of pants when a subject lay on right lateral posture in diagonal array. Therefore, in practical and geometric terms, the horizontal array was suitable for continuous ECG monitoring during sleep.

Although the purpose of experiment 2 was to increase the contact probability for a short person by increasing the height of sensing electrodes, the effects were poor. This was probably since the effect of surrounding noise was larger as the area of the sensing electrode was bigger. Consequently, the noise could affect time index of R-peak and RR-intervals. Furthermore, the reason that pNN50 parameter showed relatively big error values was due to relatively small frequency. For example, pNN50 from conventional ECG system was 1 but that from the design of modified horizontal array was 2 on right posture. In this case, the error rate of pNN50 was 100%.

From the experiment 3, we verified that ECG could be measured up to six layers of cotton cloth (thickness, about 2 mm) on textile electrodes. Moreover, even though textiles were laminated by material without conductivity, ECG was even measured on many layers of cotton cloth on them. This result is important in practical aspects since laminating makes the system more durable about water and contaminations.

Unlike other papers mentioned in introduction, three textile electrodes were connected to ground for reduction of common mode noise, not to a driven circuit. A system that uses the driven circuit for noise reduction can not be used with polysomnography, because the driven signals eliminate electroencephalography that is similar to noise wave. We made the system considering this point and showed the results with ground. However, because using the driven circuit for noise reduction has been known to give better performances than ground, there will be no problem even if we use a driven circuit for common mode rejection.

The main limitation of the textile ECG measurement system is that sometimes ECG may not be measured when changing lateral posture into supine posture, as blanket could be sandwiched between textile electrode and the body. In addition, if person rises up or goes down on bed during sleep, ECG could not be monitored because the body do not contact with two sensing electrodes at the same time. Therefore, we will let users know beforehand by giving user’s guide about matters that require attention, such as the maximum thickness of clothes and the position of the system on bed.

Since the HRV parameters were guaranteed in the horizontal array, ECG data from the textile design will be
used to algorithms of arrhythmias detection, OSA detection and sleep stages that were mentioned in introduction and compared the results from reference systems.

5. Conclusion

Home-based healthcare systems that focus on continuous bio-signal monitoring at home are in the spotlight of consumers. Bed-related systems are a larger percentage of many unconstrained systems due to little movement. In the present study, three designs made of conductive textiles for capacitive ECG measurement on a bed were compared by practical and numerical aspects (HRV). In addition, the maximum possible thickness between a subject and the textile electrodes with or without laminating process were tested. The horizontal array design was best of three and ECG was measured to about 2 mm on textile and about 1.5 mm on textile with laminating. The system of horizontal design can be applied in real life to analyze sleep-related disorders.

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References


