Fibers and Polymers 2016, Vol.17, No.12, 2069-2077
DOI 10.1007/s12221-016-6346-6

ISSN 1229-9197 (print version)
ISSN 1875-0052 (electronic version)

Efficacy Research of Electrocardiogram and Heart Rate Measurement in Accordance with the Structure of the Textile Electrodes

Hakyung Cho, Hosun Lim[1]*, and Sangwoo Cho[2]

Department of R&D, Blackyak Co. Ltd., Seoul 06745, Korea
[1]*Department of Clothing & Textiles, Sookmyung Women's University, Seoul 04310, Korea*
[2]*Department of Sports Science, Hoseo University, Asan 31499, Korea*
(Received March 17, 2016; Revised October 19, 2016; Accepted October 22, 2016)

Abstract: Recently, the demand for 24-hour biological signal monitoring in various fields such as health care and sports is increasing rapidly because of lifestyle changes and increasing interests in health. Thus, the field of clothing for continuous monitoring of biological signals is again illuminated increasing the market. However, smart clothing used to monitor biological signals has disadvantages affecting the motion artifact which are due to movements of the human body, so studies for minimizing motion artifact is underway from various angles. In this research, we configured the structure of the textile electrodes can be applied inside of the clothing, of the flat type and the three-dimensional type, and tried to derive the electrocardiogram and the structure of the suitable structure to measure the heart rate through measuring and comparing the electrocardiogram signal and the heart rate accuracy by structure. For this process, the heart rate accuracy and electrocardiogram signals of 8 men, with a standard body shape in their twenties, were measured and analyzed when walking and standing. At this time, the subjects were wearing clothes in which three-dimensional electrodes and flat type electrodes could be applied, respectively, to measure the electrocardiogram signal and heart rate in accordance with the experimental protocol. The results of the stability of the waveform, the signal size and the SNR (Signal to Noise Ratio) of the three-dimensional electrode when measuring the electrocardiogram signal were higher than those of the flat electrode. In addition, in the heart rate measured at the time when walking and standing, the accuracy of the three-dimensional electrode was shown to be higher than the flat type electrode, so the three-dimensional electrode was analyzed in a suitable structure for measuring the electrocardiogram and heart rate.

Keywords: Motion artifact, Structure of the textile electrode, Flat type electrode, Three-dimensional electrode, Electrocardiogram and heart rate

Introduction

Recently, in response to interest of health care and the development of fusion technology between clothing and the information technology, clothing products for measuring biological signals is developing rapidly [1]. Clothing for measuring biological signals that are based on textile sensors are variously developed for military, sports, and daily life [2], developed for measuring biological signals of the electrocardiogram, respiration, and movement [3-8]. Change in the position of the electrode between sensors and the human body while wearing smart clothing to monitor biological signals act as influencing factors on the measurement of electrocardiograms, which is defined as a motion artifact generated by the body's movement factor, structural factor of the clothing, and device factor [9]. Operating noise from the biological signal measurement clothing can be broadly classified into the spatial occurrence between the human body and the electrode due to the movement of the human body, the noise generation between the human body and the electrode due to the movement of clothing, and the noise generation due to electrical factors [10].

The noise signal could be included when reading an electrocardiogram in the dynamic environment. There are typical examples that can be classified as muscle sounds due to the muscle movement, a baseline noise due to chest movement, or the electric power line noise of 60 Hz device [11]. Electrocardiogram sensing smart clothing is used to obtain a signal by integrating the textile electrodes to clothing, unlike existing common electrodes and the electrode of the smart clothing should be stable in contact with the human body [9]. Thus, the dynamic noise of the electrocardiogram measurement clothing is mainly arising from changes of baseline due to the change of impedance between the electrode and the skin by the movement of the electrode. The movement of the electrode is generated from the change of the body surface and clothing due to the movement [12].

Researches which to minimize the motion artifact [13,14] by applying an algorithm and to minimize noise by filtering have been conducted around the engineers. Recently, such researches that minimizes motion artifact [1,15,16] through the structure of the clothing and the electrode on the wearable systems have been conducted. However, research to minimize the operating noise by measuring the electrocardiogram by configuring of the electrode structure in the clothing is inadequate.

Therefore, in this research, we configured the electrodes to measure the electrocardiogram inside of the clothing, of the flat type and the three-dimensional type, and then tried to

*Corresponding author: lhs@sm.ac.kr

research the effectiveness of the electrode structure located in the clothing to measure the electrocardiogram through analyzing the accuracy of the electrocardiogram signal and the heart rate measurement during standing and walking.

Experimental

Electrode Design

In this research, we developed a conductive thread based on a silver thread for optimization of the electrode structure to be applied to clothing having an electrocardiogram measurement function, and designed and developed a knit electrode by considering the compatibility of human body and the accuracy of signal measurement. On the basis of it, we designed the electrode of flat type and the three-dimensional type to apply to the form of a suitable electrode design to the clothing. We have also developed and designed the smart clothing for electrocardiogram and heart rate measurement.

Development of Conductive Thread

In this research, the thread for implementation of textile electrode consisted of the structure of textile threads and metallic wires using a metal (Ag) wire with high conductivity. The structure of the yarn with conductivity for measuring electrocardiogram and heart rate was made using PET (polyester) 150 Denier as a core yarn and 4 strands of silver thread 30 μm as a covering thread as shown in Figure 1. At this time, if a silver thread used as a core yarn, elongation would be generated by thread that covers the core of centrifugal force acting on the silver thread; consequently, silver thread was used as only covering thread. We have configured the electric resistance of conductive yarn could have a characteristic value of 6.44 Ω/m. It has also been designed and made so that it can have more than 10 % of an elongation percentage, and it can reduce snapping of thread when knitting.

Configuration of Electrode

Configuration of the electrode was composed of a knit electrode; the electrode by making of the conductive yarn based on a slit silver thread is difficult in applying to a tight fitted t-shirt in close contact to the human body due to the foreign body sensation and weakening of the elastic recovery force. Thus, electrodes developed in this research are configured to provide a conductivity capable heart rate

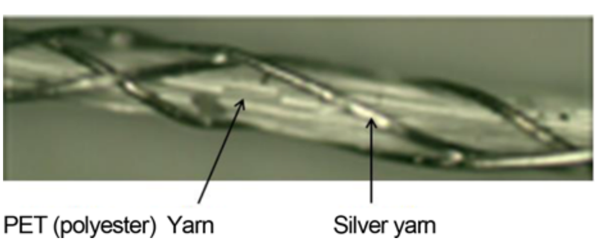

Figure 1. Appearance of yarn for measuring human body signal.

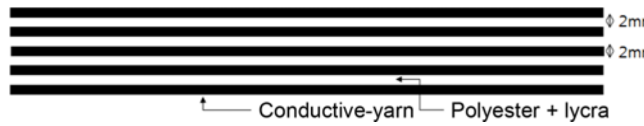

Figure 2. Knitting electrode design for the electrode configuration.

Figure 3. Knitting design and knitting electrode for the electrode configuration.

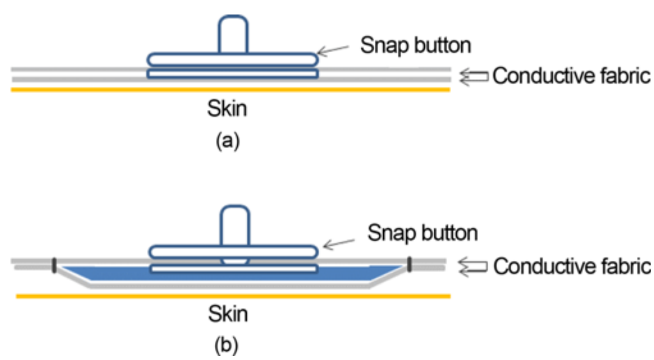

Figure 4. Electrode design of the flat type and the 3D type; (a) flat type electrode and (b) 3D type electrode.

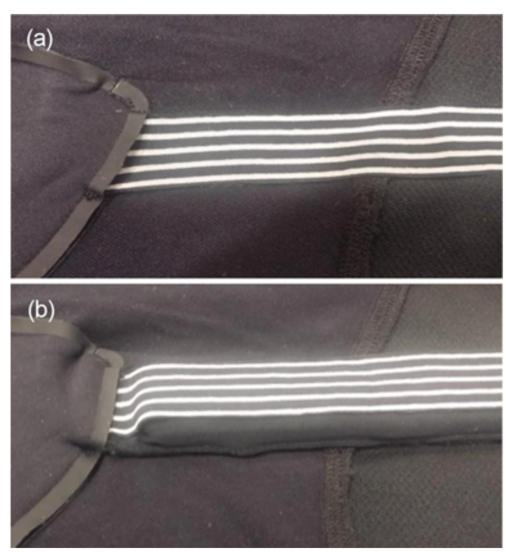

Figure 5. Electrode configuration applied to clothing; (a) flat type electrode and (b) 3D type electrode.

measurement with minimal human foreign body sensation and even have an elastic recovery force by cross-knitting with the yarn of the lycra and polyester and the conductive yarn by 2 mm as shown in Figure 2 and Figure 3.

Electrode Structure Design for Measuring the Electrocardiogram and the Heart Rate

In order to derive a suitable electrode structure for measuring the electrocardiogram and the heart rate, we compared the accuracy and efficiency of the heart rate measurement of two electrodes by developing two types of the flat type and the three dimensional type as shown in Figure 4. The flat type electrode is configured with a snap button between the two layers of conductive fabrics to prevent the snap button touching the skin directly. Two layers of conductive fabrics are sewn to touch each other and were formed for electricity through each other as shown in Figure 5(a). The three-dimensional electrode, that is put in a polyurethane foam having a thickness of 3T between the conductive textile of the flat type electrode, was configured to have a three dimensional appearance as shown in Figure 5(b).

Configuration of Experimental Clothing

For this experiment, we decided the position of the electrode on either side of the bottom of the chest and designed the clothing based on the result of the analysis of the optimum position shown in previous research [10]. Two types of the experimental clothing were designed with the same pattern and material for evaluation according to the electrode structure. Materials of 82 % polyester and 18 % lycra were applied the most, and 92 % polyester and 8 % lycra was applied to the part of the electrode in order to improve the skin adhesion and to reduce the movement of the electrode. Two types of the experimental clothing of the flat and the three dimensional type electrodes are respectively shown in Figure 6.

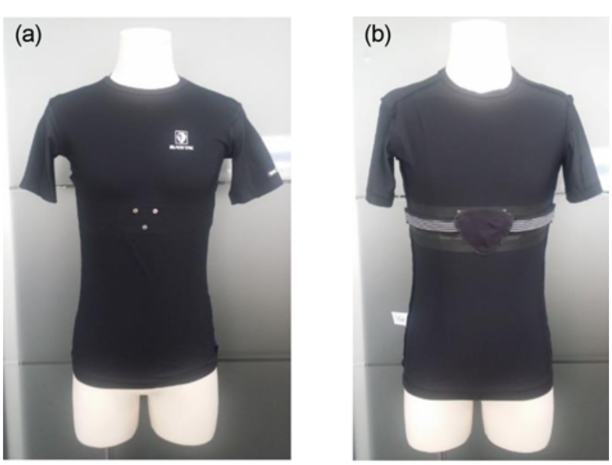

Figure 6. Design plan of two experiment clothing; (a) outside part and (b) inside part.

Electrocardiogram and Heart Rate Measurement

In this research, we configured the flat type electrode and the 3D type electrode, and the experiment was conducted in two stages in order to evaluate the accuracy of the electrocardiogram and the heart rate measurement in accordance with the electrode configuration.

Signal amplitude values are reduced by noise and performance can be accurately evaluated through the signal amplitude. In addition, noises appear due to diverse causes and affect the measurement of the accuracy of signal. SNRs are the measures of relative sizes of signal vs. noise and can be an indicator for measurement of signal's accuracy [17,18]. Therefore, in the present study, to compare the accuracy of measurement of electrocardiograms and heart rates using flat and 3D electrodes, the measured values of signal amplitudes, noise sizes, and SNR (dB) were compared and analyzed by t-test statistical analysis.

In addition, to evaluate the accuracy of the heart rates measured through the flat and 3D type electrodes applied in the present study, the positions of clinical heart rate signals measured through Ag-Agcl electrodes and the positions of heart rate signals measured through the textile electrodes (flat and 3D electrodes) were comparatively analyzed [19]. In addition, the heart rates appearing at positions identical to the positions of clinical signals were measured and the results were presented as measured %.

Evaluation of the Electrocardiogram Signal

Each subject was wearing clothing that respectively configured with the flat type electrode and three-dimensional electrode, each for the characterization of the electrocardiogram signal in accordance with the electrode structure; each electrocardiogram waveform was measured while standing and walking at 4 km/h each. The subjects, after wearing the experimental clothing, according to the protocol took a rest for 3 minutes by sitting in a chair and then the electrocardiogram is measured while standing for 3 minutes, then taking another 3 minute rest, the electrocardiogram of each subject was repeatedly measured three times. The electrocardiogram measurement while walking was completed in the same way. According to the protocol, the subject took a rest for 3 minutes and then the electrocardiogram is measured while walking at 4 km/h for 3 minutes, then taking another rest for 3 minutes, repeating each measure three times as shown in Table 1.

Table 1. Experiment process

3 min	3 min	3 min
Rest	Test	Recovery
← Electrocardiogram measurement cycle → 3 times repeated measurement		
← heart rate measurement cycle → 3 times repeated measurement		

Accuracy Evaluation of Heart Rate Signal

Accuracy evaluation of the heart rate signal through the flat type electrode and the three dimensional type electrode was carried out with the same protocol of the electrocardiogram measurement. The accuracy of the heart rate signal measurement through the heart rate measurement, while standing and walking on the treadmill at 4 km/h after wearing the experimental clothing, was compared and analyzed. For this process, the heart rate was measured 3 times at 3 minutes intervals when standing and walking at 4 km/h after a rest for 3 minutes while wearing 2 types of the experimental clothing; the average values of it was compared with the reference heart rate as shown in Figure 7. The reference signal by applying the medical Ag-Agcl electrode was acquired using the wireless electrocardiogram measurement system of MP150.

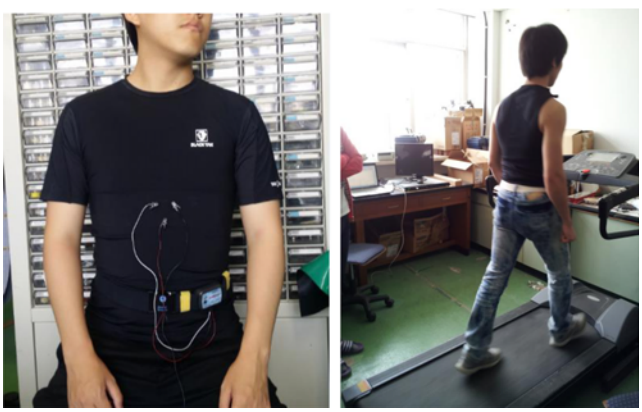

Figure 7. Experimental appearance of standing (left) and walking (right).

Figure 8. Measurement devices (MP150 and BioNomadix).

Measurement Device and Analysis Method

In this experiment, BN-RSPEC BioNomadix ECG which measuring the electrocardiogram and transmitting signals wirelessly is used in conjunction with the MP-150 as shown in Figure 8. A filter of the measuring device for the experiment was set to Notch Filter, 60 Hz, and the measured signals were presented and analyzed through the Acknowledge 4.0 program. Table 2 shows the specifications of measurement devices.

Subjects

For the electrocardiogram and the heart rate measurement from two types of the flat type electrodes and the 3D type electrode, 8 male subjects in the standard BMI region were selected. Table 3 shows the characteristics of them. In this

Table 2. Specifications of measurement devices

BioNomadix	BN-ECG2
Signal type:	Dual Channel ECG
Bandlimits max:	0.1 Hz to 100 Hz
Factory preset:	0.5 Hz to 1.0 Hz
Filter options:	0.005 Hz HP, 1 Hz LP
Notch filter:	50/60 Hz user-controlled switch; typically not required-factory preset OFF. See Appendix for additional hardware-specific output options.
Noise voltage (short input):	up to 10 mV P-P
Output voltage range:	±10 V (receiver output)
Operating time:	72-90 hours
MP150 System specifications	
Number of channels	
Absolute maximum input	±15 V
Operational input voltage	±10 V
A/D resolution	16 Bits
Accuracy (% of FSR)	±0.003
Input impedance	1.0 MΩ

Table 3. Characteristics of the subjects

Subject	Age	Sex	Height (cm)	Weight (kg)	BMI
Subject 1	26	Male	175	86	28.08
Subject 2	26	Male	174	70	23.12
Subject 3	26	Male	177	72	22.98
Subject 4	35	Male	173	76	25.39
Subject 5	24	Male	171	77	26.33
Subject 6	24	Male	178	70	22.09
Subject 7	26	Male	177	78	24.90
Subject 8	24	Male	173	80	26.73
Average	25.15	-	174.75	76.13	24.93

research, subjects were limited to males in consideration of adhesion and the body curve in accordance with the characteristics of the body surface area in order to derive the structure of the electrode suitable for the signal measurement.

Results and Discussion

Electrocardiogram Signal according to Electrode Structure

Electrocardiogram Signal Measurement in Standing

In the comparison result of the electrocardiogram signal during the standing condition derived from the flat type electrode and the 3D type electrode, it was analyzed that the size of the signal in the 3D type electrode is displayed larger in all subjects. The result of the size of the signal and the SNR (Signal to Noise Ratio) is as shown in Table 4. The signal amplitude, noise size, and SNR(dB) measured through flat electrodes and those measured through 3D electrodes in standing were analyzed and all the measured values showed statistically significant differences as shown in Table 5. According to the results of analyses of the values of signal amplitudes ($p<0.01$), noises ($p<0.01$), and SNR(dB) ($p<0.01$) during standing, all the values showed statistically significant differences indicating that 3D electrodes have higher accuracy of electrocardiograms compared to flat electrodes (Table 5).

Table 4. Comparison of electrocardiogram signals obtained through flat electrodes and 3D electrodes in standing

Subjects	Electrode Type	Signal amplitude (V)	Noise (V)	SNR (dB)[a]
Subject 1	Flat type electrode	1.22	0.01	41.76
	3D type electrode	1.89	0.01	44.71
Subject 2	Flat type electrode	0.85	0.01	38.58
	3D type electrode	1.63	0.01	40.77
Subject 3	Flat type electrode	1.77	0.02	37.33
	3D type electrode	3.36	0.00	57.31
Subject 4	Flat type electrode	0.66	0.01	35.88
	3D type electrode	1.63	0.01	44.25
Subject 5	Flat type electrode	1.30	0.03	33.22
	3D type electrode	3.20	0.01	46.97
Subject 6	Flat type electrode	0.78	0.04	25.64
	3D type electrode	2.99	0.02	45.84
Subject 7	Flat type electrode	3.01	0.02	43.55
	3D type electrode	4.02	0.01	52.09
Subject 8	Flat type electrode	2.30	0.02	41.21
	3D type electrode	3.64	0.01	51.22

[a]SNR(dB)=10*LOG10(SNR), SNR=signal to noise ratio.

Table 5. Results of T-test analysis of electrocardiogram signals obtained through flat electrodes and 3D electrodes in standing

	Flat type electrode	3D type electrode	F
	Mean±SD	Mean±SD	
Signal amplitude (V)	1.399±0.938	2.842±1.002	.001**
Noise (V)	0.200±0.010	0.008±0.003	.026**
SNR (dB)[a]	37.138±5.738	47.895±5.299	.003**

*p<0.05, **p<0.01, ***p<0.001, [a]SNR(dB)=10*LOG10(SNR), SNR=signal to noise ratio.

Figure 9 shows the electrocardiogram waveform of the flat and 3D type electrode in standing. The amplitude value of the electrocardiogram of the flat type electrode showed that 1.22 V (subject 1), 0.85 V (subject 2), 1.77 V (subject 3),

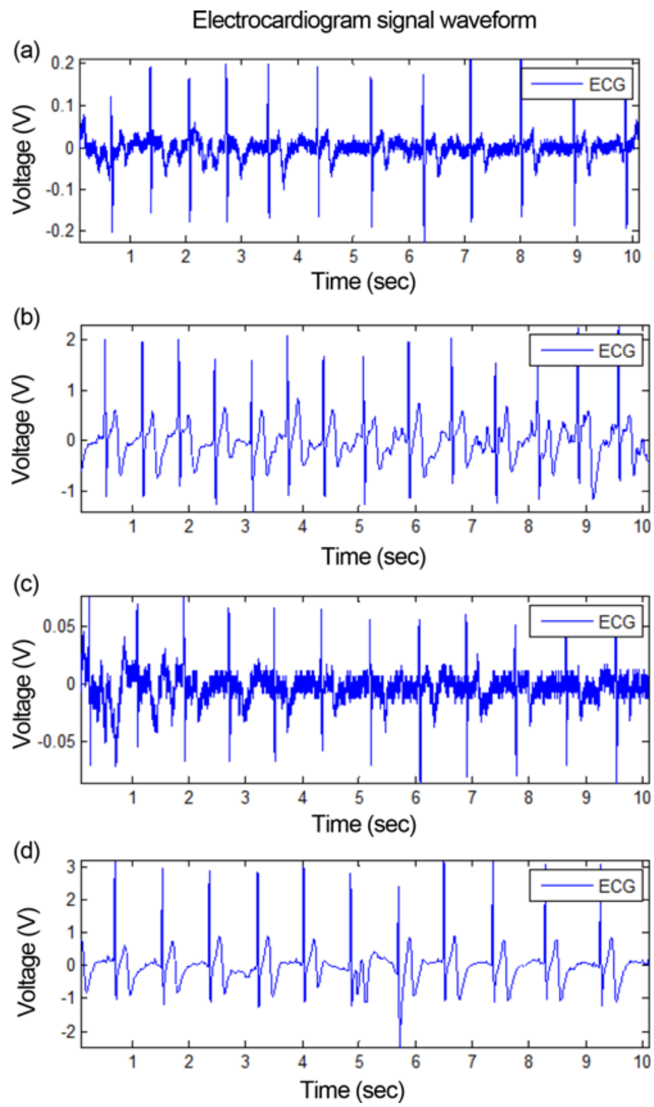

Figure 9. Electrocardiogram waveform example of the flat and the 3D type electrode in standing; (a) flat type electrode standing (Subject 1), (b) 3D type electrode standing (Subject 1), (c) flat type electrode standing (Subject 3), and (d) 3D type electrode standing (Subject 3).

0.66 V (subject 4), 1.30 V (subject 5), 0.78 V (subject 6), 3.01 V (subject 7) and 2.30 V (subject 8).

The electrocardiogram signal of the 3D type electrode showed that 1.89 V (subject 1), 1.63 V (subject 2), 3.36 V (subject 3), 1.63 V (subject 4), 3.20 V (subject 5), 2.99 V (subject 6), 4.02 V (subject 7) and 3.64 V (subject 8), and were analyzed to be larger than the electrocardiogram signal of the flat type electrode. The noise is generally equal or smaller in the 3D type electrode as compared with the flat type electrode, in which the noise appears relatively small because of the adhesion between the electrode and the human skin enhanced by the structure of the electrode of 3D type electrode which is composed in a three dimensional form.

As the result of the SNR (Signal to Noise Ratio) of the flat type electrode and the 3D type electrode by each subject, the flat type electrode showed that 41.76 dB (subject 1), 38.58 dB (subject 2), 37.33 dB (subject 3), 35.88 dB (subject 4), 33.22 dB (subject 5), 25.64 dB (subject 6), 43.55 dB (subject 7) and 41.21 dB (subject 8). By comparison, the three dimensional electrode showed that higher SNR values of 44.71 dB (subject 1), 40.77 dB (subject 2), 57.31 dB (subject 3), 44.25 dB (subject 4), 46.97 dB (subject 5), 45.84 dB (subject 6), 52.09 dB (subject 7) and 51.22 dB (subject 8). Therefore, the three dimensional electrode was analyzed to be accurate for the electrocardiogram signal measurement as compared with the flat type electrode.

Table 6. Comparison of electrocardiogram signals obtained through flat electrodes and 3D electrodes in walking

Subjects	Electrode type	Signal amplitude (V)	Noise (V)	SNR (dB)[a]
Subject 1	Flat type electrode	2.15	0.07	29.75
	3D type electrode	2.27	0.04	35.06
Subject 2	Flat type electrode	1.28	0.1	22.15
	3D type electrode	1.91	0.05	31.64
Subject 3	Flat type electrode	0.98	0.02	33.79
	3D type electrode	3	0.02	43.51
Subject 4	Flat type electrode	1.09	0.1	20.74
	3D type electrode	1.55	0.05	29.82
Subject 5	Flat type electrode	2.22	0.03	37.39
	3D type electrode	2.73	0.01	48.71
Subject 6	Flat type electrode	1.73	0.05	30.8
	3D type electrode	2.91	0.01	49.27
Subject 7	Flat type electrode	3.51	0.04	38.86
	3D type electrode	3.56	0.01	51.03
Subject 8	Flat type electrode	3.22	0.03	40.61
	3D type electrode	3.53	0.02	44.93

[a]SNR(dB)=10*LOG10(SNR), SNR=signal to noise ratio.

Result of the Electrocardiogram Signal Measurement in Walking

Table 6 and Figure 10 show the result of the signal measurement of the flat type electrode and 3D type electrode during walking. The amplitude value of the clothing with the flat type electrode showed that 2.15 V (subject 1), 1.28 V (subject 2), 0.98 V (subject 3), 1.09 V (subject 4), 2.22 V (subject 5), 1.73 V (subject 6), 3.51 V (subject 7) and 3.22 V (subject 8). That of the 3D type electrode showed that 2.27 V (subject 1), 1.91 V (subject 2), 3.00 V (subject 3), 1.55 V (subject 4), 2.73 V (subject 5), 2.91 V (subject 6), 3.56 V (subject 7) and 3.53 V (subject 8). The signal size measured by the 3D type electrode has a larger than the flat

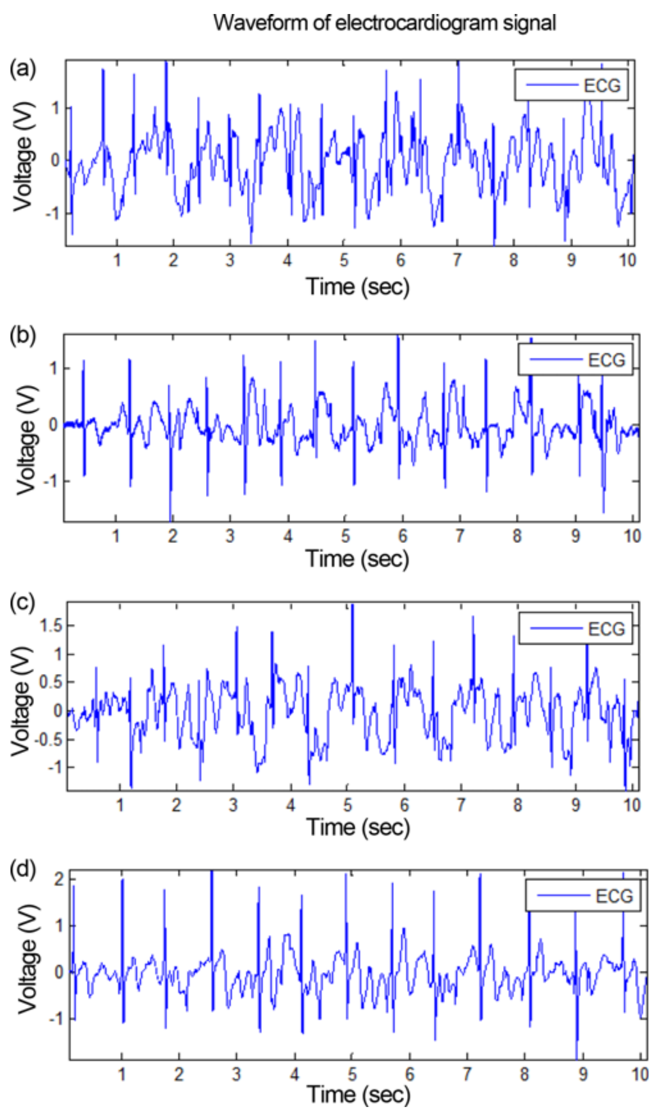

Figure 10. Electrocardiogram waveform example of the flat and the 3D type electrode in walking; (a) flat type electrode waking (subject 1), (b) 3D type electrode waking (subject 1), (c) flat type electrode waking (subject 3), and (d) 3D type electrode waking (subject 3).

type electrode. The noise size of the flat type electrode during walking corresponding to the electrode configuration was 0.07 V (subject 1), 0.10 V (subject 2), 0.02 V (subject 3), 0.10 V (subject 4), 0.03 V (subject 5), 0.05 V (subject 6), 0.04 V (subject 7) and 0.03 V (subject 8). That of the 3D type electrode was 0.04 V (subject 1), 0.05 V (subject 2), 0.02 V (subject 3), 0.05 V (subject 4), 0.01 V (subject 5), 0.01 V (subject 6), 0.01 V (subject 7) and 0.02 V (subject 8). Thus, the noise size of the flat type electrode has a larger than the 3D type electrode. The result of the reduced motion artifact has been reflected because the 3D type electrode has a high adhesion to the skin than the flat type electrode, like the previous results during standing.

As the result of the analysis of the SNR (Signal to Noise Ratio), the 3D type electrode showed greater value of the SNR, and has a higher accuracy in the signal measurement as compared to the flat type electrode during walking, the same as the stationary condition.

As a result of comparative analysis of the SNR of the flat type electrode and the 3D type electrode by each subject, the flat type electrode appeared at 29.75 dB (subject 1), 22.15 dB (subject 2), 33.79 dB (subject 3), 20.74 dB (subject 4), 37.39 dB (subject 5), 30.80 dB (subject 6), 38.86 dB (subject 7) and 40.61 dB (subject 8), by comparison, the 3D type electrodes appeared higher SNR values at 35.06 dB (subject 1), 31.64 dB (subject 2), 43.51 dB (subject 3), 29.82 dB (subject 4), 48.71 dB (subject 5), 49.27 dB (subject 6), 51.03 dB (subject 7) and 44.93 dB (subject 8). The 3D type electrode was analyzed to be accurate for the electrocardiogram signal measurement as compared with the flat type electrode.

Table 7. Results of T-test analysis of electrocardiogram signals obtained through flat electrodes and 3D electrodes in walking

	Flat type electrode	3D type electrode	F
	Mean±SD	Mean±SD	
Signal amplitude (V)	2.022±0.948	2.682±0.726	.024*
Noise (V)	0.055±0.031	0.026±0017	.003**
SNR (dB)[a]	31.761±7.399	41.746±8.397	.000***

*p<0.05, **p<0.01, ***p<0.001, [a]SNR(dB)=10*LOG10(SNR), SNR=signal to noise ratio.

According to the results of analyses of the values of signal amplitudes ($p<0.05$), noise sizes ($p<0.01$), and SNR(dB) ($p<0.001$) during walking, all the values showed statistically significant differences indicating that 3D electrodes have higher accuracy of electrocardiograms compared to flat electrodes (Table 7).

Accuracy Analysis of Heart Rate Measurement according to Electrode Structure

Heart Rate Measurement in Standing

For the accuracy analysis of the flat and the 3D type electrode in standing, the heart rate in standing is measured and compared with the clothing of the flat and 3D type electrode in standing as shown in Table 8. At this time, in order to analyze the accuracy of the measured heart rate from each of the clothing, the heart rate measured through the Ag-AgCl electrode using an MP150 device was used as a reference signal. The heart rate accuracy when wearing the clothing of the flat type electrode in standing was an average of 98.90 %, therefore, it had a higher accuracy compared to the flat type clothing with 97.59 %. However, the values of the heart rate measured at both the flat type electrode and the 3D type electrode were lower than the most standard value. As seen at the result, the size of the R-peak is reduced as contact resistance increase between the clothing with the built-in electrode and skin, therefore, the heart rate is considered to appear low because it could not distinguish the noise and the signal in the peak detection algorithm and considered it as the noise.

When viewed as indicated the heart rate measurement accuracy appeared lower in case of the flat type electrode, the noise due to the contact of the flat type electrode is considered to be greater than the noise of the 3D type electrode. Thus, the 3D type electrode, in comparison to the skin adhesion of the flat type electrode, appeared lower noise -originated with motion and contact- due to its high

Table 8. Comparison of the accuracy of the heart rate measurement of the flat and the 3D type electrode in standing

Subject	Aver. of heart rate (n) (flat electrode)	Aver. of heart rate (n) (3D electrode)	Aver. of heart rate (n) (reference value)	Accuracy (%) of flat electrode	Accuracy (%) of 3D electrode
Subject 1	68.52	69.32	69.97	97.93 %	99.07 %
Subject 2	67.24	71.19	71.94	93.47 %	98.96 %
Subject 3	62.23	62.71	63.39	98.17 %	98.93 %
Subject 4	82.92	82.94	84.58	98.04 %	98.06 %
Subject 5	77.24	78.19	78.94	97.85 %	99.05 %
Subject 6	62.24	62.45	63.13	98.59 %	98.92 %
Subject 7	69.08	70.06	70.68	97.74 %	99.12 %
Subject 8	63.56	63.65	64.26	98.91 %	99.05 %
Average	69.13	70.06	70.86	97.59 %	98.90 %

Table 9. Comparison of the accuracy of the heart rate measurement of the flat and the 3D type electrode in walking

Subject	Aver. of heart rate (n) (flat electrode)	Aver. of heart rate (n) (3D electrode)	Aver. of heart rate (n) (reference value)	Accuracy (%) of flat electrode	Accuracy (%) of 3D electrode
Subject 1	74.20	76.35	80.25	92.46 %	95.14 %
Subject 2	80.50	81.23	86.50	93.06 %	93.91 %
Subject 3	65.12	68.23	74.23	87.73 %	91.92 %
Subject 4	86.25	90.25	96.12	89.73 %	93.89 %
Subject 5	85.23	86.10	96.70	88.14 %	89.04 %
Subject 6	66.20	68.12	72.12	91.79 %	94.45 %
Subject 7	75.23	76.25	84.25	89.29 %	90.50 %
Subject 8	68.25	70.00	73.00	93.49 %	95.89 %
Average	75.12	77.07	82.90	90.62 %	92.97 %

degree of adhesion with the skin than the flat type, therefore, the heart rate accuracy is considered that it has become higher due to the size of the measurement signal is greater.

Heart Rate Measurement in Walking

The heart rate measured by the flat type electrode and the 3D type electrode is also tended to show lower numbers than the reference value in walking. For the heart rate analysis of each individual, the analysis of the accuracy was performed through the comparison and the analysis of the distance between the peaks of the electrocardiogram on the basis of the reference signal.

The accuracy of heart rates measurement during walking measured through 3D electrodes was shown to be higher than that measured through flat electrodes in all study subjects. When the average of accuracy of heart rates measured through the two electrodes were compared based on the reference value, the accuracy of heart rates measured through flat electrodes was 90.62 % while the accuracy of heart rates measured through 3D electrodes was 92.97 % indicating that 3D electrodes have higher. In other words, the accuracy in the heart rate of the individual appeared that the heart rate measurement accuracy of the 3D type electrode was higher than the flat type electrode, and the 3D type electrode had a higher accuracy in walking than the flat type electrode.

Conclusion

This research tried to minimize the dynamic noise, made from movements of smart clothing, for continuous measurements of an electrocardiogram and heart rate, and to develop a textile electrode to improve the accuracy of the measurement signal. For this, textile electrodes in two types of the flat and 3D electrodes were configured. And then throughout the application of these electrodes to the clothing, we tried to evaluate the effect by the electrode structure on the accuracy of the electrocardiogram and the heart rate measurement of the textile electrodes.

The signal amplitude, noise size, and SNR(dB) measured through flat electrodes and those measured through 3D electrodes in standing and walking were analyzed and all the measured values showed statistically significant differences. The result of the measurement and comparison of the electrocardiogram of the flat type electrode and the 3D type electrode is as follows. As the result of the electrocardiogram measurements in standing and walking, the size of the signal and the size of the SNR from the clothing with the 3D type electrode was larger than the flat type electrode in all subjects. Thus, the signal of the 3D type electrodes have shown to be more accurate.

In other words, it was found that the size of the signal and the size of the SNR in the clothing with the three-dimensional electrode were larger than the flat type electrode in both standing and walking. The size of the noise was reduced because the 3D type electrode has a greater skin adhesion force than the flat type electrode, and it caused a greater size of the signal, the analysis showed. In addition, the results of heart rate in standing and walking were similar to the results of the electrocardiogram signal.

As shown by the results described above, the electrocardiogram signal size and the SNR of the three-dimensional electrode clothing is higher than the flat type electrode clothing when measuring the electrocardiogram and the heart rate. As the result of the heart rate accuracy, the three-dimensional electrode is higher. It is analyzed that it could increase the size of the measurement signal and reduce the noise between the skin and the electrode because the three-dimensional electrode has higher skin adhesiveness and pressure according to the structure of the electrode than flat type electrode.

Thus, it is estimated that the three-dimensional electrode is better for measuring an electrocardiogram and heart rate. However, this research was limited to male subjects, and so the evaluation of the effectiveness will be carried out and applied to women in future research, examining results from the subjects of various body types. The present study compared the utility of electrocardiogram and heart rate measurements through 3D electrodes and flat electrodes according to the degree of close contact with human bodies. In future, follow-up studies to derive optimum 3D electrodes through experiments to measure electrocardiograms and heart rates using different thicknesses of 3D electrodes should be conducted.

Acknowledgements

This Research was supported by the Sookmyung Women's University, Research Grants (Project No. 1 – 1409-0006).

References

1. Y. Jeong, S. H. Kim, and Y. Yang, *J. Korean Soc. Clothing Text.*, **34**, 112 (2010).
2. L. M. Castano and A. B. Flatau, *Smart Mater. Struct.,* **23**, 1 (2014).
3. R. Paradiso, G. Loriga, and N. Taccini, *IEEE Trans. Inform. Technol. Biomed.,* **9**, 337 (2005).
4. D. D. Finlay, C. D. Nugent, M. P. Donnelly, P. J. McCullagh, and N. D. Black, *IEEE Trans. Inform. Technol. Biomed.,* **12**, 433 (2008).
5. H. Y. Song and J. H. Lee, *J. Korea Fashion. Costum. Design Assoc.*, **12**, 119 (2010).
6. Y. Zhai, X. Liu, Y. Wang, and X. Li, *J. Miner. Mater. Charact. Eng.,* **2**, 598 (2014).
7. S. S. Lobodzinski and M. M. Laks, *Cardiol. J.,* **15**, 477 (2008).
8. L. Vojtech, R. Bortel, M. Neruda, and M. Kozak, *Adv. Electric. Electron. Eng.*, **11**, 410 (2013).
9. S. Koo, M. D. Dissertation, Yonsei University, Seoul, 2008.
10. H. Cho, Ph. D. Dissertation, Yonsei University, Seoul, 2011.
11. H. D. Kim, C. H. Min, and T. S. Kim, *Proc. IEIE Fall Conf. Korea*, **28**, 465 (2005).
12. S. H. Liu, *J. Med. Biol. Eng.,* **31**, 67 (2011).
13. A. Griffiths, A. Das, B. Fernandes, and P. Gaydecki, *J. Phys. Conf. Ser.*, **76**, 1 (2007).
14. Z. Zhang, I. Silva, D. Wu, J. Zheng, H. Wu, and W. Wang, *Med. Biol. Eng. Comput.*, **52**, 1019 (2014).
15. A. Cömert, M. Honkala, and J. Hyttinen, *Biomed. Eng. Online,* **12**, 1 (2013).
16. H. Cho, H. Song, H. Cho, S. Goo, and J. Lee, *Sci. Emo. Sens*, **13**, 467 (2010).
17. L. Sörnmo and P. Laguna in "Wiley Encyclopedia of Biomedical Engineering" (M. Akay Ed.), Vol. 2, pp.1298-1313, Wiley, Hoboken, 2006.
18. M. S. Manikandan and K. P. Soman, *Biomed. Signal Process. Control.*, **7**, 118 (2012).
19. H. Cho and J. H. Lee, *J. Med. Syst*., **39**, 1 (2015).