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Exploration of AgNW/PU Nanoweb as ECG Textile Electrodes and Comparison with Ag/AgCl Electrodes

Eugene Lee[1], Inhwan Kim[1], Hang Liu[2], and Gilsoo Cho[1]*

[1]*Department of Clothing and Textiles, Yonsei University, Seoul 03722, Korea*
[2]*Department of Apparel, Merchandising, Design and Textiles, Washington State University, Pullman, WA 99164, USA*
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Abstract: This study aims to measure ECG signals by the AgNW/PU nanoweb electrodes, and, to compare with signals measured by the conventional Ag/AgCl electrodes. Finally, to investigate the usage potential of the AgNW/PU nanoweb as ECG textile electrodes. The ECG textile electrodes were fabricated, using the polyurethane (PU) nanoweb (Pardam, s.r.o., Czech Republic) coated with 1 wt% of silver nanowires (AgNW) dispersed in ethanol (KLK Co., Korea). To measure the ECG signals, eight participants (Male:Female=1:1) were collected, and then, the signals were measured at rest-state and stress-state in anechoic chamber using Lead I method. From the measured ECG signals, heart rate (HR) and R-R intervals were acquired by using MP150 (Biopac system Inc., USA) and Acqknowledge (ver. 4.2, Biopac system Inc., USA), and then, analyzed by using Kubios HRV (ver. 2.0., Biosignal Analysis and Medical Imaging Group, Finland). To examine the morphology of the signals, direct visual evaluation was performed. Also, to statistically compare to the signals, Wilcoxon signed-rank test was conducted by using R statistical language and RStudio (1.0.143 ver., RStudio, Inc., USA). As a result, the ECG waveforms measured by the two different types of electrodes looked similar, especially, QRS-complex, P-wave and T-wave as well as R-peaks properly appeared. Also, there was not a significant difference of HR and RR-intervals measured by the two different types of electrodes. It demonstrated that the new AgNW/PU nanoweb electrodes could perform properly as ECG electrodes.

Keywords: Polyurethane nanoweb, AgNW, ECG, Textile electrode, Smart textile

Introduction

Smart clothing is currently getting more attention by textile researchers, and one of the main purposes of smart clothing is related to biomonitoring, especially bio-signals such as electrocardiogram. To develop smart clothing for biomonitoring, advances in smart textiles, especially electronic textiles (e-textiles), should be preceded as fundamental materials for smart clothing [1,2].

Materials of e-textiles for ECG signals monitoring have been studied by utilizing stainless steel/viscose yarns [3], silver yarns [4,5], silver/polyester covered yarns [6], or intrinsically conductive polymers such as carbone nanotube, graphene, polypyrrol [7-9], poly(3,4-ethylenedioxythiophene) doped with poly(styrene sulfonate) (PEDOT:PSS) [10,11]. Textile electrodes for ECG measurement in the previous studies have been developed by utilizing the conductive yarns or fabrics with ICPs or metals. In particular, the previous studies [12-15] have conducted to develop the textile ECG electrodes by applying the silver nanowire with the textile materials as substrate as usual, and most researches have kept considered the stretchability or flexibility of the materials. Still, the textile electrodes developed in the previous studies had limitations such as thickness of the electrodes or induction skin irritation etc. Thus, to overcome the limitations of the previous researches, the silver nanowire was applied to the polyurethane nanoweb in this study.

Nanoweb has a large surface area, high vapor and air permeability and breathability [16], also a thin membrane and is light weight due to its micro-porous nature [17,18]. Furthermore, it can have various mechanical properties according to the types of polymer, especially, polyurethane nanoweb has excellent durability and elasticity as well as chemical stability due to the characteristics of polyurethane polymer fiber [16,19]. Thus, the polyurethane nanoweb having the nano~micro sized thickness is believed to irritate the skin less as the electrodes are attached for a long time. Recently, the polyurethane nanowebs were imparted electrical conductivity with the use of silver nanowire (AgNW), they are called as AgNW/PU nanowebs, turned out to have good mechanical property and verified the potential usage for textile sensors related to strain sensors [20,21].

Thus, this study aims to measure ECG signals by PU nanoweb imparted electrical conductivity utilizing silver nanowires. And then, to compare with signals measured by the conventional ECG electrodes, and finally, to investigate usage potential of the AgNW/PU nanoweb as ECG textile electrodes.

Experimental

Materials and Preparation Conductive Nanoweb

A commercially available polyurethane nanoweb was purchased from Pardam, s.r.o. (Czech Republic), and diameters of the fibers ranged from 500 nm to 1000 nm, with a weight of 13 g/m^2. The nanoweb was manufactured by centrifugal spinning. 1 wt% silver nanowires (AgNWs) dispersed in ethanol were provided by KLK Co. (Korea). The length of

*Corresponding author: gscho@yonsei.ac.kr

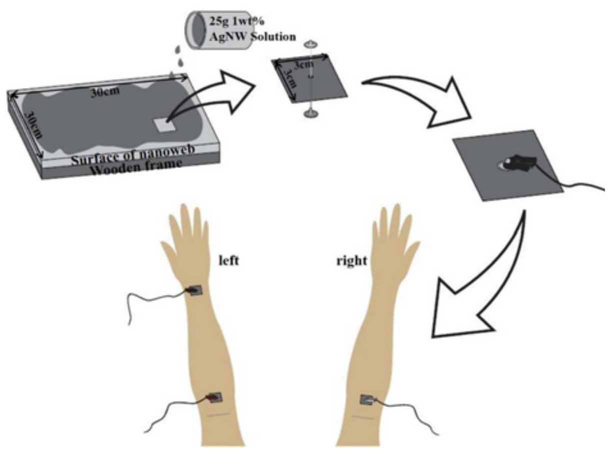

Figure 1. Specimens preparation of ECG textile electrodes.

the silver nanowires was 20-25 m and diameter of those was 30-35 nm.

The polyurethane nanoweb was imparted electrical conductivity by a pour-coating process using 25 g 1 wt% AgNWs solution as shown in Figure 1. After the treated PU nanoweb was fully dried at room temperature for 24 hours, an AgNWs-network was formed on the surface of the nanoweb as the evaporation of the ethanol.

Fabrication of Textile Electrodes

As presented in Figure 1 and Figure 2, to measure ECG signals, the specimens imparted electrical conductivity were cutted by 3 cm×3 cm. The specimens were made at the same size of the conventional ECG electrodes, and commercially available Ag/AgCl electrodes were used as references. Snap was positioned on center of the cutted specimens by using snap plier (tools), and these textile electrodes were used to ECG measurement.

Microstructure Morphology and Electrical Conductivity of Specimens

To investigate the microstructure of the AgNW-treated and untreated nanowebs, field emission scanning electron microscopy (FE-SEM, JSM-6701F, JEOL Ltd.) was used. To confirm whether the silver nanowires were attached uniformly, the surface appearances of the PU nanoweb and AgNW/PU nanoweb were inspected by FE-SEM. Also, to verify the electrical conductive property of the AgNW/PU nanowebs, electrical resistance of the specimens sized 3 cm×3 cm was measured by using Digital Multimeter (DM1010, DONG HWA, Korea). And the electrodes measured the sheet resistance. The sheet electrical resistance of the textile electrodes was measured using four-point probe measurement via Surface Resistance Meter (FPP-40K, DASOLENG Co., Ltd., Korea). All data was measured five times for reliability.

Participants

To examine the ECG signals measured by textile electrodes, eight participants who were healthy adults in their twenties were collected (Table 1). Also, the participants were forbidden to smoke, drink alcohol, and take any pills because it could affect their physiological signals. And participants with normal auditory functions were chosen because the fabric frictional sound was to be heard to measure ECG signals during the part of experimental procedures mentioned in the next section.

Data Acquisition from ECG Signals

The ECG signals of participants were measured at rest-state and stress-state in anechoic chamber using Lead I method. Details of the experimental protocol are presented in Figure 3. A 10 minute adaption time was given to every participant. And then, ECG signals of the sedentary participants, not moving but resting, were measured in anechoic chamber for 3 minutes (rest-state). Next, the ECG signals were measured for 3 minutes again (stress-state), and then, the participants were given a 5 minute break.

Table 1. Profile of participants for ECG measurement

Age		Sex	Number of participants
Mean	24	Male=4	8
SD	2.23	Female=4	
Range	20-26	(M:F=1:1)	

Figure 2. ECG electrodes: Conventional Ag/AgCl electrode (left) and AgNW/PU nanoweb electrode (right).

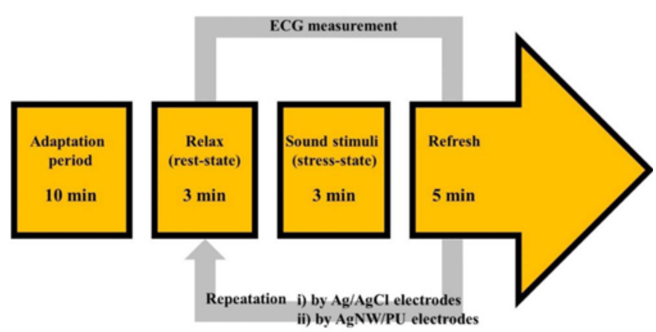

Figure 3. Experimental procedure for ECG measurement.

To measure the ECG signals of the participants at stress-state, the fabric frictional sound was generated and each participant was allowed to hear the sound. In this study, the frictional sound of combat uniform fabrics with woodland pattern for water repellent function was adopted to stimulate the participants. According to the previous study [22,23], this combat uniform fabric frictional sound was generated at 77.9 dB of SPL (sound pressure level). And based on the previous study [28], when the fabric frictional sound was generated over 60 dB of SPL, sympathetic nervous system of wearers (participants) was aroused. The fabric frictional sound used in the previous study [22,23] was played through a portable stereo speaker (S-0329A, Logitech, USA) as a wave file, and sound pressure level (decibel) of the sound was adjusted by using Sound level meter (Type 2240, B&K, Denmark).

These experimental procedures were repeated two times to measure ECG signals by using the reference Ag/AgCl electrodes and textile electrodes respectively. The ECG signals were measured by using MP150 (Biopac system Inc., USA) and HR (heart rate) and R-R intervals were acquired by Acqknowledge (ver. 4.2, Biopac system Inc., USA), And then, HR and R-R intervals acquired from the ECG signals were analyzed by using Kubios HRV (ver. 2.0., Biosignal Analysis and Medical Imaging Group, Finland).

Data Analysis

ECG Signals Morphology

To compare the signals of AgNW/PU nanoweb electrodes and those of conventional Ag/AgCl electrodes, direct visual evaluation of the ECG signals was performed [5]. The evaluation is a method to directly compare morphology of the ECG waveforms by looking them with the naked eye, two ECG waves measured by two different types of electrodes were overlaped and compared. Especially, the ECG waveforms acquired by using the textile electrodes were observed whether QRS-complex, P-wave and T-wave were properly appeared.

Statistical Analysis

To analyze data statistically in this study, R statistical language and RStudio (1.0.143 ver., RStudio, Inc., U.S.A) were used. Because the number of subjects who participated in the experiments was only eight, data analysis was conducted by nonparametric statistics instead of paired t-test. To compare the ECG signals measured by two different types of electrodes at rest- and stress-state, Wilcoxon signed-rank test was performed.

In this study, two main ECG signal analysis methods were used. 1) morphology analysis 2) RR interval analysis (pacing analysis). The ECG signals morphology analysis is a method for diagnosing heart disease due to electrical conduction abnormality of heart [24]. The statistical RR interval analysis is a method for evaluating physical activity such as exercise [25,26].

It would be better to choose the former when there isn't any movement, such as sleeping, during the ECG measurement [27]. While it would be better to choose the latter when there is any activity, such as exercising, during the ECG measurement [25]. To be applicable for the smart clothing based on the results of this study, it should be considered that the garments also move along the body movement. Accordingly, in this study, the RR interval analysis could be more meaningful. That is because the author thought that analyzing the ECG signals by both sources of information would be better.

Results and Discussion

The Characteristics of AgNW/PU Nanowebs

The FE-SEM micrographs (Figure 4) presented the surface appearance and presence of the silver nanowire networks, and showed that the silver nanowires were attached uniformly to the surface of polyurethane web. Also, 3 cm×3 cm of the PU nanoweb treated with 1 wt% silver nanowires had an electrical resistance of 1.012 Ω. The result had a similar level to the electrical resistance of the specimen treated with 100 % AgNW concentration in the previous study (0.7 Ω) [20]. And the sheet resistance of the textile electrode was 0.873 Ω/□. Thus, it showed that the AgNW/PU nanoweb had enough electrical conductivity to apply textile sensors.

Comparison of Morphology of ECG Waveforms

ECG signals of eight participants were measured by using

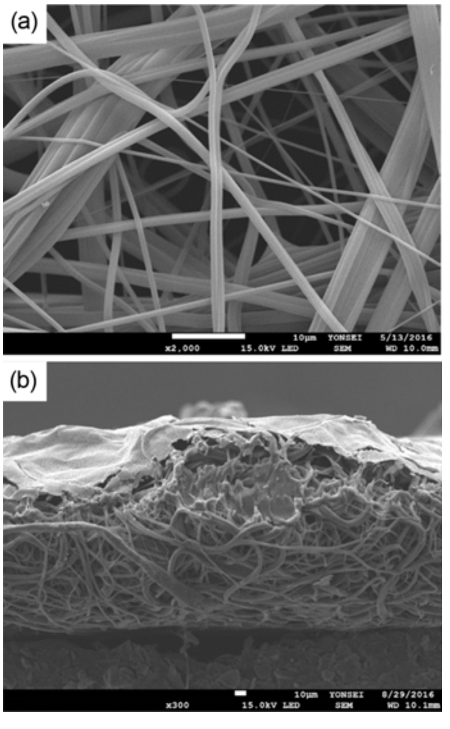

Figure 4. FE-SEM images: Untreated PU nanoweb, x2,000 (a) and PU nanoweb after treatment with 1wt% AgNW, x300 (b).

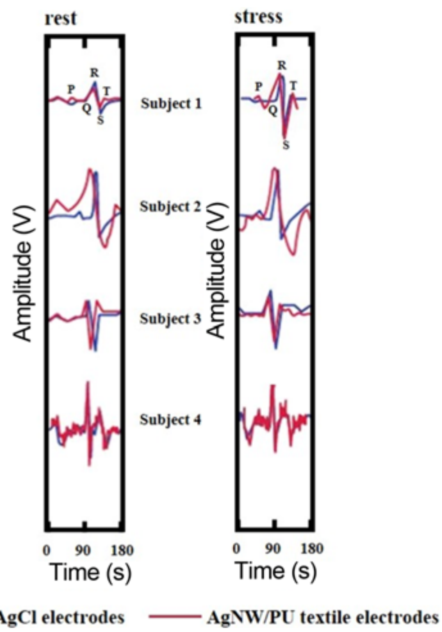

Figure 5. Comparison examples of ECG electrodes in morphology of ECG waveforms.

the Ag/AgCl electrodes and AgNW/PU textile electrodes. To verify ECG signals measured by the textile electrodes properly, morphology of the ECG waveforms was directly observed. And for an accurate observation, as presented in Figure 5, the ECG waveforms were compared to the signals measured by the conventional electrodes. As a result, the waveforms of ECG signals measured by the two different types of electrodes looked similar, and also, QRS-complex, P-wave and T-wave as well as R-peaks were properly appeared in all graphs. Thus, the ECG signals of the AgNW/PU nanoweb electrodes had similar waveforms to those of the conventional Ag/AgCl electrodes.

Comparison of HR and R-R Intervals of ECG Signals

By using the Ag/AgCl electrodes and AgNW/PU textile electrodes, ECG signals of eight participants were measured at rest-state and stress-state, and also, from the measured ECG signals, heart rate (HR) and R-R intervals were extracted. First of all, whether the fabric frictional sound used in this study actually aroused stress of the participants was investigated. According to the previous study [28], HR of rest-state significantly increased average 1.1 (1.2) bpm after sound stimuli, which implied that the fabric frictional sound effected negatively on the physiology of participants (eg., stress). The result of this study showed that the difference between HR at stress-state and HR at rest-state ranged 0.3-6.1 bpm measured by the Ag/AgCl electrodes and 1.4-4.8 bpm measured by the AgNW/PU nanoweb electrodes. Thus, it was confirmed that the frictional sound used in this study caused a stressful effect to the participants.

In Figure 6 and Figure 7, mean values of HR and R-R

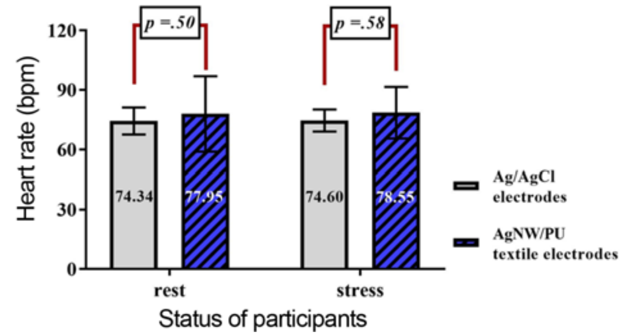

Figure 6. Comparison of ECG electrodes in HR.

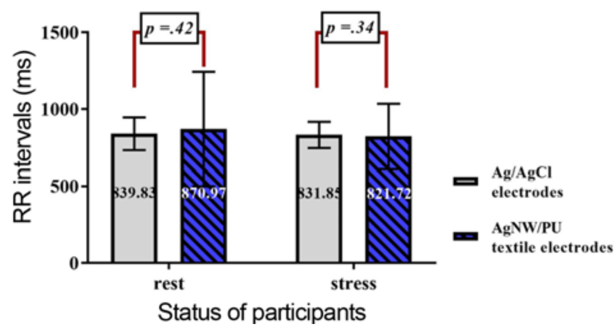

Figure 7. Comparison of ECG electrodes in R-R intervals.

intervals at rest-state and stress-state were presented. Regardless of the participants at rest- or stress-state, almost all values of HR and R-R intervals measured by the textile electrodes showed higher than those of the conventional electrodes.

To statistically figure out whether there was a significant difference of HR and R-R intervals between the Ag/AgCl electrodes and the AgNW/PU nanoweb electrodes or not, Wilcoxon signed rank test of nonparametric statistics was conducted. As a result shown, in Figure 6 and Figure 7, in the case of HR the p-value turned out to be 0.50 at rest-state and 0.58 at stress-state, and were more than the .05 significance level. Thus, the null hypothesis could not be rejected at .05 significance level. In the case of R-R intervals, as the p-value turned out to be 0.42 at rest-state and 0.34 at stress-state, and were more than the .05 significance level. Thus, the null hypothesis could not be rejected either. Therefore, there was not a significant difference of HR and RR-intervals measured by the two different types of electrodes in all ECG data. It implied that the new AgNW/PU nanoweb electrodes performed properly as ECG electrodes.

Conclusion

In this study, polyurethane nanoweb was coated with silver nanowire to impart electrical conductivity, and ECG signals were measured by using it. And then, usage potential of the AgNW/PU nanoweb as ECG textile electrodes was investigated. The result showed that PQRST-peaks were exhibited clearly in waveforms of the ECG signals measured by the nanoweb electrodes, and they had similar morphology to those of conventional Ag/AgCl ECG electrodes. Also, heart rate and R-R intervals were acquired from the ECG signals measured by the textile electrodes and compared to those of the conventional electrodes. As a result, it demonstrated that there was no significant difference of HRV between two different types of electrodes. Thus, this study confirmed that the AgNW/PU nanoweb could properly play a ECG textile electrode role. In future study, the potential of the AgNW/PU nanoweb as reusable electrodes might be needed to explore by test for durability and resistance to laundering.

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