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Probes of New Types of Electrodes of ECG

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Abstract: Long-term electrocardiography (ECG) monitoring can scrutinize human health, which is very essential for the early detection and treatment of cardiovascular disorders. For present, commercially used silver/silver chloride (Ag/AgCl) electrodes have drawbacks, and these would be more obvious in long-term monitoring. Therefore, people are developing new types of electrodes for ECG from different perspectives. At present, innovations are made: 1) Applying conductive thread into sewing to make textile electrodes for wearable ECG monitoring. 2) New material (Graphite Based Electrode) replacing the conventionally used Ag/AgCl.

Keywords: Textile electrodes, Material, ECG, Graphite based electrodes, Wearable.

1. Introduction

The cardiovascular diseases are the main prevalent and severe life-threatening health issues in the world and the major foundation and reason of death for the people in the ages between 44 and 64 [1–2]. Electrocardiogram (ECG) has a remarkable significance in all bio-signals from human body, containing consequential information about the individual heart and performance [3]. It is a standard process in cardiac medical care and also a main investigated element for people with cardiovascular diseases [4-5]. In the life-saving circumstances, an early recognition of pathological symptoms could significantly improve the healing rate of disease [6–8]. Therefore, wearable ECG monitoring could be necessary for specific group of people.

To date, the most common utilized electrodes for ECG is Ag/AgCl electrodes, because of its low and stable half-cell potential. However, Ag/AgCl electrodes cannot directly applied on human skin, due to a dry dielectric coat on the external layer known as "stratum corneum", which would lead to a transporting reduction from ions to electrons. Therefore, a conductive gel is required to moisturize the skin external layer, conducting cardiac microcurrent to the monitoring circuit. However, it is likely that may be gel residues on skin, which will cause a short circuit of the electrodes. Nevertheless, this gel-coating process is kind of difficult to handle, bringing difficulties in production. Another shortcoming of Ag/AgCl electrodes is its short service time, which is fatal in long-term monitoring, limiting the monitoring condition in daily routine [9-10]. Additionally, since the skin preparation is required in ECG measurement using Ag/AgCl electrodes, which would lead to an abrasion to the external skin layers. There is likelihood that causing uncomfortableness even pain to the users who habitually use Ag/AgCl electrodes in ECG during the skin preparation for attaching electrodes. And it could be accounting for infection or allergy. Moreover, with the reproduction of the skin stratum corneum cells, the quality of signal would be degraded over time. Furthermore, Ag/AgCl electrodes are not reusable and the recycling process would also require time and extra efforts, increasing the cost to use (CTU).

Solutions are provided to handle the problems that is stated above based on textile electrodes, which can assemble different conductive materials within flexible and variable patterns [11–13]. On this basis, Young-Jin Cha et al. [14] introduce and compare Plain Weave and Honeycomb Weave ECG electrodes with different contents of conductive yarns in ECG acquisition. Thap, Tharoeun et al. [15] introduce graphite-based electrodes for ECG monitoring that can be applied in freshwater- and saltwater-immersion without movement conditions, suggesting that it has bright prospects in new research area concerning underwater vital sign monitoring (including sea water). Similarly, Lee, Eugene et al. [16] explore the potential of AgNW/PU used in electrodes.

In this paper, I am making probes into the possibility of applying textile electrodes and the electrode with innovative materials, the graphite based electrode.

2. The Feasibility of Tixtile ECG Electrodes

It is necessary to state the feasibility of textile ECG electrodes. The first to concern about is the fidelity. Only with enough fidelity can ECG monitor the voltages generated by heart. Otherwise, the signal of ECG would be meaningless. Then we should focus on the duration of the wearable electrodes. For it is used in daily routine, we should consider the effect from real life. In this part, duration would be tested with stretch, bend and wash.

2.1. Fidelity Test

The first research is aim to test a sewn textile electrode fidelity, compared to the conventionally used Ag/AgCl electrode. During the comparison, three hypotheses are set: (1) average R-R interval will be the same between both electrodes, (2) average HR will be the same between both electrodes. (3) average comfort will be the same between both electrodes. Although R-R interval and HR are using the different calculation, both of them are relying on the accurate detection of the R peak. While HR is measured after each beat.

The following figure show the textile electrodes from previous study.

Table 1. This table presents flexible electrode studies found in the literature.

Group	Conductive Material	Method of Application	Durability Testing
Mestrovic et al., 2007	yarns: silver, copper, steel	knitting	N/A
Li et al., 2020	silver-coated nylon yarn	knitting	N/A
Pola and Vanhala, 2007	silver-coated yarn	knitting, weaving, sewing	N/A
Ankhili et al., 2019	silver-coated thread	embroidery	wash
Kannaian et al., 2012	silver-coated thread	embroidery	wash
Vojtech et al., 2013	pre-fabricated textile	sewing	N/A
Yoo et al., 2009	silver paste	screen printing	N/A
Kim et al., 2009	gold particles	sputtering	wash
Baek et al., 2008	metal particles	chemical etching on elastomer substrate	N/A
Jin et al., 2017	silver ink	stencil printing; dipping	wash
La et al., 2018	silver-particle/fluoropolymer composite ink	permeating into porous textile	stretch
Yokus and Jur, 2016	silver/silver-chloride conductive ink	screen printing	N/A
Lam et al., 2017	graphene ink	dip and dry	N/A
Cho et al., 2011	copper ink	sputtering	N/A

Those with an "N/A" value under durability do not list any stretch, bend, or wash testing results. The studies above the divider use conductive threads and yarns, while those below it use conductive pastes, inks, and particles. Note that none of these studies conducted comfort tests.

The study shown above are convincing that the textile electrodes have the fidelity no less than the commercially used Ag/AgCl electrodes.

2.2. Duration Test

The performance of the wearable electrodes would be tested in situation like stretching, bending and washing. The duration would be assessed be the electrical resistance change of the electrodes.

B.1.*Material*

In this test, a set of three sewn of electrodes are developed to support 3-lead ECG data collection. For reference, the traditionally used electrodes consist of a silver/silver-chloride disk mounted on an adhesive patch with conductive gel underneath to enhance the connection with skin. For textile electrodes, the silver thread consists of a standard nylon thread with silver nanoparticles on the external. The silver thread is two-stranded, which are separately coated. The textile electrodes are stitched in the overlapping zig zags onto an inextensible fabric clothing, with the use of a sewing machine (CS5055PRW, Brother). The conductive area of the electrodes is a 3x3 square, as it is shown in figure 1. The sizing of the electrodes is introduced from the paper of Yokus and Jur [17].

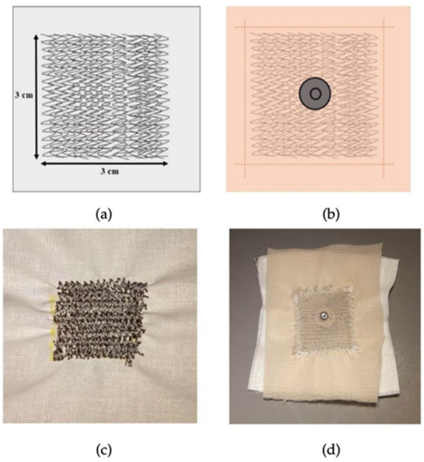

Figure 1. (a) Sewn electrode stitch design; (b) Design of fabric protective cover and snap connector;(c) Stitched electrode; (d) Complete electrode with protective cover and snap connector

The overlapping wiring path increase the conductive pathway in the electrodes, lowering the electrical resistance. With measurement from a standard multimeter, the conventional silver/silver-chloride electrodes have an electrical resistance of 2.0 Ω, while the textile electrodes have a much smaller electrical resistance of 0.3 Ω. Electrical resistance is an important parameter for electrodes, indicating the ability of the electrodes to obtain the relatively small voltages, which is produced by human body and going through the external skin layers. The low electrical resistance of textile electrodes shows the potential in daily use, allowing ECG monitoring to run without applying conductive gel to moisture the skin [18]. At the back of each electrode, a conductive snap is applied, serving as the connection point between the sensing area and the BIOPAC system connector clips. To be clarify, the electrical resistance is measured from the clip to the edge of the electrode.

The electrodes are not stretchy themselves, and they are applied to stretchy fabric in order to simulate the tight-fitting clothing condition, which could keep contact with skin, during the test.

B.2.*Stretching Testing*

The test would measure the electrical resistance of electrodes in different extents: 0% stretch (control), 12.5% stretch and 25% stretch. The electrodes would be tested in four directions across the electrode for each stretch case: vertical (along the stitch direction), horizontal (perpendicular to the stitch direction), corner to corner diagonally, and the opposite corner to corner. Each measurement was repeated three times.

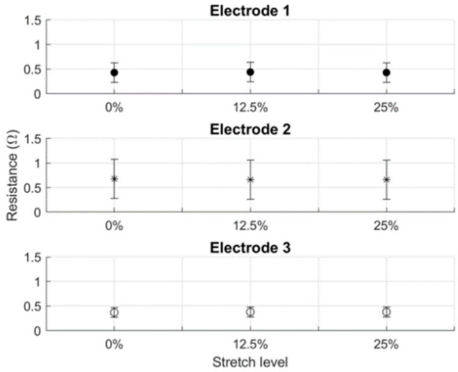

Figure 2. Stretch testing results for each of the three electrodes with error bars representing one standard deviation. Resistance change between stretch levels for all three electrodes is within the standard deviation of the three measurements taken, so there is no observable change

B.3.*Bending Testing*

The bending testing is conducted with three different bend angles: 180◦ (control), 135◦, and 90◦. Each of three electrodes were tested at all three bend angles in the vertical and horizontal directions (parallel or perpendicular to the stitch direction) three times each.

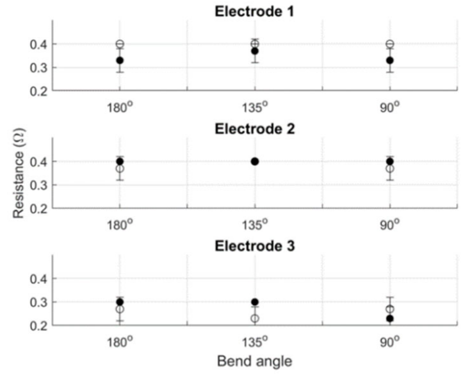

Figure 3. Vertical measurements are the filled circles, and horizontal measurements are the open circles. Many of the measurements returned the exact same results, so not all data points have visible standard deviations

B.4.*Washing Testing*

Washing testing included washing and drying phases, simulating the condition in washing machine. The hypotheses of this test are set as: one month of ECG monitoring with textile electrodes, with ECG garment worn four times per week. Assuming that garment will be washed twice each week, eight times in total in a month. The electrodes were washed with a regular-sized of laundry using commercially available liquid detergent with a normal wash cycle type. The electrodes were hang-dried over a two-hour period indoors. The electrical resistance of each electrode was measured before the first wash cycle and subsequently after each complete cycle.

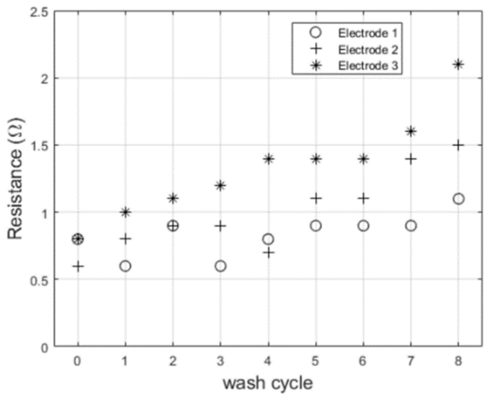

Figure 4. Resistance change after each wash cycle for a separate set of three electrodes

2.3. Conclusion

The textile electrodes show the capability to produce accurate data that is enough for ECG measurement, but also showing the good durability in stretching, bending and washing, since there are no significant changes in electrical resistance of sensing unit in the period of stretching and bending testing and minimal changes in washing testing. This is an encouraging result showing the feasibility of the development of wearable ECG monitoring.

3. Graphite-based Electrode

Based on various clinical needs, much effort has been made to make ECG monitoring to be more available as "anywhere-anytime" [19-28]. To extend the limited monitoring environments, graphite-based electrodes are developed to enable the ECG monitoring to work in the water-submerged condition.

Graphite is an allotrope of carbon, which is completely made of pure carbon. The detailed properties and characteristics of graphite have been specifically described in other works [29-31]. Here, the graphite pencil lead (GPL) would be evaluated for ECG under freshwater and saltwater circumstances. The electrodes are evaluated in seven different conditions: dry condition, freshwater immersion with/without movement condition, post-freshwater condition (i.e., freshwater wet condition), saltwater immersion with/without movement condition, and post-saltwater condition (i.e., saltwater wet condition).

3.1. Fabrication of GPL Electrodes

In the pre-experiment, the GPL is cut and placed on the metal cap. Holding them altogether with duct tape as it is shown in Figure 5a. Connecting the GPL with the PowerLab 8/35 and DualBioAmps FE135 (ADInstrument, Sydney, Australia). Contiguously placed for a standard 1-channel ECG monitor with sampling rate of 1 kHz and low pass filter cutoff frequency at 50 Hz. The signal output is shown in Figure5b. With this evidence, two types of GPL electrodes are fabricated: pencil lead solid type (PLS) and pencil lead powder type (PLP).

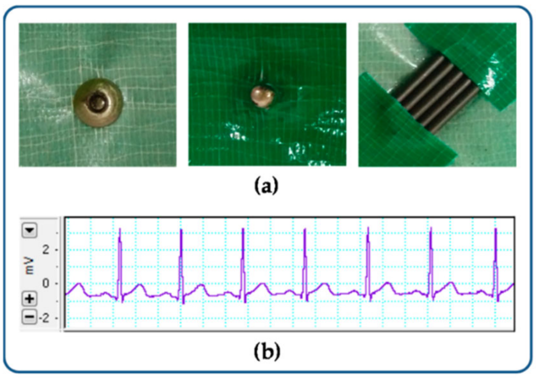

Figure 5. Pre-experiment for testing the usability of a graphite pencil lead electrode. (a) GPL on the metal cap; (b) Resultant output signal

A.1. *Fabrication of Pencil Lead Solid-Type (PLS) Electrode*

The material is from the 4B pencil.

(1) The pencil leads are cut into pieces as shown in Figure 6a.

(2) The cut leads were flattened to form a rounded rectangle cross-sectional shape as shown in Figure 6b.

(3) The flattened pencil leads are arranged parallelly with the metal cap, which is placed on the top. Attaching the cap and leads to each other by using an ethyl cyanoacrylate bond. The surface is perfectly attached and conducted without bond infiltration as shown in Figure 6c. The bond is applied again around the metal cap. Placing a piece of paper on it to support the pencil leads and the cap.

(4) Circularly trimmed the edge. The face and the back view of the PLS electrode are shown in Figure 6d.

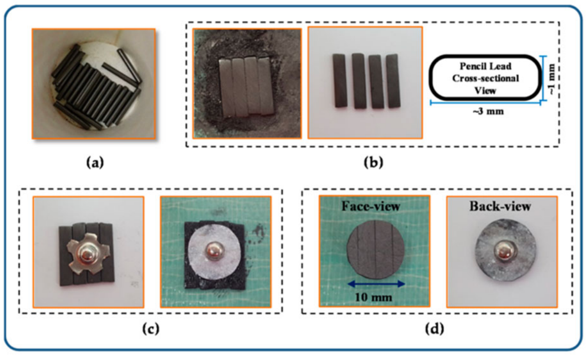

Figure 6. (a) Pencil leads; (b) Flattened pencil leads; (c). Each metal cap and lead are attached using a bond and then supported with a piece of paper; and (d) Pencil lead solid-type electrode

A.2 *Fabrication of Pencil Lead Powder-Type (PLP) Electrode*

The 4B pencil leads were used as raw materials as the. same as the PLS type.

(1) The pencil leads were grinded into powder as shown in Figure 7a

(2) Mixing the pencil lead powder with chloroprene-rubber based bond, pouring it into a piece of cylindrical acrylic tube within an electrical wire being placed at the bottom as shown in Figure 7b

(3) Sanding the surface of the electrode to made it smooth and flat.

(4) Applying the hot melted glue to support the wire on the backside. As it is shown in Figure 7c

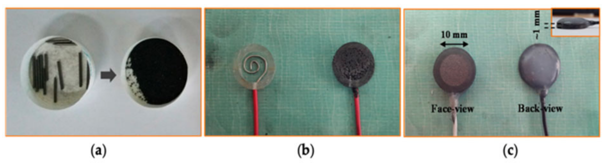

Figure 7. a) Pencil lead grinding powder; (b) small. piece of. acrylic tube within electrical wire being placed at the bottom; and (c) pencil lead powder-type electrode.

3.2. Assessement Preparation

B.1 *Testing electrodes*

To evaluate the performance, the PLS electrodes and the PLP electrodes are made in the pattern of round with a diameter of 10mm and the 1mm of thickness in order to compare with the commercially applied Ag/AgCl electrodes (3M health care). All these electrodes are shown in Figure 7.

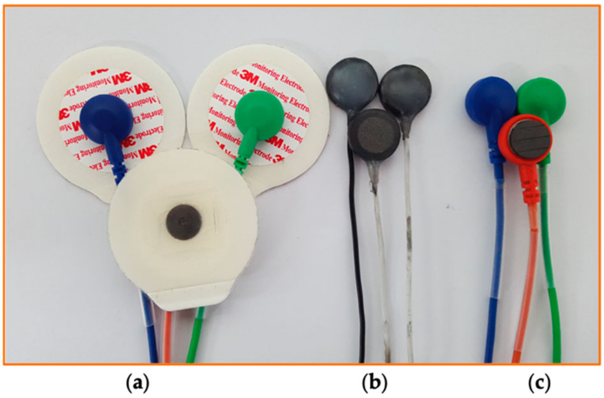

Figure 7. Three types of electrodes being used to perform the experiment: (a) commercial Ag/AgCl electrodes; (b) pencil lead powder-type electrodes; and (c) pencil lead solid-type electrodes.

B.2 *Signal processing*

The PowerLab 8/35 and DualBioAmps FE135. (ADInstrument) were simultaneously used to acquire ECG signals from the subjects. The ECG signals are recorded and displayed by using the LabChart software (Ver. 7.3.7 Profeesional). The sampling rate is selected as 1kHz with low pass filter, with which the cutoff frequency at 50Hz for the frequency content of a QRS complex. [32-35]

3.3. Assessment

The ECG signals would be compared as follows: (Experiment-I) Ag/AgCl electrodes vs. PLS electrodes, and (Experiment-II) Ag/AgCl electrodes vs. PLP electrodes. Each experiment is performed under two conditions: freshwater and saltwater. When all the experiments under freshwater condition are completed, the pool will be washed and refilled with 400 liters of clean water mixed with 14 kg of coarse salt in order to make salt concentration similar to seawater (i.e., on average 35 g/kg) [36]. The assessment is as shown in Table 2.

Table 2. Experimental protocol

Index	**Experiment-I: Ag/AgCl *vs.* PLS**		**Experiment-II: Ag/AgCl *vs.* PLP**	
(i)	Dry Condition (5 min)		Dry Condition (5 min)	
	Case-I: Freshwater	***Case-II: Saltwater***	***Case-I: Freshwater***	***Case-II: Saltwater***
(ii)	Immersion without Movement (5 min)		Immersion without Movement (5 min)	
(iii)	Immersion with Movement (3 min)		Immersion with Movement (3 min)	
(iv)	Wet Condition (5 min)		Wet Condition (5 min)	

The steps of the experiment are as follows (shown in Figure 8):

(1) Five minutes in a sitting position outside the pool (the dry condition

(2) Five-minute relaxation (lying position) inside the water pool (the immersion condition without movement).

(3) Three-minute side-to-side moving condition inside the water pool (the immersion condition with movement).

(4) Five minutes in the standing position outside the water pool (the wet condition).

The pool water temperature was 20.50±66661.30 °C; room temperature, 25 °C; and the outdoor temperature, 4.0±1.0 °C. During the 5-min dry condition (Step 1), the subjects were asked to remain relaxed in the sitting position outside the pool; the electrodes at this point were completely dry. Step 1 is similar to a regular ECG measurement in a clinical environment. During the 5-min water-immersed condition (Step 2), the subjects were asked to immerse in the water pool, with water coming up to their neck so that all electrodes were fully immersed. Subsequently, the subjects were asked to perform side-to-side turning movements with the speed about 2 turns per second for 3 min (Step 3). Finally, the subjects were asked to exit the pool and remain relaxed in the standing position with the wet electrodes still applied to their skin for 5 min (Step 4).

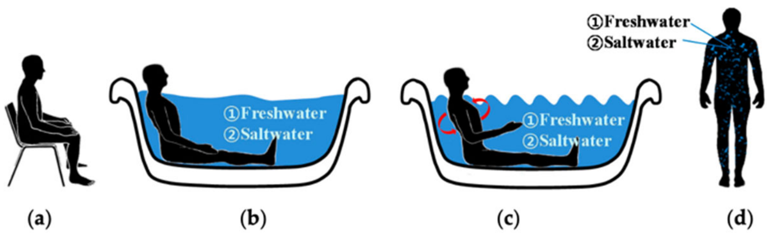

Figure 8. Experimental protocol for electrocardiogram data acquisition: (a) dry condition; immersed condition (b) without movement, and (c) Side-to-side movement; and (d) wet condition.

3.4. Signals

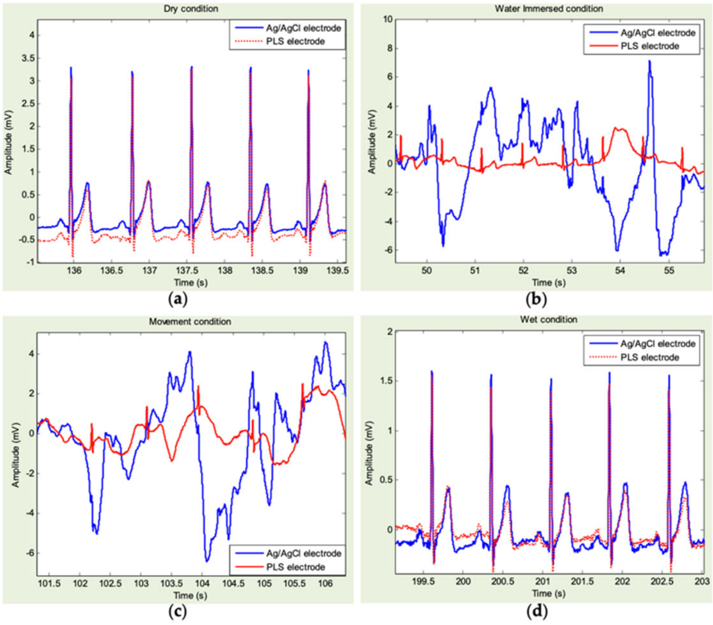

Figure 9 (Experiment I—Pencil lead solid-type (PLS) electrode compared with Ag/AgCl electrode) Example of electrocardiogram (ECG) signals for each experimental condition: (a) dry condition; freshwater immersed condition: (b) without movement; and (c) with movement; and (d) freshwater wet condition. ECG signals acquired with Ag/AgCl (blue line) and PLS electro des (red line).

From figure 9, it is shown that the PLS electrodes are capable to provide all the morphological components of ECG signals. In all conditions, especially in freshwater immersion (with/without movement), the PLS electrodes provide signals with higher quality than the one from Ag/AgCl electrodes.

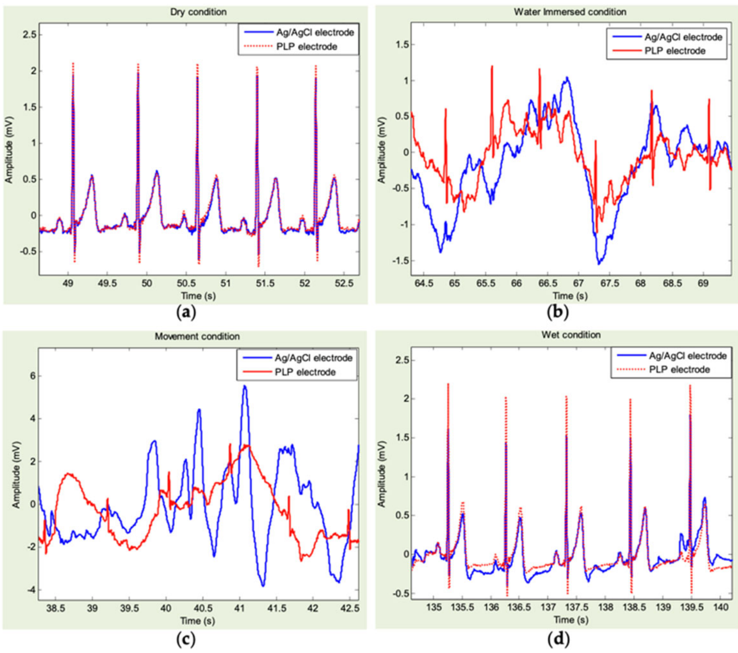

Figure 10 (Experiment II—Pencil lead powder-type (PLP) electrode compared with Ag/AgCl Example of electrocardiogram (ECG) signals for each experimental condition: (a) dry condition; freshwater immersed condition (b) without movement; and (c) with movement; and (d) freshwater wet condition. ECG signals acquired with Ag/AgCl (blue line) and PLP electrodes (red line).

From Figure 10, it is shown that the PLP electrodes are also capable to provide all the morphological components of ECG signals. Similar to PLS, the PLS electrodes provide signals with higher quality than the one from Ag/AgCl electrodes in all conditions, especially in freshwater immersion (with/without movement).

3.5. Conclusion

From the result, the PLS and the PLP electrodes have the capability to provide all morphological components that

Ag/AgCl electrodes provide. And the PLS and PLP electrodes have a nice performance in water-submerged condition. It is encouraging that the signals provided by PLS and PLP under the condition of freshwater- and saltwater-immersion without movement still have the enough quality for readability of the signals. This shows a promising prospect for ECG monitoring in underwater condition.

Acknowledgment

This paper is to make probes into new types of ECG electrodes

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