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A Pilot Study on Long-term Physiological Signal Monitoring using Anhydrous Viscoplastic Electrodes

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***Abstract*—Electrocardiography (ECG) and Electromyogram (EMG) are widely used to help physicians to diagnose various diseases. Besides, long-term physiological signals monitoring is of great significance for circumstances where certain diseases may not be observed in short-term monitoring. At present, wet electrodes are widely used in the clinic and are considered as a standard method to acquire physiological signals in high fidelity. However, current wet electrodes achieve high-quality signal acquisition by using conductive gel which will dry up as time elapses and finally leads to degradation of the signal quality. Therefore, an anhydrous viscoplastic electrode was proposed in this paper to solve the abovementioned problem. The proposed electrode, which is anhydrous and viscoplastic, enables high quality physiological signal acquisition with firm contact with the skin and it will not dry up within a long period of time. The results showed that the impedance of the proposed viscoplastic electrode could maintain relative stability after two days while that of the gel electrodes would increase significantly due to the gel dried up. Besides, the proposed electrode obtained physiological signals with high quality in both ECG and EMG tasks. After 24 hours of monitoring, the signal quality of the proposed electrode remained unchanged, indicated by the clearly recognizable time-domain signals. However, the signal waveform completely submerged in noise after the gel dried up. Moreover, the superior performance of the viscoplastic electrodes could be confirmed by the SNR difference between the two days, SNR further confirmed the superiority of the, with -2.03±2.10 dB and -3.40±8.27 dB for ECG and EMG respectively, and the SNR difference of gel electrodes were -7.59 ± 5.70 dB and -35.39±15.71 dB respectively. The proposed electrodes could be a great candidate for long-term physiological signal monitoring in risk management of healthcare.**

***Clinical Relevance*— The proposed electrode could achieve long-term physiological signals monitoring with high quality.**

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I. INTRODUCTION

Physiological signals contain plenty of information on personal health conditions, motion intentions and disease indications. The electrocardiography (ECG) is usually used to record the potential of the heart, according to which the clinician can diagnose some diseases and judge the health condition of the heart [1]. In some important circumstances, long-term ECG monitoring is essential to save one's life, since many reversible adverse events start in patients without being monitored [2]. The electromyogram (EMG) is also widely used in both clinical settings and scientific research [3, 4]. Long-term EMG monitoring can help with the study on rehabilitation assessment of muscle function.

Since the electrodes can deliver the physiological signals from human's body to a digital device for real-time display and further analysis, there are many studies about electrodes trying to improve the acquisition of physiological signals. In the clinical setting, wet electrode is mostly used, in which conductive gel is needed to reduce the impedance between skin and the electrode [5]. This combination provides great signal quality at the beginning. However, as time goes by, the conductive gel dries up, which finally degrades the signal's quality and even makes the subjects uncomfortable.

In order to overcome the aforementioned problem, there were plenty of studies focused on the improvement of materials and acquisition mechanisms [6-10]. The dry electrode can record signals without conductive gel, so it makes it more convenient but also make it sensitive to the motion artifacts which makes it unsuitable for long-term monitoring [11]. Non-contact biopotential sensors for ECG and EEG have also been proposed in rigid versions and flexible versions [12, 13]. This kind of electrode can achieve detect physiological signals without directly contact the skin, which also makes it sensitive to motion artifacts and unconducive to long-term monitoring.

In this paper, we proposed a viscoplastic electrode and systematically investigated its performance on physiological signals acquisition in two adjacent days (to simulate a long-term monitoring circumstance) by comparing to that of

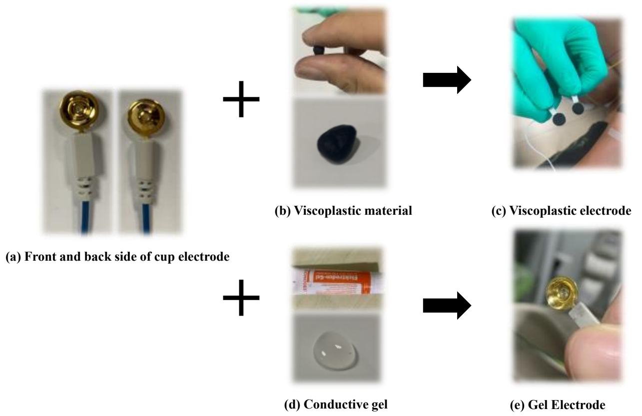

Fig. 1 The photographs of electrodes used in this paper

gold standard. First, the impedances of two electrodes group in two adjacent days were tested to investigate the impedance change. Then the physiological signals (ECG and EMG) were obtained by two electrode groups on two adjacent days. Finally, we calculated the difference of the SNR of signals obtained on different days to quantify the performance.

II. METHODS

A. Subjects

In this experiment, four subjects (three males, one female) aged from 24 to 26, with a mean age of 25.25, were recruited. All subjects reported no cardiac diseases, abnormal muscle function, nor cognitive impairments. Before the experiment conduction, the whole experiment procedures were clearly explained to the subjects, and informed consent forms had been obtained from all subjects. Subjects were asked to sit on a chair quietly and keep relax. The skin of subjects was wiped by using an alcohol pad to reduce the impedance between electrodes and skin. The data collection procedures were carried out in an ordinary official environment with no electromagnetic shielding device which might cause the recoreded signals were contaminated by the power-line interference. All the experimental protocols were approved by the Institutional Review Board (IRB) of Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences (SIAT-IRB-190615-H0352).

B. Electrodes groups and their locations

In this study, two electrode groups were used, one was disk electrode with conductive gel (SONOGEL Elektroden-Gel, Germany) which was referred to gel electrode, and another was disk electrode with viscoplastic electrode (viscoplastic electrode). The photograph of these electrode groups was shown in Fig. 1. A viscoplastic electrode is made by using a novel viscoelastic material which is consist of polydimethylsiloxane (PDMS), and carbon black. Hydroxyl-terminated polydimethylsiloxane (PDMS) (Mn~2000) was mixed with boron acid by Thinky mixer, then heated to 190 °C for 2 h. After cooled to room temperature, the viscoelastic PDMS matrix was obtained. Certain amount of the viscoelastic PDMS and carbon black were dispersed into chloroform. The mixture was first sonicated for 30 min, then magnetic-stirred for another 30 min. The dispersion was poured into a polytetrafluoroethylene (PTFE) mold and evaporated at room temperature. Finally, the product was collected by a spatula. In physiological signals acquisition tasks, gel electrodes served as the gold standard in the comparison of signals' quality. The electrode locations in different physiological signals detection tasks were shown in Fig. 2.

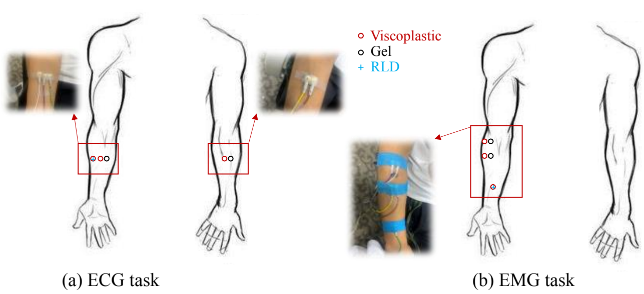

Fig. 2 The positions of the electrodes in (a) ECG and (b) EMG detection tasks

C. Physiological signals acquisition and processing

The tasks of physiological signals acquisition consisted of two tasks, ECG task and EMG task. In EMG task, the subjects were asked to do hand movements (hand-close and rest) repeatedly. The signals acquisition was achieved by our customized hardware and customized GUI software (Mathworks Inc.). A 3-order Butterworth high pass filter with the cut-off frequency of 0.1 Hz was applied to remove the baseline drift. And no other filter was applied to raw data. The electrodes were used for a discrete time and the impedance of them was recorded in two adjacent days to study the time-related impedance change.

III. RESULTS

A. The comparison of the impedance

In this part, the impedance change of different electrode groups in two adjacent days was studied. The total impedance of a RC parallel circuit model was proposed by Wang et al. [14], and the impedances were shown in Fig.3. The change of impedance between different electrode groups under different testing days was obvious. On Day 1, the impedance of the

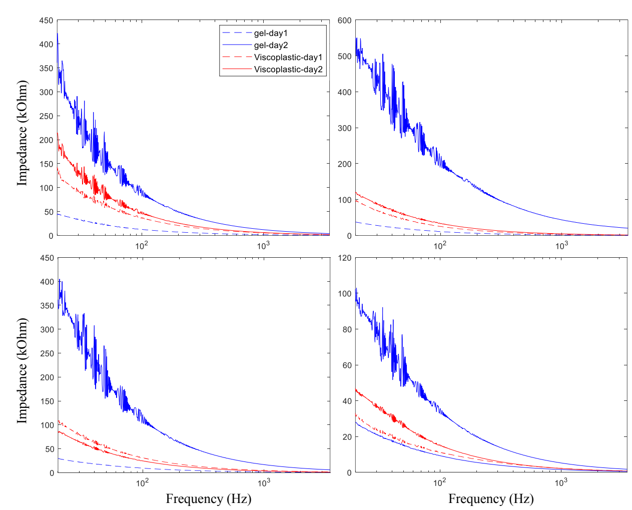

Fig. 3 The comparison of impedance between gel and viscoplastic electrodes on two adjacent days

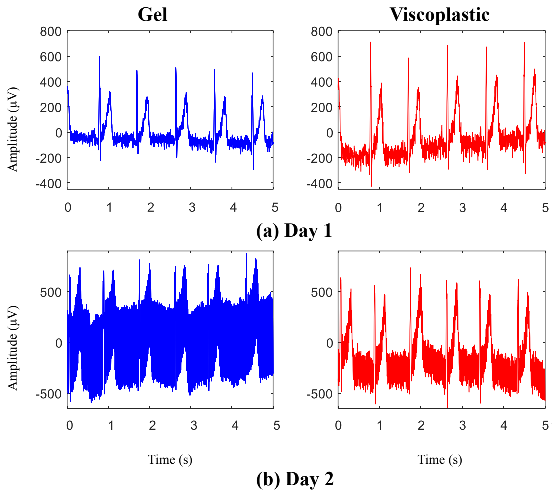

Fig. 4 The comparison of signal quality on ECG between gel and viscoplastic electrodes on (a) day 1 and (b) day 2 without filtering

viscoplastic electrode performed well during the whole frequency range, while the gel electrodes performed even better than the viscoplastic one within all subjects. On Day 2, the impedance of the gel electrodes showed obvious increase when compared to that of the viscoplastic ones. As time elapsed, the impedance of the gel electrodes increased sharply while that of the viscoplastic ones stayed stable. All the mentioned circumstances could be observed in all subjects.

B. *The comparison of the quality of ECG signals*

In this part, the quality of ECG signals obtained from two different electrode groups on two days was taken into consideration. The ECG signals collected by gel and viscoplastic electrodes on two adjacent days were shown in Fig. 4, using red and blue to present signals obtained by gel electrodes and viscoplastic electrodes respectively. On Day 1, the signals obtained from both electrode groups achieved the nearly the same performance, with both ECG signals clear waveform morphology. It was noteworthy that the amplitude of ECG signals obtained by viscoplastic electrodes was near one-third of that obtained by gel electrodes. A similar circumstance could also be found in Day 2. But when considering the quality of ECG signals of Day 2, it could be clearly found that the signals' quality acquired by gel electrodes became worse, which could be reflected by the fact that the ECG signals had been submerged in the noise, while the ECG signals of viscoplastic electrodes still show relative clearer waveform morphology than that of gel electrodes.

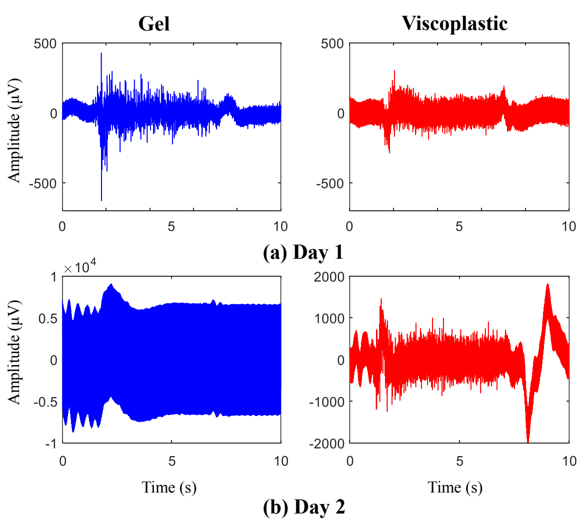

Fig. 5 The comparison of signal quality on EMG between gel and viscoplastic electrodes on (a) day 1 and (b) day 2 without filtering

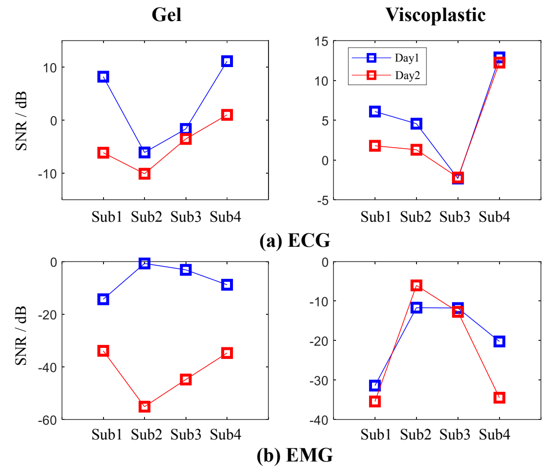

Fig. 6 The SNR of the ECG and EMG from all four subjects

C. *The comparison of the quality of EMG signals*

In this part, EMG signals were taken into consideration to further compare the performance of physiological signal acquisition by two different electrode groups on two adjacent days. The results showed that the EMG signals on Day 1 obtained by gel electrodes had a little bit better performance than that of viscoplastic electrodes for the worse baseline. Besides, the difference in amplitudes obtained by different electrode groups was still evident as same as what could be noticed in the aforementioned ECG testing. The difference in signals' quality became greater in the EMG signals obtained on Day 2. To be more specific, on Day 2, EMG signals detected by viscoplastic electrode could be also obtained successfully in Day 2 while that of gel electrode had already been submerged in noise. It was clearly that while comparing with the signals of Day 1, the quality of the EMG signals obtained by gel degraded obviously while the quality of signals obtained by viscoplastic electrodes still kept well.

TABLE I. THE DIFFERENCE OF SNR BETWEEN TWO DAYS

	The difference of SNR between two adjacent days SNR(Day 2) – SNR(Day 1)			
	ECG		***EMG***	
	Gel (dB)	Viscoplastic (dB)	Gel (dB)	Viscoplastic (dB)
Mean	-7.59	-2.03	-35.39	-3.40
SD	5.70	2.10	15.71	8.27

D. *The comparison of the SNR of physiological signals*

In this part, we calculated the SNR of signals under all conditions for all four subjects across different electrode groups and different physiological signals and plotted the SNR in Fig. 6. The SNR of Day 2 decreased compared to that of Day 1, illustrated by the red line located under the blue one.

To show the comparison between the change of SNR obtained in Day 1 and Day 2, the difference of SNR was calculated and presented in Table I. The difference of SNR of ECG signals obtained by gel electrodes was -7.59 ± 5.70 dB while that of ECG signals obtained by viscoplastic electrodes was -2.03±2.10 dB. In EMG session, the SNR difference obtained by gel and viscoplastic electrodes was -35.39±15.71 dB and -3.40±8.27 dB, respectively.

IV. Discussion

In clinical setting, conductive gel is often required to achieve high quality signal extraction. However, because gel is hydrous, the quality of the signals will decrease as time goes by because the gel becomes dry which makes it difficult for long-term monitoring [15]. Dry electrodes and non-contact electrodes are designed to overcome the problem. However, dry electrodes cannot ensure the stable contact impedance without using conductive gel, while non-contact electrodes are easily affected by motion artifacts [11, 13, 16]. To solve this problem, an anhydrous and viscoplastic electrodes was proposed. The viscoplastic electrodes can achieve long-term monitoring without getting dry. Besides, based on its elasticity, the viscoplastic electrodes can contact the skin more tightly.

In our study, we first compared the impedance change of these two electrode groups between two adjacent days. Results showed that all the four subjects showed the same trend on the impedance change. These results told the truth that with the conductive gel becoming dry, the impedance of gel electrodes became much higher than that of viscoplastic electrodes. That was why the physiological signals' quality degraded in Day 2. Then, we evaluated the performance of these two electrode groups in physiological signals detection task. In ECG detection task, comparing from the electrodes aspect, we could see that both electrodes groups could successfully detect ECG signals in Day 1 but the viscoplastic one had a lower amplitude which might because the different conductive principle. On Day 2, it was obvious that the ECG signals obtained by gel electrodes seemed to be submerged by noise (especially power line interference) while the signals obtained by viscoplastic one still had competitive waveforms. From the time dimension aspect, when compared with the signals obtained in Day 1, the signals on Day 2 had different degree degradation on the signal's quality. The gel electrodes degraded much more than the viscoplastic one. Similar results could be noticed on EMG detection tasks. In ECG test, the results showed that the difference of SNR of ECG obtained by gel electrodes had lower mean and larger standard deviation compared to that of viscoplastic electrodes, which illustrated that as time went by, the viscoplastic electrodes could maintain the signal' s quality better than the gel electrodes. Similar results could also be noticed on EMG detection task. Chon et al. used carbon black and PDMS to make a novel electrode which could measure physiological signals under water [17, 18]. Comparing with them, the proposed electrodes achieved better elasticity which helped to contact closely with the skin based on the mixature of boron acid. Moreover, the proposed electrodes had the potential of acquiring signals only using its stickness. For the evidence provided aforementioned, the conclusion could be drawn that the viscoplastic electrodes could be used in long-term monitoring comparing to the traditional gel electrode.

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