Performance Evaluation of Carbon Black based Electrodes for Underwater ECG Monitoring

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***Abstract*— Underwater electrocardiogram (ECG) monitoring currently uses Ag/AgCl electrodes and requires sealing of the electrodes to avoid water intrusion, but this procedure is time consuming and often results in severe irritations or even tearing of the skin. To alleviate these problems, our research team developed hydrophobic electrodes comprised of a mixture of carbon black powder (CB) and polydimethylsiloxane (PDMS) that provide all morphological waveforms without distortion of an ECG signal for dry and water-immersed conditions. Performance comparison of CB/PDMS electrodes to adhesive Ag/AgCl hydrogel electrodes was carried out in three different scenarios which included recordings from a dry surface, water immersion, and post-water immersion conditions. CB/PDMS electrodes were able to acquire ECG signals highly correlated with those from adhesive Ag/AgCl electrodes during all conditions. Statistical reduction in ECG amplitude ($p<0.05$) was only found during the immersed condition with CB/PDMS electrodes when compared to Ag/AgCl electrodes sealed with their waterproof adhesive tape. Besides this reduction readability of the recordings was not obscured and all morphological waveforms of the ECG signal were discernible. The advantages of our CB/PDMS electrodes are that they are reusable, can be fabricated economically, and most importantly, high-fidelity underwater ECG signals can be acquired without relying on the heavy use of waterproof sealing.**

I. Introduction

Humans are susceptible to hazardous conditions such as hypothermia, hypoxia, and decompression sickness [1]–[3] when exposed to cold temperatures and increased hyperbaric pressures found in depth water environments. In these situations, early detection is crucial for prompt corrective actions, and analysis of electrocardiogram (ECG) morphological changes and heart rate variability (HRV) analysis can be used for these early detection purposes. However, the cardiac health and physiological information that can be garnered from subjects fully immersed in water environments is scant due to the absence of ECG electrodes able to operate there for prolonged periods of time without time consuming and cumbersome application procedures.

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The current practice consists in waterproofing the standard Ag/AgCl electrodes [4], but this approach has many limitations including severe skin irritation and tearing of the skin which leads to prolonged recovery periods between experimental trials. Standard Ag/AgCl hydrogel electrodes also have their own limitations, e.g. gel dehydration over time, disposability of the electrodes, and expiration dates. Although high fidelity ECG signals can be observed as long as water does not penetrate the sealed Ag/AgCl electrodes, quality of the signals degrades to the point where ECG morphological waveforms are not discernible when water infiltrates the Ag/AgCl electrode-skin interface [4].

Reusable Carbon Black/Polydimethylsiloxane based electrodes (CB/PDMS electrodes) were recently developed with the aim of overcome the limitations currently faced when waterproofing clinical standard Ag/AgCl electrodes for ECG underwater monitoring [5]. The objective of this paper is to analyze their impedance behavior, and to compare their performance when exposed to dry, water immersed, and wet conditions versus the results from adhesive Ag/AgCl electrodes with and without water infiltration.

II. Materials and Methods

A. Carbon Black/PDMS electrodes

Two active components provide the basic properties of our developed hydrophobic ECG electrodes shown in Fig. 1:

1. *Polydimethylsiloxane (PDMS)*. Polymer providing an elastomeric matrix with hydrophobic, non-toxicity to cells, and elastic properties [6].
2. *Carbon Black (CB)*. Conductive material uniformly distributed inside the polymer matrix to facilitate the transport of electrons [7].

Details about the fabrication procedure and cytotoxicity tests of the CB/PDMS electrodes can be found in reference [5]. For the purpose of this study, 14 CB/PDMS electrodes of 3cm x 2mm (diameter x thickness) were fabricated.

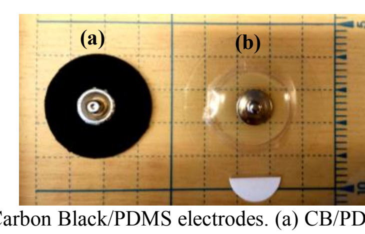

Figure 1. Carbon Black/PDMS electrodes. (a) CB/PDMS electrode, (b) Adhesive Ag/AgCl electrode. Ruler scale in cm.

B. Impedance analysis

An impedance analyzer (IM3570, Hioki E.E. Corporation; Cranbury, NJ, USA) was used to measure the electrode-skin contact impedance. Seven (N=7) pairs of electrodes were randomly created for this test. Each pair of electrodes was placed 2 cm apart from each over on the anterior forearm skin. Prior to each measurement, the skin area was cleaned with 70% isopropyl alcohol. An elastic compression bandage was used to fix them to the skin with three different pressure levels: 1) low pressure, 2) medium pressure, and 3) high pressure; with low pressure being the minimum to keep the electrodes in place and high pressure as the maximal force comfortable for the subject. Measurements were done 30 seconds after fixation to allow stabilization of skin area. All measurements were performed on the same day and the frequency range from 4 Hz to 100 kHz was selected in agreement with previous studies [8].

C. ECG Experimental Protocol

Twelve (N=12) healthy male volunteers were enrolled in this study (ages: 29.50 ± 8.93 years, weight: 74.80 ± 8.93 kg, height: 174.90 ± 5.34 cm, mean ± SD). The study protocol was approved by the Institutional Review Board of Worcester Polytechnic Institute, MA, USA. Simultaneous ECG signals from volunteers were acquired using two types of electrodes:

- *Adhesive Ag/AgCl hydrogel electrodes* (Cleartrace 1700, CONMED, Utica, NY, USA) with an active area of 2 cm diameter. Directly placed on the skin because of the waterproof adhesive surface.
- *CB/PDMS electrodes*. Kept in place with regular surgical tape (Transpore, 3M, St. Paul, MN, USA).

Electrodes were connected to Holter recorders (RZ153+, Rozinn Electronics, Glendale, NY, USA) with a sampling frequency of 180 Hz. Each set of electrodes was placed to create a 1-channel ECG recording in a configuration that mimics the traditional Lead II ECG [9]. Randomization of the Holter recorders and contiguous placing of electrodes around the selected areas were done. The 3 electrodes used for each subject were randomly selected from the fabricated batch in a way that all electrodes were reused throughout the duration of all experiments. Skin sites preparation only consisted of cleaning with 70% isopropyl alcohol. Finally, an elastic compression band was wrapped around the thoracic area containing both sets of electrodes to minimize water penetration to conductive Ag/AgCl hydrogel as well as ensure adhesion of CB/PDMS electrodes to the body sites.

Each experiment consisted of around 20 min and included the following conditions for the electrodes (Fig. 2):

I. *Dry condition*: 5 minutes in standing position outside the water.
II. *Immersed condition*: 10 minutes in seated position inside the water-filled bathtub with the water coming up to their neck.
III. *Wet condition*: 5 minutes in standing position after exiting the bathtub.

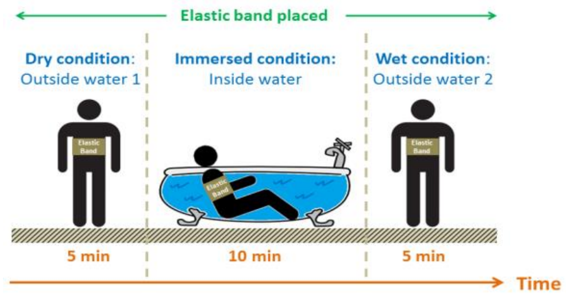

Figure 2. ECG data acquisition protocol involving dry, immersed, and wet conditions for the electrodes. Immersed condition acquired inside a bathtub for athlete's training and rehabilitation filled with temperature controlled water (33.3 ± 1.34 °C, mean ± SD).

To further compare the hydrophobicity of the two types of electrodes, the elastic band was removed from some subjects and they were asked to go back inside the bathtub and perform torso movements in water immersion condition.

D. ECG signal processing

Digital processing of acquired ECG signals included filtering with a 4^{th} order bandpass Butterworth filter between 0.05 to 4 Hz in a zero-phase distortion scheme, filtering with a non-local mean algorithm to minimize Gaussian noise observed [10], and automatically alignment of the simultaneous ECG recordings.

For each condition, a segment of at least 2 consecutive minutes was manually extracted from simultaneous ECG recordings. These segments were selected to be free of severe motion and noise artifacts simultaneously in both ECG recordings from Ag/AgCl and CB/PDMS electrodes and to allow heart rate variability analysis [11].

ECG R-wave peaks were automatically detected using a robust detection algorithm [12] and with manual correction when needed. RR interval series were computed by cubic spline interpolation with a sampling frequency of 4 Hz. The power spectrum of the RR interval series were estimated using the Welch's modified periodogram. Finally, ECG templates were computed for each condition by averaging and aligning the ECG cycles with respect to their R-peak locations.

E. Performance Evaluation

Performance of CB/PDMS electrodes was tested by extracting temporal and spectral parameters from the RR intervals as defined in the literature [11] and comparing with the corresponding ones from adhesive Ag/AgCl electrodes regarded as reference in these short-duration experiments as they were additional protected with the elastic band. Temporal HRV measures considered were: 1) mean RR interval (meanNN, ms units), 2) standard deviation of all RR intervals (SDNN, ms units), 3) square root of the mean of the sum of the squares of differences between adjacent RR intervals (RMSSD, ms units). Spectral parameters considered were: 1) power in low frequency band from 0.04-0.15 Hz (LF, ms^2 units), 2) power in high frequency band from 0.15 to 0.4 Hz (HF, ms^2 units), and 3) HF/LF ratio (unitless). ECG templates were used for two purposes: 1) to quantify the signal amplitude reduction throughout experimental different conditions via the peak-to-peak amplitude (Vpp, mV units), and 2) to quantify the signal distortion of CB/PDMS electrodes in comparison to Ag/AgCl electrodes via the cross-correlation coefficient (ρ, unitless) given by:

$$\rho = \frac{\sum_{i=1}^{N} \overline{ECG}_{Ag/AgCl} \cdot \overline{ECG}_{CB/PDMS}}{\sqrt{\sum_{i=1}^{N} \left(\overline{ECG}_{Ag/AgCl}\right)^2 \cdot \sum_{i=1}^{N} \left(\overline{ECG}_{CB/PDMS}\right)^2}} \quad (1)$$

with $\overline{ECG}$ defines the corresponding ECG template of length N. Statistical comparison between the mentioned parameters from CB/PDMS and Ag/AgCl electrodes was performed with the paired t-test with $p<0.05$ considered as significant.

III. Results

A. Impedance characterization

The CB/PDMS electrode-skin impedance was dependent on the applied pressure level and its value decreased with increasing frequency as shown in Fig. 3, where it can be seen a decrease in the CB/PDMS electrode-skin impedance as the pressure level applied to them increases. Because these results showed a small difference between a medium and a high pressure, the CB/PDMS electrodes were fixed to the body by wrapping them with a medium pressure level around the thoracic area.

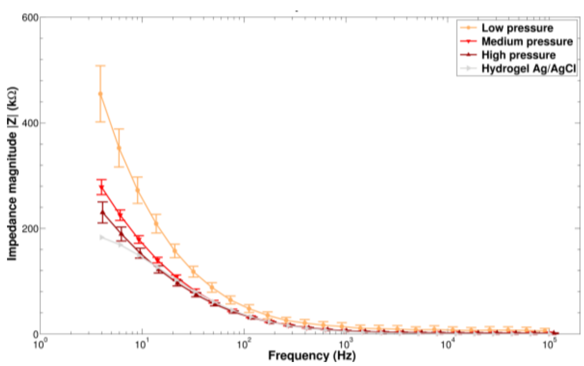

Figure 3. Electrode-skin impedance of CB/PDMS electrodes at different pressure levels. Measurements for Ag/AgCl electrodes are shown for reference.

B. ECG signal quality

The CB/PDMS electrodes were able to acquire ECG signals highly correlated with those from adhesive Ag/AgCl electrodes during dry, water immersed, and wet conditions as exemplified in Fig. 4 for one subject. The CB/PDMS electrodes were able to capture all morphological components of ECG waveforms during all conditions as shown by ECG templates exemplified in Fig. 5 from one subject. A decrease in ECG amplitude for CB/PDMS electrodes was only observed during the water immersed condition.

Statistical results of temporal and spectral HRV indices, peak-to-peak amplitudes, and cross-correlation coefficients obtained during each experimental condition for the CB/PDMS and Ag/AgCl electrodes are shown in Table I. For all experimental conditions, no significant differences ($p>0.05$) were found for all the temporal and spectral measures of HRV obtained with the CB/PDMS electrodes when compared to those obtained with the Ag/AgCl electrodes sealed with their waterproof adhesive surface.

ECG distortion seems to be low as indicated by the high cross-correlation coefficients between ECG templates from CB/PDMS electrodes in comparison to those from adhesive Ag/AgCl electrodes during all conditions.

TABLE I. ECG SIGNAL PERFORMANCE INDICES FOR EACH EXPERIMENTAL CONDITION (N=12)

Parameter	Electrodes	Dry Condition	Immersed Condition	Wet Condition
meanNN (ms)	*Ag/AgCl*	1384 ± 229	1249 ± 214	1360 ± 266
	CB/PDMS	1384 ± 229	1248 ± 213	1358 ± 265
SDNN (ms)	*Ag/AgCl*	81 ± 20	71 ± 27	98 ± 32
	CB/PDMS	82 ± 20	76 ± 24	106 ± 34
RMSSD (ms)	*Ag/AgCl*	14 ± 4	16 ± 9	16 ± 7
	CB/PDMS	14 ± 5	19 ± 9	23 ± 16
LF (ms^2)	*Ag/AgCl*	3217 ± 1831	1232 ± 1120	4062 ± 2611
	CB/PDMS	3222 ± 1838	1516 ± 1417	4206 ± 2756
HF (ms^2)	*Ag/AgCl*	622 ± 539	789 ± 1422	1000 ± 1034
	CB/PDMS	638 ± 546	1258 ± 1744	1778 ± 2591
LF/HF (unitless)	*Ag/AgCl*	7.3 ± 4.2	2.9 ± 1.4	9.2 ± 8.0
	CB/PDMS	7.3 ± 4.6	2.2 ± 1.2	6.8 ± 7.5
Vpp (mV)	*Ag/AgCl*	2.39 ± 0.75	2.14 ± 0.79	2.29 ± 0.80
	CB/PDMS	2.58 ± 0.69 *	1.52 ± 0.54 **	2.54 ± 0.62 *
ρ (unitless)	*Ag/AgCl*	---	---	---
	CB/PDMS	0.966 ± 0.051	0.978 ± 0.015	0.983 ± 0.021

Values expressed as mean ± standard deviation
* indicates higher values compared to adhesive Ag/AgCl electrodes ($p<0.05$)
** indicates lower values compared to adhesive Ag/AgCl electrodes ($p<0.05$)

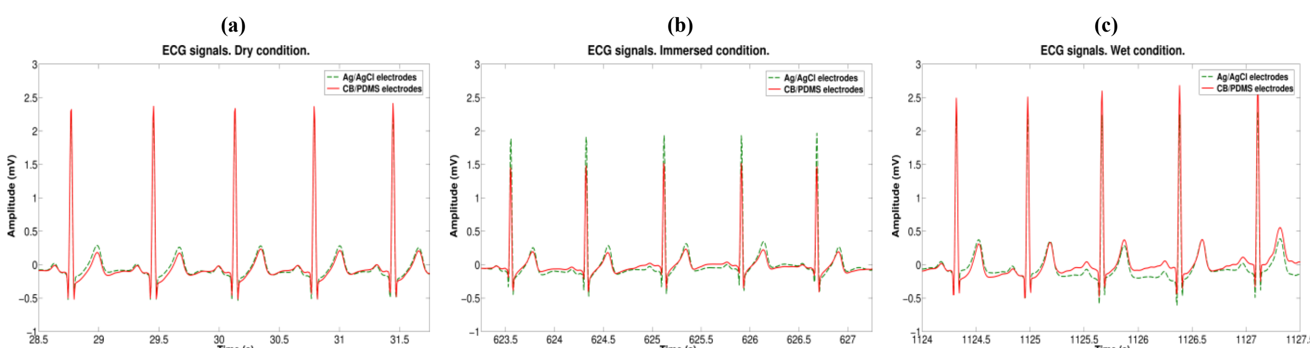

Figure 4. Example of ECG signals during each condition. (a) Initial period outside water (dry condition). (b) Inside water period (immersed condition), (c) Final period outside water (wet condition). ECG signals acquired with adhesive Ag/AgCl electrodes (green dashed line), and CB/PDMS electrodes (red solid line).

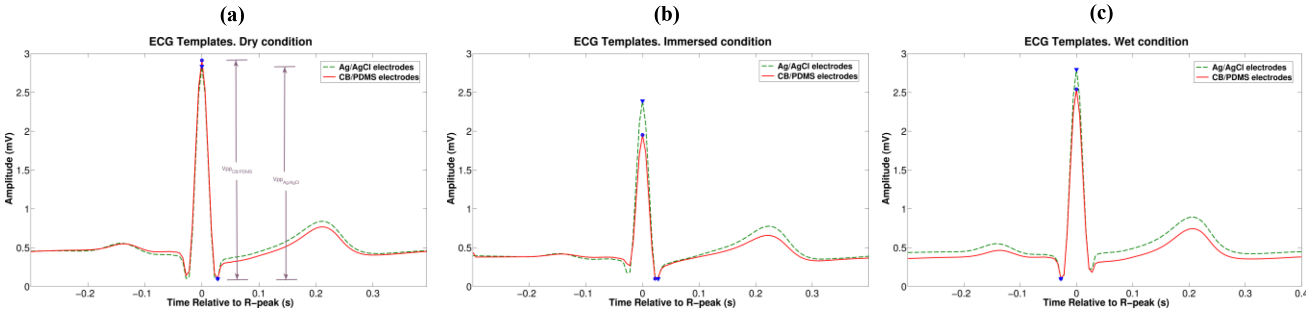

Figure 5. Example of ECG templates during each condition. (a) Initial period outside water (dry condition). (b) Inside water period (immersed condition), (c) Final period outside water (wet condition). ECG signals acquired with adhesive Ag/AgCl electrodes (green dashed line), and CB/PDMS electrodes (red solid line).

In terms of the amplitude of ECG templates, they were found to be significantly higher for the CB/PDMS electrodes compared to adhesive Ag/AgCl amplitude ($p<0.05$) during the dry and wet conditions, while they were significantly lower for the CB/PDMS electrodes compared to adhesive Ag/AgCl ($p<0.05$) during the water immersed condition.

Problems found when water penetrates the Ag/AgCl electrode-skin interface is exemplified by the ECG signals of Fig. 6 where the elastic band was removed from subject's torso resulting in exposure of Ag/AgCl hydrogel to water due to loss of their adhesive bounding to the skin. Observe that ECG waveform analysis and HRV analysis is not feasible in such situations.

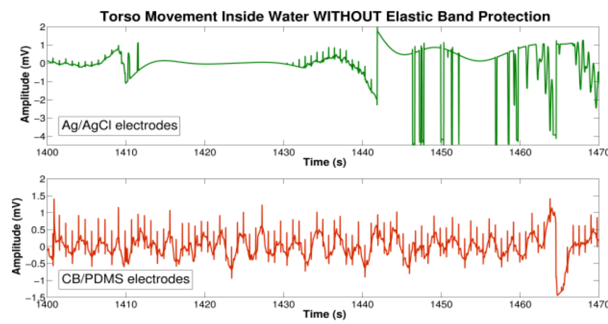

Figure 6. Example of ECG signals acquired during a body motion period inside the water without extra protection to the electrodes. Water penetrated the Ag/AgCl electrodes leading to loss of ECG signal.

IV. Discussion

In this study, different pressure levels were applied to CB/PDMS electrodes against the skin sites in order to investigate the pressure effect on the CB/PDMS electrode-skin impedance. In agreement with a previous study [8], this impedance was found to decrease as the applied pressure level increased.

The performance of the CB/PDMS electrodes was tested when the electrodes were exposed to dry, water immersed, and wet conditions in comparison to Ag/AgCl electrodes protected by their waterproof adhesive surface. In accordance to the impedance results, CB/PDMS electrodes were kept in place on the thoracic area using an elastic band wrapped with a comfortable pressure level. This wrapping over the Ag/AgCl electrodes also provided stronger adhesive bonding to the skin that water did not penetrate them and allowed us to obtain non-water contaminated ECG signals and consider them as reference to compare the CB/PDMS electrodes. As exemplified in the results section, when the Ag/AgCl electrodes lost their adhesive properties water penetrates the electrode-skin interface and leads to a highly corrupted signal from which extraction of relevant parameters could not be possible. In contrast, due to their lack of hydrogel the CB/PDMS electrodes are not affected by this issue and readable ECG signals could be still observed even during body motion periods.

Despite amplitude reduction, the CB/PDMS electrodes were able to acquire ECG morphologies comparable to that of waterproofed Ag/AgCl electrodes without relying on complicate and cumbersome preparation procedures.

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