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Preliminary Results on Transthoracic Bioimpedance Measurements with a Variety of Electrode Materials*

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Abstract— **Transthoracic bioimpedance (TBI) is a simple method for assessing body fluid accumulations, and as such can be used for early detection of heart failure. In this work, we used a comfortable vest with various electrodes that was worn daily for 5 minutes to measure bioimpedance. Five different electrode types were tested on *N* = 10 healthy volunteers: Ag/AgCl, textile, copper mesh (CM) carbon black (CB) polydimethylsiloxane (PDMS), Poly(3,4-ethylenedioxythiophene) (PEDOT) textile CB PDMS, and PEDOT salt textile CB PDMS. Inter-subject TBI and ECG tests were performed on all 5 electrode types, while the obtained results were compared to results acquired with textile electrodes. In addition, intra-subject consistencies of TBI measurements were obtained for textile and CM/CB/PDMS electrodes. Acquired TBI measurements from all electrode types were statistically different compared to textile electrodes. CM/CB/PDMS electrodes achieved the highest correlation to the textile electrodes, and the smallest 95% limits of agreement, which makes them very reliable, and a suitable alternative to textile electrodes.**

I. Introduction

Heart failure (HF) affects more than 6 million people in the US, and is the most common cause of hospitalization [1, 2]. Atrial fibrillation (AF), being the most common arrhythmia, is impacting between 3 and 6 million Americans [2-4]. Moreover, patients with HF who develop AF, which is 1 in 3 individuals, are at very high risk of developing acute decompensated HF (ADHF), which often leads to hospitalization, stroke, and death [4, 5]. Some of the ADHF symptoms are shortness of breath, chest discomfort, swelling in lower extremities, and generalized fatigue [5, 6]. Therefore, the detection of ADHF requires measurement of lung fluid [5, 7]. One method, the most widely used for ADHF detection, is to simply weigh patients daily, to have an indication of total fluid accumulation. This is an inexpensive and noninvasive method, however not ideal as weight change weakly correlates with the ADHF symptomatology [8]. Therefore, there is an urgent need for a reliable, noninvasive, easy-to-use, affordable, and automated device for ADHF detection.

To this end, transthoracic bioimpedance (TBI) became a promising approach for detection of intrathoracic volume retention, and is used to measure fluid accumulation in the lung [9, 10]. TBI uses electrodes to inject alternating current, usually less than 1 mA, into the tissues, and to measure the response. Some bioimpedance (BIM) measurement devices are using adhesive electrodes, such as silver-silver chloride (Ag/AgCl) hydrogel, for measuring fluid accumulation from the skin, however, the problem in those set-ups is the poor repeatability of electrode placement on the skin, as well as the misalignment of the electrode positions. In order to overcome this limitation, textile electrodes, usually four electrodes, embedded into a wearable vest were proposed by some device manufacturers [11, 12]. Textile electrodes require wetting before each use, because it improves signal fidelity. However, this requirement is a major limitation of textile-based electrode bioimpedance monitors. In addition, textile electrodes shift with body movement, which introduces even more variability in the impedance measurement outcomes [11, 12]. Recently, our group developed reusable dry carbon black (CB) polydimethylsiloxane (PDMS) electrodes that need no wetting prior to acquiring signals, and exhibit high tolerance to motion artifacts [13, 14].

Therefore, in this paper we explore the possibility of using dry carbon black (CB) polydimethylsiloxane (PDMS)-based electrodes with a vest for daily collection and monitoring of transthoracic bioimpedance, as well as electrocardiography (ECG) signals. We collected signals with three types of carbon black-based electrodes, textile electrodes, and Ag/AgCl hydrogel adhesive electrodes. We foresee that this in-home monitoring system could overcome the current devices' limitations, i.e., inaccuracies due to electrode misplacements on the skin, the existence of motion artifacts, and usability problems due to the necessity of wetting the electrodes.

II. Methods and Materials

A. Transthoracic Bioimpedance (TBI)

Transthoracic bioimpedance is a noninvasive and simple method for measuring body fluid accumulations [15]. The idea behind this method is to measure the impedance of the tissue at a series of frequencies. A small alternating current is injected into the tissue, while the complex impedance is measured as an output. This way, the conductivity of the tissue is obtained.

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A typical way to model biological tissue is with a resistance R_0 to represent the extra-cellular fluid, in parallel with a resistance R_I, to represent intra-cellular fluid, and a capacitance C_m to represent cell membranes [16]. At zero frequency, $f = 0$, the current runs around all cells, in which case the total resistance is equal to the resistance from the extra-cellular fluid only, i.e., R_0. On the other hand, when frequency is infinite, $f = \infty$, the current can run through the cells, in which case the total resistance can be represented as the parallel circuit of R_0 and R_I, i.e.

$$R_\infty = \frac{R_0 \times R_I}{R_0 + R_I}. \quad (1)$$

By rearranging (1), we can calculate R_I:

$$R_I = \frac{R_0 \times R_\infty}{R_0 - R_\infty}. \quad (2)$$

By measuring whole-body impedance over a range of frequencies, after applying the well-known Cole-Cole model [17], we obtain an arc-like plot, known as a Cole-Cole plot, in the impedance plane [16, 18]. In this study, we used 16 different frequencies in the range from 10 to 999 kHz.

It is worth noting that a low amount of extra-cellular fluid will result in a high value of R_0, whereas a low amount of intra-cellular fluid will lead to high value of R_I. Since relative amounts of body fluids can be derived from R_0 and R_∞, these are the two parameters we computed in this study.

B. Experimental Set-up

Ten healthy volunteers participated in this study, $N = 10$ (5 males, 5 females), with ages ranging from 18 to 54 years (mean ± SD: 27.7 ± 11.6), weight 62.9 ± 11.5 kg, and height 171.5 ± 8.3 cm. The study protocol was approved by the Institutional Review Board of the University of Connecticut, and all volunteers signed the consent form.

At the beginning of the experiment and before signal acquisition, volunteers were asked to scrub their skin on the lateral side of the abdomen, to remove any undesirable excess of dead cells. Prior to placement of any electrode type, the skin was cleaned with 70% isopropyl alcohol. In addition, every electrode was also cleaned with alcohol to remove any remaining sweat. During the experiment, the Heart Cycle vest (Philips, Eindhoven, the Netherlands) was employed, and is shown in Fig. 1. In order to secure the position of the electrodes during the data collection, an elastic strap was applied over the vest, as shown in Fig. 1A. At the back of the vest we attached a measuring device (Fig. 1B) that was paired via a secure Bluetooth connection with a mobile phone (Samsung Galaxy Gio GT-S5660, Samsung Electronics Co., Seoul, South Korea).

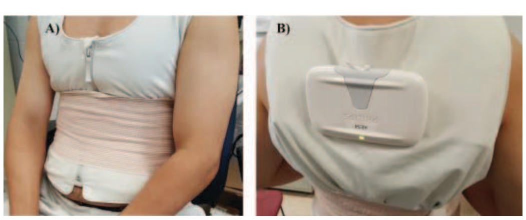

Figure 1. Subject wearing the Heart Cycle vest. A) Front side of the vest and elastic strap; B) Back side of the vest showing the measuring device.

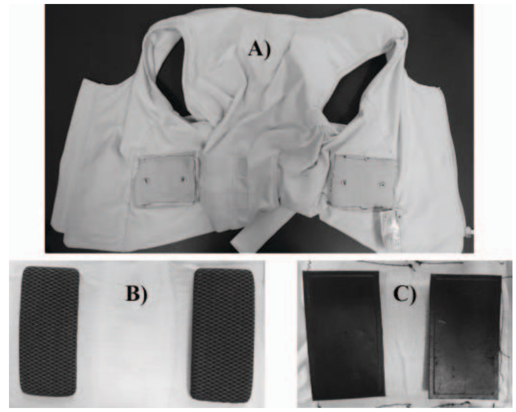

Figure 2. A) Heart Cycle vest with snap connectors; B) Original embedded textile electrodes; C) Carbon black PDMS electrodes attached to the vest with two electrodes on both sides

We tested five types of electrodes for collection of TBI and ECG signals: 1) commercially available Ag/AgCl (CLEARTRACE 1700-005, CONMED Corporation, Utica, NY); 2) textile electrodes (Philips, Eindhoven, the Netherlands); 3) copper mesh carbon black polydimethylsiloxane (CM/CB/PDMS) [14]; 4) Poly(3,4-ethylenedioxythiophene) (PEDOT) textile CB PDMS (PT/CB/PDMS); and 5) PEDOT salt textile CB PDMS (PST/CB/PDMS). The Heart Cycle vest has textile electrodes already embedded, while for the other four electrode types we modified the vest so that the electrodes could be attached to it via snap connectors, as shown in Fig. 2A. The original embedded textile electrodes are shown in Fig. 2B, while the carbon black PDMS electrodes are shown in Fig. 2C. Note that all three types of carbon black PDMS-based electrodes look identical.

The experiments we performed consisted of two parts: 1) inter-subject TBI and ECG tests, and 2) intra-subject TBI measurements. For both parts, the volunteers were asked to wear the Heart Cycle vest with four electrodes of the same type, positioned on both sides of their abdominal region. Volunteers were asked to stay still in a seated posture for five minutes at a time while the recordings were acquired. TBI and ECG recordings were stored in an extractable memory, and transferred to a PC for further analyses.

During the inter-subject TBI and ECG tests, each of the five types of electrodes was used consecutively in the following order: Ag/AgCl, textile, CM/CB/PDMS, PT/CB/PDMS, and PST/CB/PDMS. For these measurements, the textile electrodes were considered as reference, since they are embedded in the vest. Hence, once R_0 and R_∞ values were procured from all electrode types, the t-test was used for determining the statistically-significant differences with respect to the values obtained with textile electrodes. In addition, Bland-Altman analyses were performed with respect to the textile electrodes. Regarding the ECG measurements, amplitudes of the obtained R-peaks were calculated, and compared to the values procured with textile electrodes using t-test as well.

The intra-subject TBI test was implemented with a goal to explore the consistency of repeated bioimpedance measurements acquired with two electrode types of interest, for the same volunteer. These measurements should exhibit low variations. For this test, the following electrode types were selected: textile, and CM/CB/PDMS electrodes. Volunteers consecutively repeated TBI measurements with each electrode type five times. Bland-Altman analyses were used for both R_0 and R_∞ values.

III. Results

An example of the Cole-Cole plots for all five electrode types for one of the volunteers is shown in Fig. 3. The resulting values of R_0 and R_∞, as well as the peak-to-peak ECG amplitudes calculated for $N = 10$ volunteers are presented in Table I. As can be noted, R_0 and R_∞ values for all electrode types were significantly different than for textile electrodes. Textile electrodes provided the lowest values for both R_0 and R_∞, 20 ± 1.9 Ω and 8.7 ± 2.7 Ω, respectively, represented as mean ± standard deviation. The possible cause for this could be the textile material itself. Regarding the peak-to-peak ECG amplitudes, no significant differences were found between any of the tested electrodes and textile electrodes.

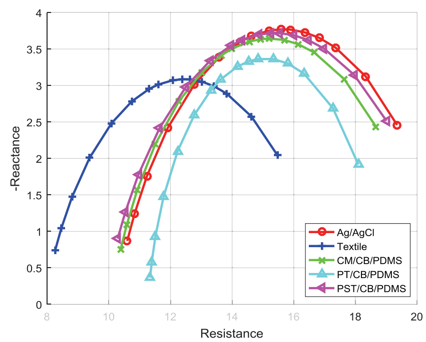

Figure 3. Cole-Cole plots for all five electrode types acquired on one volunteer.

TABLE I. Resulting Values of R_0 and R_∞ and Peak-to-peak ECG Amplitudes For $N = 10$ Volunteers

Electrode Type	R_0 (Ω)	R_∞ (Ω)	ECG amplitudes (V)
Ag/AgCl	22 ± 2.2*	11 ± 1.5*	1.5 ± 0.72
Textile	20 ± 1.9	8.7 ± 2.7	1.6 ± 0.65
CM/CB/PDMS	25 ± 3.4*	12 ± 2.3*	1.55 ± 0.74
PT/CB/PDMS	24 ± 3.2*	12 ± 2.7*	1.44 ± 0.92
PST/CB/PDMS	25 ± 3.1*	12 ± 2.2*	1.55 ± 0.68

Values are expressed as mean ± standard deviation.
*Statistically significant difference with respect to Textile ($p < 0.05$)

The results from the Bland-Altman analysis are presented in Table II. The mean value of the five consecutive measurements acquired with textile electrodes was considered as a reference. As can be noted from Table II, the CM/CB/PDMS electrodes achieved the highest r^2 for both R_0 (0.84) and R_∞ (0.74) measurements, and the smallest 95% limits of agreement for R_0, 2.32 – 8.52 Ω. The bias between CM/CB/PDMS and textile electrodes was the highest for R_0, 5.42 Ω, however it is worth noting that the main goal of this study was not to obtain identical TBI measurements to the ones procured with textile electrodes, but to explore whether CM/CB/PDMS could be used for acquisition of reliable and consistent TBI measurements. Bland-Altman plots for R_0 and R_∞ values between the CM/CB/PDMS and textile electrodes are shown in Fig. 4.

TABLE II. Bland-Altman Analysis Results For Inter-Subject Test For R_0 and R_∞ And $N = 10$ Volunteers

					95% limits of agreement	
	r^2	bias (Ω)	1.96·sd (Ω)	sd (Ω)	lower (Ω)	upper (Ω)
	R_0					
Ag/AgCl	0.46	2.15	4.31	2.20	-2.16	6.46
CM/CB/PDMS	**0.84**	**5.42**	**3.10**	**1.58**	**2.32**	**8.52**
PT/CB/PDMS	0.30	3.23	5.73	2.92	-2.50	8.96
PST/CB/PDMS	0.44	4.37	4.89	2.50	-0.52	9.26
	R_∞					
Ag/AgCl	0.62	1.50	2.13	1.09	-0.63	3.64
CM/CB/PDMS	**0.74**	**2.22**	**2.80**	**1.43**	**-0.58**	**5.02**
PT/CB/PDMS	0.20	2.41	4.83	2.46	-2.41	7.24
PST/CB/PDMS	0.76	1.85	2.13	1.06	-0.28	3.97

r^2: coefficient of determination; sd: standard deviation.

The intra-subject TBI analysis was implemented only on the two selected types of electrodes: textile and CM/CB/PDMS. Bland-Altman analyses between the mean values of the five consecutive measurements obtained with each electrode type separately and the corresponding single measurement procured during the first part of the experiment were performed. The results are shown in Table III. As can be noted, the CM/CB/PDMS electrodes again achieved the highest r^2, and the smallest 95% limits of agreement for both R_0 (0.86, and -3.96 Ω to 1.63 Ω, respectively) and R_∞ (0.88, and -1.98 Ω to 1.68 Ω, respectively). In addition, the bias for R_∞ was smaller for CM/CB/PDMS electrode than for textile, and had value of -0.15 Ω. These results imply that the CM/CB/PDMS electrodes are providing reliable and consistent TBI measurements.

TABLE III. Bland-Altman Analysis Results For Intra-Subject Test For R_0 and R_∞ And $N = 10$ Volunteers

					95% limits of agreement	
	r^2	bias (Ω)	1.96·sd (Ω)	sd (Ω)	lower (Ω)	upper (Ω)
	R_0					
Textile	0.79	-0.64	3.02	1.54	-3.67	2.38
CM/CB/PDMS	**0.86**	**-1.17**	**2.80**	**1.43**	**-3.96**	**1.63**
	R_∞					
Textile	0.50	-1.08	3.79	1.93	-4.86	2.71
CM/CB/PDMS	**0.88**	**-0.15**	**1.83**	**0.93**	**-1.98**	**1.68**

r^2: coefficient of determination; sd: standard deviation.

IV. Conclusion

The objective of this study was to explore the possibility of dry carbon black-based electrodes being used for collection and monitoring of transthoracic bioimpedance and ECG signals. We have tested five electrode types (Ag/AgCl, textile, CM/CB/PDMS, PT/CB/PDMS, and PST/CB/PDMS)

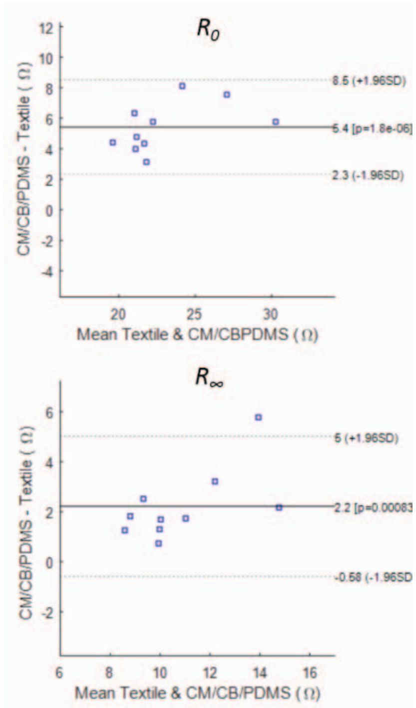

Figure 4. Bland-Altman plots for R_0 and R_∞ values between CM/CB/PDMS and textile electrodes.

on 10 healthy volunteers. Textile electrodes embedded in the Heart Cycle vest detected the lowest values of both R_0 and R_∞. All electrode types achieved similar peak-to-peak ECG amplitude values, which shows that all 5 types are equally good for monitoring and collection of ECG signals. We have found good correlation between CM/CB/PDMS and textile electrodes for both R_0 and R_∞, with r^2 of 0.84 and 0.74, respectively. In addition, the CM/CB/PDMS electrodes exhibited very small values of 95% limits of agreement, which represents good agreement between these electrodes and reference electrodes.

These preliminary results show that the dry carbon black-based electrodes could be a suitable alternative to the textile electrodes for measuring TBI and ECG via the Heart Cycle vest. In our future work, we plan to expand the number of volunteers of both genders.

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