Comparison of Different Polymeric Materials for Mobile Off-the-Person ECG

Daniel N. Osório, Alexandre Pitães, Nuno Gonçalves, Ricardo Freitas, Carlos Ribeiro, Ricardo Sá, Hugo Gamboa, and Hugo P. Silva

1 Introduction

Home health care has seen a significant growth over the recent years, with both an increasing interest by individuals in self-managing their health and an increase in preference for aging at home rather than in an institution [3]. This has been possible due to major advances in technology, increasing the availability of health solutions, which in turn helps patients to gain more flexibility, and helps physicians in the assessment of the health of the patient, providing insights into their daily life [1].

One of those technologies is the electrocardiogram (ECG), a measure of the heart's electrical activity. With cardiovascular diseases (CVDs) being responsible for a large percentage of deaths worldwide, proper monitoring of the heart by health professionals is more important than ever [4, 7], and recent studies emphasize the decrease in mortality due to prevention and acute care [2].

D. N. Osório (✉) · H. Gamboa
LIBPhys-UNL - Lab. de Instrumentação, Eng. Biomédica e Física da Radiação, Caparica, Portugal
e-mail: d.osorio@fct.unl.pt

H. P. Silva
PLUX - Wireless Biosignals, S.A., Lisboa, Portugal

IT - Instituto de Telecomunicações, Lisboa, Portugal

EST/IPS - Escola Superior de Tecnologia do Instituto Politécnico de Setúbal, Setúbal, Portugal

A. Pitães · N. Gonçalves · R. Freitas · C. Ribeiro
PIEP - Innovation in Polymer Engineering, Guimaraes, Portugal

R. Sá
SIOSLife - For Younger Spirits, Braga, Portugal

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The placement of the electrodes used in recording this activity can be divided into three different categories according to their intrusiveness, namely: in-the-person, on-the-person, and off-the-person [6]. In-the-person refers to devices that are designed to be either surgically implanted,[1] placed sub-dermal, or ingested. On-the-person devices are those where the electrodes are attached directly on the body surface and are the most common type of devices. The least intrusive are the off-the-person devices, where the electrodes are embedded into objects, recording an ECG signal when the user interacts with them.

In the context of telehealth continuous monitoring, an off-the-person monitoring solution provides a frequent ECG signal source with low intrusiveness. There are already some devices on the market offering off-the-person ECG, focusing on embedding the electrodes on smart-phone cases, building some wireless accessories, or telehealth systems,[2] but these devices rely on stainless steel electrodes, which are difficult to embed.

This paper focuses on the evaluation of different types of polymeric electrodes to be used in a mobile off-the-person ECG monitoring approach. The usage of polymeric electrodes makes it easier to embed the sensors in end-user devices (e.g., a tablet or mobile phone), allowing the production of cases for different devices capable of capturing the ECG signal with relatively low production costs and in a user friendly way. In the following sections, a brief description of all the materials is presented, as well as the methodology used to perform the comparison between the different materials, ending with the results for each of the metrics used and a reflection about them.

2 Material and Methods

2.1 Polymeric Materials

In the scope of our work, different materials were tested, namely: stainless steel (SS) rectangles pads, used to get a baseline since they are widely used as a dry electrode in the state of the art; PolyOne's OnForce (PO), a polyamide with high elastic modulus and material strength; Vectra's 840i LDS LCP (LDS), a liquid crystal polymer modified to be used in printed circuit boards; LUVOCOM 1850-8023 PTB (LV), a polybutylene terephthalate polymer reinforced with carbon fiber designed to be electrically conductive; ET445 (CF), carbon fiber using an epoxy matrix; and RTP's 199 X 137556 E (RTPE), a polypropylene reinforced with carbon and stainless steel fibers designed for electrical conductive solutions.

[1] Medtronic Reveal LINQ.

[2] AliveCor Kardia Band and Kardia Mobile or Docobo Careportal.

2.2 Data Acquisition

To benchmark the different electrode materials for the purpose of ECG data acquisition, a biosignalsplux system from PLUX[3] was used. This hardware is capable of recording data up to 4000 Hz with a 16-bit resolution. For this study, a sample rate of 1000 Hz was chosen. A BITalino (r)evolution[4] ECG sensor was used, with the interface to each of the materials being done using metal alligator clips. This sensor can be used in a configuration using only two electrodes, a positive and a negative terminal, using a virtual ground to improve the common-mode rejection [5]. This configuration was used to simulate the assembly on a practical use case of hardware integration in a mobile device, which will have only two polymeric surfaces to record the signal.

To compare the usability of each material as an electrode, more specifically, if it was able to record a cardiac trace with medical grade quality, data from a clinical grade ECG system was simultaneously recorded. To this effect, a GE© MAC 800 ECG unit was used as gold standard. This system is capable of recording a 12-lead ECG with a sampling rate of 500 Hz, and exports the recordings in digital format as XML files (with a recording window length of only 10 s).

In [6], the authors state that the ECG signal obtained from electrodes placed between both hands correlates with lead I of the 12-lead ECG medical placement system. As such, out of the 12-leads, only lead I was recorded. The electrodes were placed following a typical Einthoven-triangle lead placement: one electrode on the right wrist and one on the left wrist. A third electrode, the reference (or ground), was placed in the right leg. A representation of the electrode placement can be seen in Fig. 1.

2.3 Experimental Protocol

To test the similarity of both signals, data was acquired simultaneously using the aforementioned setup using the following experimental protocol:

1. On the material in study, make a marking at 1, 2, and 3 cm from the electrode-alligator clips interface;
2. Place the MAC 800 system electrodes on the user, and verify the ECG signal;
3. Start data recording on the biosignalsplux software[5];
4. Ask the subject to hold the material at the 1 cm mark, wait for the signal from the electrode to stabilize (if possible) and record a 10 s window on the MAC 800;
5. Repeat the previous step for the remaining distances;
6. Export the data from the MAC 800 and change material.

[3] http://biosignalsplux.com/en/.

[4] http://bitalino.com/en/.

[5] http://biosignalsplux.com/en/software/opensignals.

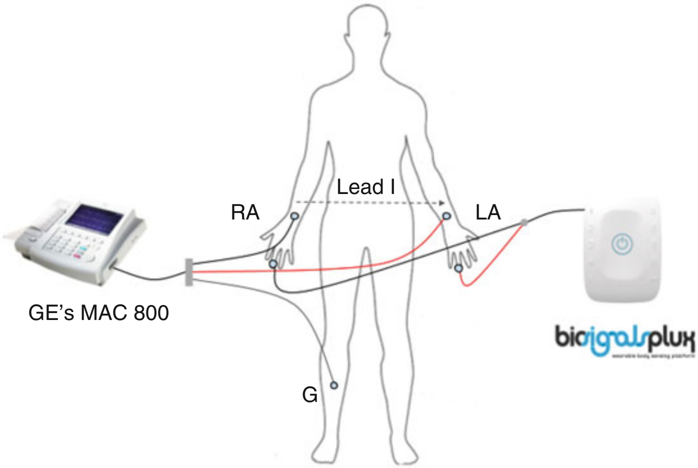

Fig. 1 Electrode placement for both signal recording systems. RA: Right Arm; LA: Left Arm; G: Reference/Ground

This protocol was used in four different test subjects, all of them males and with no reported cardiac pathology. Their mean age was 24.5 years with a 2.6 years standard deviation.

2.4 Data Processing and Signal Similarity

The first step was downsampling the biosignalsplux ECG to 500 Hz, in order to be compared with the ECG recorded using the MAC800. Afterwards, both ECG sources were time aligned. To that effect, the beat to beat pattern from the 10 s ECG of the MAC800 was matched to that obtained using the polymeric electrodes, with the R peak positions used to obtain the matching sequence. The R peak location was manually annotated. After synchronizing the signals, a digital notch filter with a cutoff frequency of 50 Hz was used to reduce power-line interference. Each source was then segmented by beats and each beat was standardized (Eq. (1)) and also normalized (to calculate the root mean square error, Eq. (2)), where μ is the signal average and σ the signal standard deviation. Figure 2 serves as an example of the processing stage output.

To compare the similarity of the signals, each beat from both sources was compared using the cosine similarity (Eq. (3)), root mean square error (RMSE, Eq. (4)), and Spearman correlation coefficient (Eq. (5)). To calculate the RMSE, the signal is normalized (Eq. (2)) instead of standardized. The cosine distance was used since its result is independent from the magnitude of the input signals, giving an output between [0, 1], with 1 being very similar signals and 0 very dissimilar signals. The RMSE gives a magnitude dependent signal, and therefore both inputs must be

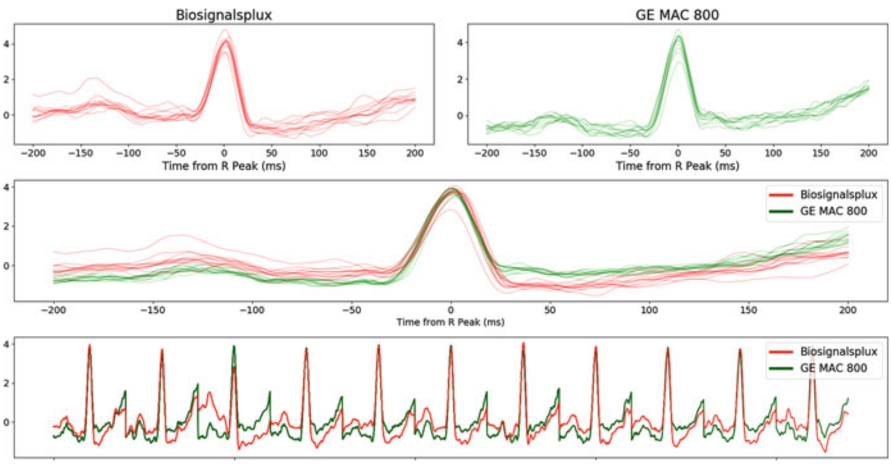

Fig. 2 Example of heart beat segmentation. Biosignalsplux signal acquired using LDS electrodes

normalized. This metric is an indication of the mean difference between both waves. Finally, the Spearman correlation was used to provide an alternative objective metric between the two waves. Unlike the two mentioned before, the correlation was used to assess the linear relation between them in addition to their morphological similarity. The range of results span from −1 (perfect negative correlation), 0 (no correlation), and 1 (perfect positive correlation).

$$x_{stand}(k) = \frac{x[k] - \mu(x)}{\sigma(x)} \tag{1}$$

$$x_{norm}(k) = \frac{x[k] - \min(x)}{\max(x) - \min(x)} \tag{2}$$

$$cos_{sim} = \frac{\sum_{i=1}^{n} x_i y_i}{\sqrt{\sum_{i=1}^{n} x_i^2}\sqrt{\sum_{i=1}^{n} y_i^2}} \tag{3}$$

$$d_{RMSEnorm} = \sqrt{\frac{\sum_{i=1}^{n} (x_{norm\ i} - y_{norm\ i})^2}{n}} \tag{4}$$

$$r_s = 1 - \frac{6\sum_{i=1}^{n}(rank(x_{norm\ i}) - rank(y_{norm\ i}))^2}{n(n^2 - 1)} \tag{5}$$

In Eq. (3), x_i and y_i are, respectively, the reference signal and the signal using the polymeric electrodes, with n the total number points. In Eqs. (4) and (5), $x_{norm\ i}$ and $y_{norm\ i}$ are, respectively, the normalized reference signal and the normalized signal using the polymeric electrodes, with n the total number points. The rank function is built in the correlation function from the Python SciPy library.

3 Results

The results for cosine similarity can be seen in both Fig. 3 and Table 1. Examining the box plots in Fig. 3 and Table 1, both PO and LDS have a very high similarity between the signals recorded using these materials and the reference, having comparable values to those obtained using stainless steel. In Fig. 3, a blue vertical line separates these materials from the remaining LV, CB, and RTPE. With LV, the similarity values are more inconsistent; however, the mean value using all subjects and all distances is still high.

Distance between the point of contact of the subject with the material and the sensor interface does not appear to play a big role in the first three materials, with their standard deviation being relatively small for each individual. For the final three, there is an increase in the standard deviation, with RTPE being the most affected by distance.

The results for the RMSE can be seen in both Fig. 4 and Table 2. The results for RMSE are in alignment with those obtained from signal similarity analysis, with PO and LDS having low RMSE and the remaining materials having a bigger and more scattered value.

The results for the Spearman correlation can be seen in both Fig. 5 and Table 3. Again, the results are consistent with the previous metrics; however, there is a higher dispersion in the results of PO and LDS when compared with stainless steel.

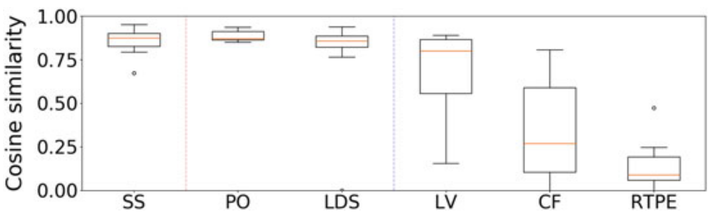

Fig. 3 Cosine similarity for each material. Values near to 1 represent more similar signals

Table 1 Cosine similarity values for each material and at different distances from the alligator clips

Distance	SS	PO	LDS	LV	CF	RTPE
1 cm	0.88 ± 0.06	0.89 ± 0.02	0.84 ± 0.07	0.66 ± 0.30	0.31 ± 0.34	0.16 ± 0.18
2 cm	0.89 ± 0.02	0.89 ± 0.03	0.87 ± 0.02	0.65 ± 0.17	0.38 ± 0.26	0.13 ± 0.10
3 cm	0.80 ± 0.08	0.88 ± 0.03	0.67 ± 0.39	0.79 ± 0.12	0.36 ± 0.27	0.10 ± 0.06
Mean	0.86 ± 0.07	0.89 ± 0.03	0.79 ± 0.24	0.70 ± 0.22	0.35 ± 0.29	0.13 ± 0.13

Values near to 1 represent more similar signals

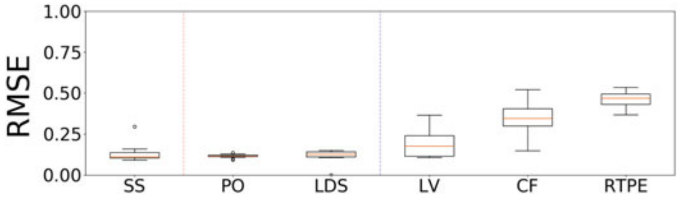

Fig. 4 RMSE for each material. Values near to 0 represent more similar signals

Table 2 RMSE values for each material and at different distances from the alligator clips

Distance	SS	PO	LDS	LV	CF	RTPE
1 cm	0.12 ± 0.02	0.11 ± 0.01	0.14 ± 0.02	0.20 ± 0.09	0.33 ± 0.09	0.45 ± 0.06
2 cm	0.11 ± 0.01	0.12 ± 0.01	0.13 ± 0.01	0.24 ± 0.09	0.35 ± 0.08	0.48 ± 0.04
3 cm	0.17 ± 0.08	0.12 ± 0.00	0.09 ± 0.05	0.15 ± 0.03	0.34 ± 0.13	0.47 ± 0.02
Mean	0.13 ± 0.05	0.12 ± 0.01	0.12 ± 0.04	0.19 ± 0.08	0.34 ± 0.11	0.46 ± 0.05

Values near to 0 represent more similar signals

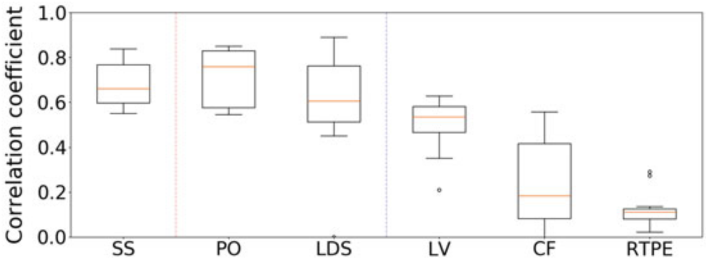

Fig. 5 Correlation for each material. Values near to 1 represent more similar signals

Table 3 Correlation values for each material and at different distances from the alligator clips

Distance	SS	PO	LDS	LV	CF	RTPE
1 cm	0.71 ± 0.10	0.73 ± 0.10	0.67 ± 0.13	0.50 ± 0.17	0.19 ± 0.24	0.15 ± 0.08
2 cm	0.71 ± 0.08	0.73 ± 0.13	0.67 ± 0.16	0.48 ± 0.08	0.29 ± 0.18	0.13 ± 0.09
3 cm	0.64 ± 0.09	0.70 ± 0.13	0.47 ± 0.30	0.54 ± 0.05	0.23 ± 0.18	0.08 ± 0.05
Mean	0.69 ± 0.09	0.72 ± 0.12	0.61 ± 0.23	0.51 ± 0.12	0.23 ± 0.21	0.12 ± 0.08

Values near to 1 represent more similar signals

4 Conclusion

The comparison between the different materials and a clinical grade ECG system revealed that stainless steel, PolyOne's OnForce (PO), and Vectra's 840i LDS LCP (LDS) is very similar to their respective clinical grade signal when comparing waveform morphology. Considering that stainless steel is widely used as an electrode, the results obtained for PO and LDS point to their possible use in this role.

By being polymeric materials, these materials are more easily embedded, e.g., in a casing of a mobile device. For the rest of the materials tested, the waveform morphology was very different, with these differences easily visible on the result section boxplots. For metal, PO, and LDS, distance does not play a significant role, with their standard deviations being relatively small. These results do not reflect the difficulty in gathering a clean segment of ECG signal. With the exception of stainless steel, PO, and LDS, it was very difficult to gather a 10 s window of clean signal, either due to the signal taking too long to stabilize or being impossible to record it.

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