Experimental Study and Evaluation of Paper-based Inkjet Electrodes for ECG Signal Acquisition

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Abstract: Applications involving biosignals, such as Electrocardiography (ECG), are becoming more pervasive with the extension towards non-intrusive scenarios helping targeting ambulatory healthcare monitoring, emotion assessment, among many others. In this study we introduce a new type of silver/silver chloride (Ag/AgCl) electrodes based on a paper substrate and produced using an inkjet printing technique. This type of electrodes can increase the potential applications of biosignal acquisition technologies for everyday life use, given that there are several advantages, such as cost reduction and easier recycling, resultant from the approach explored in our work. We performed a comparison study to assess the quality of this new electrode type, in which ECG data was collected with three types of Ag/AgCl electrodes: i) gelled; ii) dry iii) paper-based inkjet printed. We also compared the performance of each electrode when acquired using a professional-grade gold standard device, and a low cost platform. Experimental results showed that data acquired using our proposed inkjet printed electrode is highly correlated with data obtained through conventional electrodes. Moreover, the electrodes are robust to high-end and low-end data acquisition devices.

1 INTRODUCTION

Pervasive healthcare applications are becoming an invaluable tool for regular and non-intrusive monitoring. Biosignals play an important role in this kind of applications since they give information about the state of several vital organic tissues. Electrocardiographic (ECG) signals are probably the most well-known biosignals, and can be found in multiple applications in the medical and quality of life domains. It is commonly used to assess the overall cardiac function, measure the rate and regularity of heartbeats, and detect the presence of any pathology in the heart. The classical acquisition methods used in clinical or research studies typically recur to gelled silver/silver chloride (Ag/AgCl) electrodes. Given that ECG data acquisition has become more pervasive and inexpensive, enabling an easy access to continuous monitoring of the cardiac function, new and cheapest solutions have been proposed, with more practical electrodes and acquisition setups (Silva et al., 2011; Silva et al., 2013).

Paper has several advantages for ECG data acquisition in daily life scenarios; it enables: a) lower production costs; b) easier recycling; and c) simpler production, especially when considering the possibility of inkjet printing. When compared to plastic substrates such as polyethylene terephtalate (PET, ≈ 2 cent dm^{-2}) and polymide (PI, ≈ 30 cent dm^{-2}), paper has significantly lower production costs (≈ 0.1 cent dm^{-2}). In addition to this, considering the active disassembly design principles (Chiodo and Ijomah, 2012), paper is a good choice due to its environmentally friendly characteristics. Recently, it has been considered as a potential substrate for low-cost flexible electronics (Siegel et al., 2010; Leenen et al., 2009), which motivated us to do research on the possibility of using paper-based electrodes for biosignals acquisition. With such an approach and its ready availability, the electrodes can even be produced by the user himself or his caregivers.

The deposition of the conductive part of the electrodes to the paper substrate can be made recurring to photo-lithography, vacuum processes or printing

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techniques. The use of printing techniques for fabricating electronics has several advantages over laboratory scale and subtractive batch processes (Tobjörk and Österbacka, 2011); printing is fast, low-cost, and widely used. In particular digital inkjet printing, which has been used as a research tool, is facilitating initial explorations of various aspects of printed electronics targeting the consumer market (Singh et al., 2010). The focus of this work was to explore the potential use of paper-based inkjet printed electrodes for ECG signal acquisition.

The most commonly used type of electrode is the gelled Ag/AgCl electrode; however, to make an acquisition setup more convenient for everyday use applications, other alternatives are emerging. Previous work from our group has started to explore the use of dry Ag/AgCl electrodes (Silva et al., 2011), which usually leads to signals with lower signal-to-noise ratio, although still suitable for monitoring or other non-intrusive applications. Thus, to study the characteristics of the paper-based inkjet printed electrodes, we perform a comparative study against the most common alternatives: i) gelled; ii) dry.

The remainder of the paper is organized as follows: in Section 2 we describe the proposed electrodes, focusing on their production and main characteristics; Sections 3 and 4 present the methodology applied in the comparison of the different electrode types and their quantitative evaluation; and finally, in Sections 5 and 6 we provide a summary of the experimental results and outline the main conclusions.

2 PAPER-BASED INKJET PRINTED ELECTRODES

The possibility of printing materials using inkjet technology brought several advantages to the conventional manufacturing procedures used, such as photolithography, transfer printing, among others. Comparing with those standard techniques for patterning thin films with high precision, some differences stand out. The appeal of inkjet technology lies in the fact that it is based on contactless deposition, which implies a lesser risk of contaminating the material, it is a maskless approach that makes an intuitive procedure, and it is an additive procedure, i.e., it is possible to print over a previous printed pattern (Singh et al., 2010).

Producing electrodes by inkjet printing enables the use of thin and flexible substrates that may also be biocompatible, examples of which are polydimethylsiloxane (PDMS) or biocellulose. On the other hand, low-cost paper-like substrates such as photo paper can be used as an alternative substrate and several conductive inks can already be used, such as silver, gold or conductive polymer (Calvert, 2001)).

We fabricated the electrodes using photo paper as substrate, due to its flexibility, availability, reduced thickness (230 μm) and easy maneuverability. To create the conductive part of the electrode we used a commercial printable silver ink from SunTronic, which is composed of silver nanoparticles and has been shown to provide good electrical conductivity for electronic applications.

The electrodes devised in the scope of our work were designed as a flat rectangle shape, with dimensions of 8 cm length, 3 cm width and approximately 1 μm thick. Each electrode has a total of 24 cm^2 of area in contact with the skin. The electrodes were first printed with four silver layers and aftwerwards subjected to heat treatment during 20 minutes at a temperature of 85 °C. With this heat treatment, we obtained a silver resistivity of $1.68 \times 10^{-6} \Omega.m$.

The second step of the fabrication process was to produce a layer which enables the transduction of ionic concentrations measured by electrodes into electrical potentials. At the skin-electrode interface, the ionic signal (Cl^- ion transports the charge) is transformed into an electric signal. Likewise, in common silver electrodes this layer is typically made of AgCl (Clark et al., 2009). The formation of this layer was achieved by adding Cl^- ions, enabling a reaction between Ag and Cl to produce AgCl. However, due to the thin layer of silver and the fragility of the photo paper, the amount and the manner of introducing Cl^- ions is important. This process was optimized by using commercial bleach deposited by an airbrush at a distance of approximately 30 cm.

The third step in the production of these electrodes was focused on ensuring a good, long lasting, and practical contact between the electrodes and the acquisition hardware. To facilitate the connection of cables and make the electrodes practical for regular use, we use a metal stud and conductive snap. The snaps were placed in the back of the printed surface and the communication to the front was made through a hole filled with a conductive silver paste from Agar Scientific. We estimated that each electrode produced with the procedure described would cost, approximately, 0.03€.

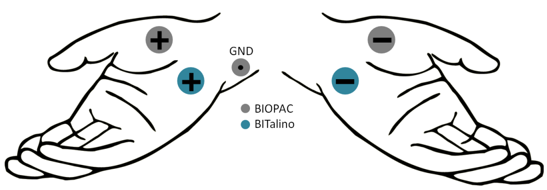


Figure 1: Electrode leads placement.

3 METHODOLOGY

We benchmarked the performance of our paper-based inkjet printed electrodes for ECG data acquisition, comparing them both to standard pre-gelled Ag/AgCl electrodes, and to the dry electrodes approach that we have been recently following (Silva et al., 2011). Reference data was collected using a BIOPAC biosignal acquisition unit, which has seen extensive use in the research domain and is considered to be a gold standard in biomedical research. However, this system has restricted operations and experimenting new customized solutions can damage the device. As such, we have used a BITalino acquisition system (Alves et al., 2013; Guerreiro et al., 2013), which give us a higher control over the system to try different experimental setups.

This work is aligned with our research towards off-the-person ECG sensing (Silva et al., 2013), reason for which the ECG signals were acquired in the palmar region of the left and right hands, as illustrated in Figure 1. The electrodes used for data acquisition with the BIOPAC were always the pre-gelled Ag/AgCl, while with the BITalino we tested the previously mentioned 3 types of electrodes.

We devised our comparative study in two objectives:

1. comparison of the BITalino performance with a gold standard acquisition system, the BIOPAC;
2. comparison of electrodes for ECG acquisition.

The BITalino acquisition device adopts the 2-electrode approach with virtual ground, while the BIOPAC system is designed to collect data with the ground electrode. In order to inquire the BIOPAC performance after removing the ground electrode, we performed two experiments, with and without the ground electrode. To evaluate the performance of the dry, and paper-based inkjet electrodes in the ECG acquisition, we did 2 experiments in which we compared them with the pre-gelled ones. The experiments are summarized in Table 1.

Table 1: Summary of the experiments.

Experiment	BIOPAC type	BIOPAC GND	BITalino
1	Gel	Yes	Gel
2	Gel	No	Gel
3	Gel	No	Dry
4	Gel	No	Paper

Each experiment consisted of a 30 seconds recording performed simultaneously with the BIOPAC and the BITalino; we used a sampling rate of $1000 Hz$ in both devices and a 12-bit resolution for the BIOPAC, whereas the BITalino has a 10-bit resolution. The BIOPAC raw data was reduced to 10 bits, to be at the same resolution as the BITalino signals. We have collected raw ECG data from 20 subjects in a static standing position, with the electrodes applied as shown in Figure 1

The data obtained by each device was pre-processed in three main steps, as represented in Figure 2. Taking the raw data as input, the baseline wander was corrected through a two-stage median filter, as proposed by (De Chazal et al., 2004), and the signals were filtered using a Finite Impulse Response (FIR) bandpass filter with a Hamming window of $300 ms$, and cutoff frequencies of $5-20 Hz$. The filtered signals were normalized to their maximum and minimum amplitudes, where the original signal is subtracted of its mean, and divided by its standard deviation. To prevent any possible electrical interference between the devices prone to bias the results and resulting from a hard wired connection between both devices, we chose to do the synchronization using the

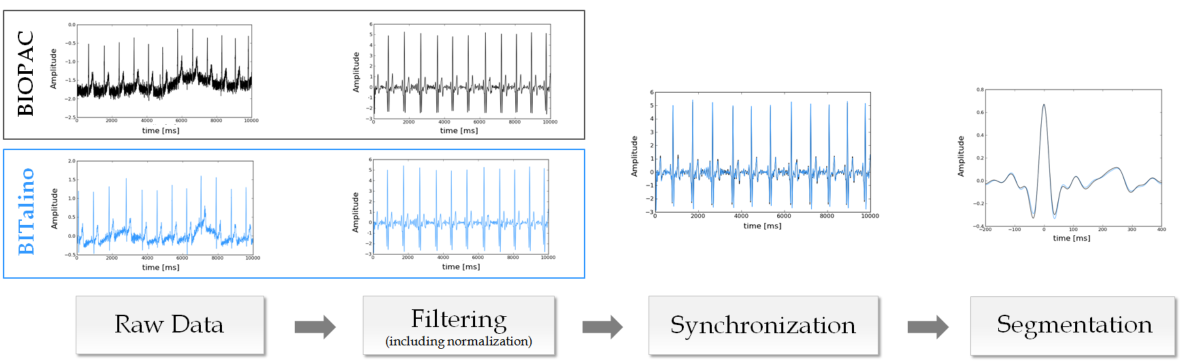


Figure 2: Block diagram of the pre-processing steps we have performed, to compare the signals acquired from both devices. The curves plotted in black were acquired using the BIOPAC while the blue ones with the BITalino.

RR time intervals. Given that the comparison of the ECG data obtained from two independent systems can only be correctly performed for data expressed in the same time base, our synchronization method consists on the following steps:

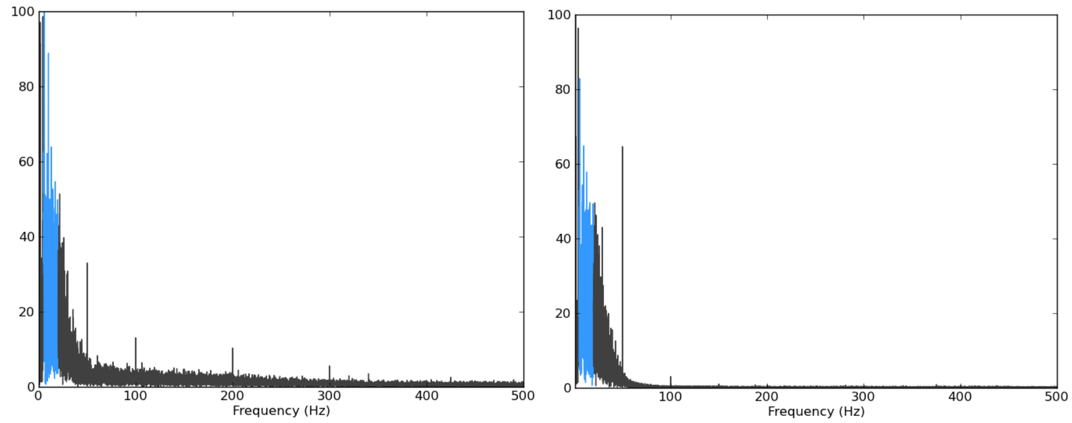
1. Detection of the QRS complex in each independent signal, using the method proposed by (Engelse and Zeelenberg, 1979)
2. Let $RR_{BIOPAC} = \{RR_{BIOPAC_0}, ..., RR_{BIOPAC_n}\}$ and $RR_{BITalino} = \{RR_{BITalino_0}, ..., RR_{BITalino_m}\}$ be a set of RR time intervals for the n and m heartbeat waveforms detected respectively in the BIOPAC and BITalino ECG time series.
3. Construct a matching matrix, M, in which the entry $M(i,j)$ corresponds to the absolute value of the difference between the RR time intervals extracted from the BIOPAC and BITalino ECG time series, that is:
$$M(i,j) = |RR_{BITalino_i} - RR_{BIOPAC_j}| \quad (1)$$
4. Let $\#M$ be the number of items where $M(i,j) \leq RR_{th}$
5. If $\#M > Sync_{th}$, the synchronization is complete. Otherwise, go to next step.
6. Consider $RR_{BITalino}(k) = \{RR_{BITalino_k}, ..., RR_{BITalino_m}\}$. Repeat steps 3 and 4 for each value of $k \in \{1, ..., m\}$ and compute each value of $M(i,j) = |RR_{BITalino_i}(k) - RR_{BIOPAC_j}|$.
7. Find the k value where $\#M$ is higher
8. Synchronize the signals by applying a delay of k samples to the BITalino signal.

The acquisition was always initiated first with the BITalino, so it has the higher time series. We defined 2 thresholds in the synchronization method, $Sync_{th}$ and RR_{th}. The $Sync_{th}$ value applied was 20, since it is approximately the minimum number of heartbeats expected in a 30 seconds ECG signal. The RR_{th} threshold represents the minimum difference of RR time intervals, from different acquisitions, where the R peaks are considered to match in the time domain. Since the acquisitions were performed by two different systems, it is expected a small deviation between the instants where the same R peaks occur. Therefore, we considered that $5\,ms$ is the maximum value where the R peaks are considered to occur in the same instant. Finally, the individual heartbeat waveforms were segmented and scaled between 0 and 1; we consider the heartbeat waveform to be the $[-200;400]\,ms$ interval around the R peak instant.

4 EVALUATION METRICS

Two metrics were employed for numerical evaluation purposes, namely the Signal-to-Noise Ratio (SNR) computed from the data collected with both devices for each of the 4 experiments, and the Root Mean Square Error (RMSE) of the cosine distance, to assess the morphological correlation between the heartbeat waveforms obtained with the BIOPAC and the BITalino, when using each type of electrodes. For the SNR calculation, we considered the interest signal to be concentrated on the $5-20\,Hz$ band of its frequency spectrum, and the remainder as noise. For each record we calculated the difference between the SNR obtained from BITalino and BIOPAC acquisition.

Figure 3 illustrates an example of the frequency spectrum of ECG data acquired in both devices, for



(a) BIOPAC (b) BITalino

Figure 3: Example of the ECG signal frequency spectrum for data collected with each acquisition device in one of the recording sessions. The blue region shows the interest spectral band and the remainder the noise.

one of the test subjects in the experiment 1. The 50 Hz power line interference is visible in both signals; however, since the BITalino ECG sensor has an analog band pass filter from 0.5 to 40Hz, the higher frequencies are almost eliminated, contrary to what happens with the BIOPAC.

For the cosine distance calculation, the synchronized signals were segmented into individual heartbeat waveforms, and the distance between a given segment in the BIOPAC time series and the matching segment in the BITalino time series was calculated. The cosine distance, D_{cos}, between the signals x and y is given by Equation 2

$$D_{cos}(x,y) = 1 - \frac{\sum_{k=1}^{m} x[k]y[k]}{\sqrt{\sum_{k=1}^{m} x[k]^2 \sum_{k=1}^{m} y[k]^2}}, \quad (2)$$

The reason why we have calculated the cosine distance for each heartbeat, instead of using the entire signal, is due to the fact that we were only interested in the ECG waveform shape, which is comprised in the heartbeat region. To validate the similarity between the signals acquired from the two devices, we compute the RMSE, as defined in Equation 3

$$RMSE(x,y) = \sqrt{\frac{\sum_{j=1}^{N} \left(D_{cos_j}(x,y)\right)^2}{N}} \quad (3)$$

5 EXPERIMENTAL RESULTS

The results obtained for each experiment in the 20 subjects are represented in Figure 4.

The box plots display the distribution of the difference between BITalino and BIOPAC SNR, for each experiment, across all the subjects. The height of the box plot indicates the degree of dispersion, the band inside the box represents the median, and the bottom and top of the box are the first and third quartiles. The smallest SNR difference between devices was obtained in the experiment 1, where the median value is lower and the degree of dispersion is reduced. This was already expected since the presence of the ground electrode in the BIOPAC device and the use of gelled electrodes in both systems correspond to the best case scenario in which the amount of captured noise is minimal. The higher dispersion obtained was in the experiment 4, due to higher noise presence in the signals.

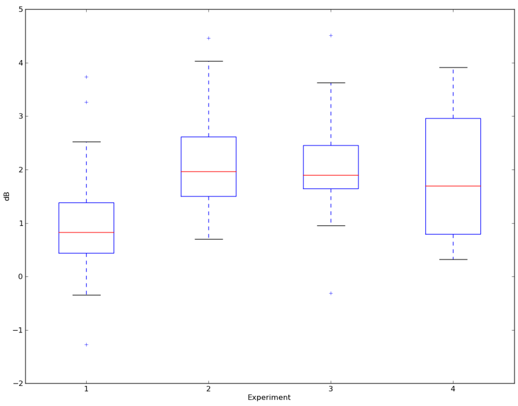


Figure 4: Boxplot of the difference between BITalino and BIOPAC Signal-to-Noise Ratio for each experiment.

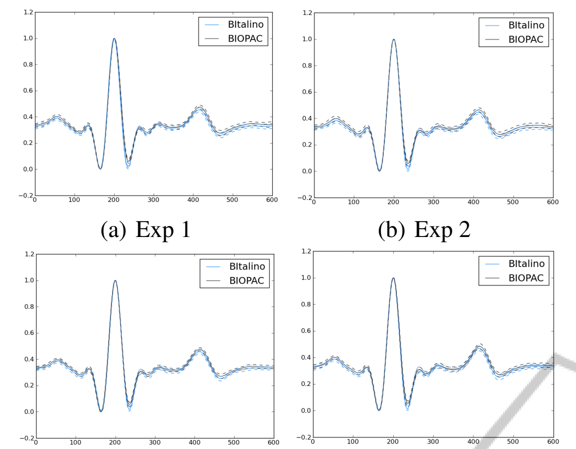
Table 2 summarizes the results obtained for the signals collected using each device. In all the experiments, the SNR of BITalino was higher than BIOPAC, which was already expected due to the analogic filtering occuring in the BITalino ECG sensor.

Table 2: Experimental Results from BIOPAC and BITalino ECG signals acquisition, in the 4 experiments.

Experiment	RMSE	SNR [dB] BITalino	SNR [dB] BIOPAC
1	0.0043 ± 0.0053	-1.02 ± 2.04	-2.04 ± 2.31
2	0.0042 ± 0.0039	-1.19 ± 1.84	-3.35 ± 2.45
3	0.0063 ± 0.0055	-1.62 ± 2.21	-3.69 ± 2.54
4	0.0042 ± 0.0043	-1.87 ± 2.14	-3.80 ± 2.66

The lowest value of SNR with the BITalino device was obtained in the experiment 4, when using the paper electrodes, indicating a higher noise presence. In what concerns the morphological correlation between waveforms, all the experiments have shown a high similarity between the ECG signals obtained from both devices. The signals acquired have a good approximation to the well known prototypical ECG waveform, providing an easy identification of the characteristic P-QRS-T complexes. Figure 5 presents an overlay with all the individual heartbeat waveforms collected in one of the recording sessions, showing the median and standard deviation of all the segments obtained from both devices in the four experiments. As we can see, the waveform morphology is maintained throughout the experiments and is virtually indistinguishable between devices and materials.

From the cosine distance results, we have calculated the Root-Mean-Square Error (RMSE), and the results are described in Table 2. For all the experiments, we verified very low RMSE values, indicating that the signals obtained from all three types of electrodes retain much of the waveform morphology when compared to the signals obtained with the gold standard BIOPAC setup. An interesting finding is that the inkjet printed electrodes shows a very good performance when compared to the other electrodes, with a RMSE of 0.0042, while with the dry elec-



(a) Exp 1 (b) Exp 2

(c) Exp 3 (d) Exp 4

Figure 5: Segmented heartbeat waveforms from the BITalino (blue) and the BIOPAC (grey); the solid wave represents the mean, and dashed line the standard deviation.

trodes we obtained the worst results, with a RMSE of 0.0063. Although the signals obtained with the paper-based electrodes present a lower signal-to-noise ratio, the ECG morphology is maintained, which results in a similar performance to that found for the case in which standard clinical-grade pre-gelled Ag/AgCl electrodes are used. Moreover, the signals acquired with the BITalino device are highly correlated to those obtained with the BIOPAC, actually exhibiting lower noise levels in raw ECG signals.

6 CONCLUSIONS

In this paper we have proposed and evaluated paper-based inkjet printed electrodes for ECG data acquisition. We presented the fabrication steps, and benchmarked our electrodes against standard clinical-grade pre-gelled Ag/AgCl electrodes, and dry electrodes. Data acquisition was performed using a BIOPAC system, considered to be a gold standard within the biosignal research community, although due to the fact that it is a closed system, we have also supported our analysis on the BITalino, a physiological computing platform first introduced by our team.

The collected data was evaluated using the Signal-to-Noise Ratio (SNR), and a morphological waveform correlation index based on the Root Mean Square Error (RMSE). Experimental results have shown that the proposed approach explored in this work achieves comparable performance when compared with a reference sensor. Our evaluation has revealed that the heartbeat waveforms measured through the proposed approach are nearly identical to those obtained with the gold standard equipment.

This approach opens new possibilities in the field of biosignals, enabling people (e.g. patients and/or caregivers) to have easier access to consumables in continuous ambulatory monitoring scenarios. We believe our approach to have the threefold advantage of reducing production costs, being easier to recycle, and being more accessible when compared to conventional approaches.

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