Fully-textile Polymer-based ECG Electrodes: overcoming the Limits of Metal-based Textiles

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Abstract

In recent years, there has been a particular interest in wearable electronics for electrocardiogram (ECG) recording. The ultimate goal is the integration of both sensors and electronics in clothes, for both clinical and non-clinical use. To date, textile ECG electrodes have been mainly based on the use of conductive metal fibers woven or stitched on a finished substrate.

In this work, textiles electrodes for ECG are obtained by treating finished fabrics with the conductive organic polymer poly-3,4-ethylenedioxythiophene doped with poly(styrene sulfonate) (PEDOT:PSS). Compared to previous works based on the treatment of a whole piece of fabric by immersion in the PEDOT:PSS solution, the adoption of a novel screen printing technique enables to achieve good definition and control over the quantity of deposited polymer. The proposed fabrication approach compares favorably with the previous one. A small trial with 10 subjects, aimed to record 12-lead ECG traces with clinical instrumentation, revealed the capability of the proposed electrodes to accurately capture the ECG signal morphology with performance comparable to off-the-shelf disposable gelled Ag/AgCl electrodes.

1. Introduction

Accurate unobtrusive long-term monitoring of bioelectric signals in various everyday life conditions represents an important research field. Fostered by the consumer applications, aiming to provide hi-tech solutions for sport and wellness, in the last years textile electrodes technologies entered the market of the devices for personal health monitoring. In fact, the advances in low-power systems design for biomedical signal processing would allow to reach acceptable power profiles for wearable embedded processing platforms [1].

Remote patients monitoring, especially chronically ill and elderly, represented the main potential application field [2]. Nevertheless, also some specific niche applications, such as non-invasive fetal ECG, either requiring a large number [3], [4] or a reduced number [5] of electrodes to be placed on the maternal abdomen, could benefit from the adoption of easy-on wearable systems [6].

Despite such premises, the application in clinical settings is still far from being widespread, even though some clinical studies appeared [7]. Originally developed to replace off-the-shelf disposable gelled Ag/AgCl electrodes, the gold standard for clinical and short-term recording but limited by short operating time and poor comfort, traditional textile electrodes used without any conductive hydrogel failed to provide an effective way to access high-quality ECG signal [8]. High skin-electrode contact impedance, the consequently higher mains interference, the typically large baseline wandering artefact, the presence of the metal wires directly in contact with the skin, are the most remarkable problems associated to their use [9]. For this reason, the fabrication of comfortable and stable textile electrodes for long-term monitoring still represents an open research issue.

In this paper, we present the development and test of novel textile electrodes based on the screen printing of finished fabrics with an organic polymer poly-3,4-ethylenedioxythiophene doped with poly(styrene sulfonate) (PEDOT:PSS). This conductive polymer has been already used in the past for extracellular biopotential, because of its biocompatibility and the reduced electrode-biological tissue electrochemical impedance mismatch that enables a gel-free use [10]. Previous works reported the fabrication of textile electrodes for ECG recording made up of finished fabrics functionalized with PEDOT:PSS by immersion in the polymer solution [11]. These electrodes revealed very good performance when used on voluntary healthy subjects by means of custom ECG devices. However, the fabrication process hampered the transfer of this technology in real-world applications, since it was not possible to selectively treat parts of a garment. The proposed approach overcomes these limitations by providing hitherto unavailable integration features.

2. Materials and methods

The textiles electrodes were produced by a screen printing technique designed to deposit the organic polymer, prepared in order to have specific density characteristics, on different fabrics. A highly conductive PEDOT:PSS dispersion (PH1000, by Heraeus Clevios) was mixed with ethylene glycol and a reticulating agent in different proportions with a magnetic stirrer until a homogeneous solution was obtained. This solution was used as ink for screen printing, after reducing it to the 65% in weight of its original volume by oven drying.

Woven cotton was used as textile substrate for the PEDOT:PSS screen printing deposition because of its low cost, revealing how the proposed technique is less aggressive than the previous ones on the fabric [11]. The printed fabrics were annealed in an oven at 90°C for just the time needed for both water and ethylene glycol to evaporate. The active area of the electrode was a 20 mm × 20 mm square. In order to improve the skin-electrode contact, a thin foam layer was sewed on the back of this area. Such a soft layer of foam has positive impact on the mechanical contact of the fabric on the skin [12] and helps to preserve wet the electrodes [13].

A thin strip of polymer was used to bring the signal out from the active area to a point where it could be acquired by the measurement instrumentation. To obtain a stable electric contact, a metallic snap button was crimped on the fabric at the end of the strip. Neither the button nor the strip were conceived to be in contact with the skin, to avoid altering the electrical characteristics of the electrode interface with the skin so, when the electrode was fixed to the skin by adhesive tape, this part was flipped back.

A prototypical scree-printed textile ECG electrode used for the tests presented in this paper is shown in Fig. 1.

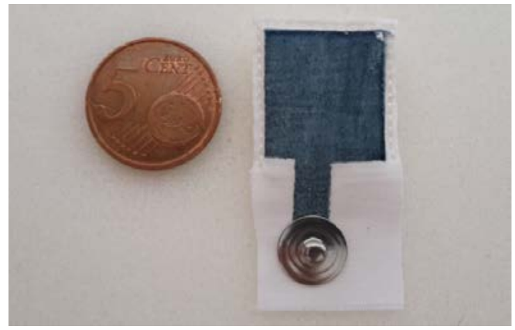

Figure 1. The screen-printed PEDOT-PSS electrode.

2.1. Recording system characteristics

In order to assess the capability of the proposed electrodes to correctly capture the waveform details analyzed for diagnostic purposes, a clinical ECG machine has been selected, the CardioSoft V6.71 recording system (by GE Healthcare). This system is a USB-based ECG device controlled by the CardioSoft software. The 15-lead ECG acquisition hardware is composed of an acquisition module (CAM-14) and a USB interface box (CAM-USB).

CAM-14 is a Class 2, defibrillation protected 14-channel analog to digital acquisition module, featuring type BF applied parts, internal impedance measurement system and lead-off detection. The input impedance is >10 MΩ at 10 Hz. Sampling frequency for normal ECG analysis is variable, up to 500 Hz. The resolution is 4.88μV/LSB with peak-to-peak noise in the 0.1 Hz – 150 Hz band <15 μV. It also integrates a 0.01 Hz high-pass filter. CAM-14 is interfaced to the CAM-USB interface box by a digital serial communication link.

CAM-USB, which is USB-powered, only acts as a serial-USB protocol converter, providing also floating isolation and the supply voltages for the CAM-14 module.

CardioSoft software provides the user interface and controls over the hardware, also featuring signal pre-processing, real-time display and the same interpretative modules available on stand-alone ECG machines. It is worth noting that some filters can be enabled or not (e.g. the cubic spline filter for baseline drift correction) whereas for others it is only possible to choose some parameters (e.g. notch filter for mains interference, low-pass filter). The adopted setting was: standard 12-lead, 500 Hz sampling frequency, 50 Hz notch, no cubic spline drift correction, high-pass filter at 0.01 Hz and low-pass filter at 150Hz (these are the settings providing the largest signal bandwidth). The Marquette 12SL ECG Analysis Program running within CardioSoft is able to extract from the preprocessed signal important measurements that can be used for clinical purposes, as detailed in the following.

2.2. Recording protocol

The study was performed following the principles outlined in the Helsinki Declaration of 1975, as revised in 2000; all the volunteers gave their informed consent to the measurements. Ten subjects (8 M, 2 F, aged 39 ± 8) were recruited by convenience sampling trying to include different conditions: healthy subjects (sedentary, trained, body builder, heavy smoker) and patients with aortic insufficiency, aortic stenosis and high hypercholesterolemia. ECG signals were recorded at rest, exploiting the standard clinical 12-lead configuration. No skin treatment was performed.

In order to enable a comparison of the textile electrodes with commercial ECG electrodes, the cardiologist applied a set of ten off-the-shelf disposable gelled Ag/AgCl electrodes (FIAB F9079, foam with solid hydrogel) and performed a 10 s recording, annotating the value of the impedance showed by CardioSoft interface on three precordial leads. Then, each commercial electrode was substituted by a textile one applied in the same point and fixed on the patient’s skin thanks to a strip of adhesive medical tape. Owing to the state of the art [11], the adoption of two drops of saline (sodium chloride 0.9%) was considered, to wet the textile electrodes improving the signal quality. A second 10 s measurement and impedance annotation was then performed. All the signal analyses were performed off-line.

2.3. Clinical and non-clinical features

In order to evaluate the quality of the textile electrodes from a clinical perspective, the signals acquired with the textile electrode were visually inspected by the cardiologists to see the signatures typical of the different subjects' conditions. Marquette 12SL ECG Analysis Program was used to automatically compute the median beats and the principal measurements from the recorded 12-lead rest ECG traces. Even though the delineation algorithms are unknown, this solution produces a clinically accurate set of measurements.

The CardioSoft XML export module was used to save the 10 s traces, the medians and the automatic measurements set performed on them. In order to perform some post-analyses, a Matlab set of functions leveraging the XML Matlab Toolbox by Geodise (www.geodise.org/toolboxes/generic/xml_toolbox.htm, University of Southampton) was created. In particular, such functions were used to compute some parameters not directly available, such as the QRS amplitude on leads V1, V3, V6 (QRS_{Vi}), the maximum QRS amplitude across all the leads (QRS_M), and the lead presenting such a high value (LM). The mean of the impedance modulus measured on leads V1, V3, V6 by the device (Z_{Vi}) was considered as indicative of the quality of the contact with the skin.

The following clinical features were also considered:

- ventricular frequency (HR),
- P wave and QRS complex duration,
- PQ and QTc intervals.

QT interval considered was the one corrected with the Bazett's formula. The measures obtained from the Ag/AgCl electrodes were compared to those from the textile ones by means of the two-tailed Student's t-test. Values of $p<0.05$ were set as the minimum level of statistical significance throughout the paper.

Furthermore, as a measure of the broadband noise level, decimated wavelet denoising (WD) was performed on the lead LM to obtain the residual signal [14], and its root mean square (rms) was taken as index of the noise level. The parameters for the WD were the following: Bior 6.8 wavelet, 5 decomposition levels, soft thresholding, Heuristic SURE thresholding method assuming a non-white noise structure, soft thresholding.

3. Results

The visual inspection of the ECG traces of the ten voluntary subjects reported a signal quality that can be considered adequate for diagnosis, without significant differences compared to disposable Ag/AgCl electrodes. Two exemplary traces related to the same precordial lead (V6) on the same subject, acquired one after the other in the same places, is showed in Fig. 2. It is possible to see the typical baseline drift of textile electrodes.

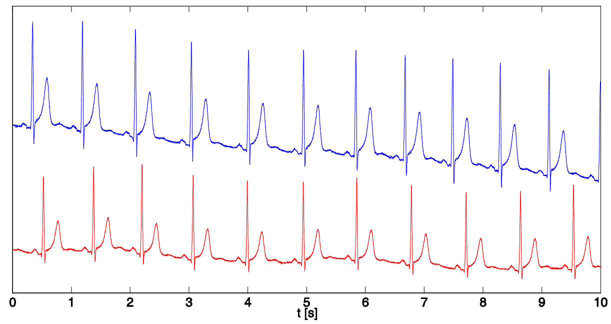

Figure 2. Comparison of the V6 lead acquired (not simultaneously) on the same subject using textile electrodes (top) and Ag/AgCl ones (bottom).

Table 1. Main temporal features comparison. Differences are not statistically significant ($p<0.05$).

Feature	Ag/AgCl	Textile
HR [bpm]	67 ± 13	66 ± 11
P duration [ms]	102 ± 13	101 ± 15
QRS duration [ms]	95 ± 6	93 ± 8
PQ interval [ms]	180 ± 80	190 ± 80
QTc interval [ms]	415 ± 20	415 ± 20

Dry textile electrodes failed in obtaining an impedance level below 600 kΩ, which is the limit in the GE ECG devices to assert a lead-off alarm. In this case, CardioSoft stops saving the signal from that lead. It should be considered that the textile electrodes application did not allow to press them on the skin, as would happen with an elastic band or t-shirt. Then, a high value of impedance is reasonable in this condition. By wetting the electrodes with saline, the impedance reaches remarkably low values, in the light of the abovementioned setup, even comparable to those achievable with the commercial electrodes and several times lower. To provide a clue on this parameter, we computed the grand mean (i.e. the mean, over the whole set of subjects, of Z_{Vi}) and the related standard deviation. The results are comparable when removing a single statistical outlier among the textile electrodes: 22 ± 23 kΩ for the Ag/AgCl electrodes and 29 ±31 kΩ for the textile ones (the outlier marked 378 ±219 kΩ due to the difficulty in applying the electrodes on the subject's skin) without statistical difference between the two types of electrode.

From the analysis of the measurements performed by the CardioSoft on the signals and medians, we obtained no statistically significant difference between the two populations of textile and Ag/AgCl electrodes for any one of the clinical features. The mean and standard deviations

Table 2. QRS_{Vi} and QRS_M features comparison. Differences are not statistically significant (p<0.05).

Feature	Ag/AgCl	Textile
QRS_{V1} [mV]	1.4 ± 0.7	1.3 ± 0.4
QRS_{V1} [mV]	1.6 ± 0.5	1.6 ± 0.4
QRS_{V1} [mV]	1.6 ± 0.6	1.6 ± 0.7
QRS_M [mV]	2.1 ± 0.6	1.9 ± 0.5

of such features are presented in Table 1.

About QRS_{Vi} and QRS_M, it is worth noting that alternate measurements with different electrodes in the same position can erroneously lead to ascribe to the electrodes the morphological differences descending from the physio-pathological time variance of the ECG waveform [14]. Taking into account the considerably larger ECG machine input impedance compared to the measured skin-electrode impedance, this parameter marginally influences QRS_{Vi} and QRS_M (Table 2).

In terms of noise analysis, performed excluding the statistical outlier for the impedance, the rms for the Ag/AgCl electrodes was 2 ± 1 μV whereas, for the textile ones, 3 ± 2 μV. The difference was not statistically significant. Remarkably, these value are low if compared to the both QRS_M and peak-to-peak noise of the ECG machine, even though the presence of the notch filter surely influenced this result. Overall, textile electrodes were noisier, with an rms increase of 19% on average, with the exception of a single subject (>300%). In that case, the subject's anxiety led to a noisy signal on which WD was too aggressive, in turn leading to larger residual, despite the quite low skin-electrode contact impedance.

The high quality of the results favorably compares to those achieved with the previous technology, with electrodes characterized by a wider active area (9 mm^2) and applied after a mild skin treatment [11].

4. Conclusion

In this work, a novel screen printing technique for the realization of polymer-based ECG electrodes is presented and evaluated. A comparison with off-the-shelf disposable gelled Ag/AgCl ECG electrodes was performed by using parameters obtained by means of commercially available clinical tools and signal post-processing. The achieved results clearly show that there is no significant difference, suggesting that the proposed textile electrodes can be used for clinical purposes with a reasonable confidence.

This result paves the way to the development of garments where the electrodes are printed on in post-processing, able to unobtrusively monitor the ECG signal with clinically acceptable signal quality.

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