# Characterization of Screen-Printed Textile Electrodes Based on Conductive Polymer for ECG Acquisition

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## Abstract

*The goal of this work was the characterization of textile ECG electrodes produced by screen printing with poly-3,4-ethylenedioxythiophene doped with poly(styrene sulfonate) (PEDOT:PSS) conductive organic polymer. In particular, screen printed ECG electrodes were analyzed in the light of the ANSI/AAMI standard EC 12:2000 to reasonably understand their potentialities for the development of smart garments. In fact, smart garments have to be able to resist to everyday use, including the typical garment maintenance.*

*Simulated washing cycles were performed following the ISO 105-C10:2006 standard, monitoring the variation of the noise and impedance, through bench procedures. Human tests revealed how the ECG signals obtained with screen printed electrodes were comparable to those achievable with disposable gelled Ag/AgCl ones. The high skin-electrode contact impedance of brand new electrodes in dry condition limited their usability, whereas the addition of an electrolyte led to comparable signal quality. Remarkably, washing cycles ameliorated the performance in dry conditions up to acceptable levels. This technique can then be used to create electrodes on finished garments, able to resist to everyday use.*

## 1. Introduction

In the last years, the interest in the wearable electronics and wearable devices able to continuously monitor physiological signals increased [1]. On the market, there are several devices for various applications, ranging from athletic performance to clinical and health monitoring. They have in common high comfort and portability, opening to specific long-term monitoring applications such as for elderly patients [2]. In fact, on these subjects, it is better to avoid a prolonged contact with typical Ag/AgCl electrodes, since the electrolytic gel and the glue could create skin irritation. In other application scenarios, such as when the number of electrodes is high (e.g., non-invasive fetal ECG [3], [4]), textile electrodes could present remarkable advantages.

The aim of this work was the characterization of ECG electrodes, produced by screen printing with poly-3,4-ethylenedioxythiophene doped with poly(styrene sulfonate) (PEDOT:PSS) conductive polymer on a textile substrate, which can be washed several times. The ink was composed of organic semiconductor and organic solvents only. In previous works [5], this biocompatible polymer covered completely the textile substrate after a dip-coating process without any control on the electrodes geometry [6]. Screen printing process allows controlling precisely the area to be functionalized. Even though the amount of ink deposited on the surface is reduced compared to dip-coating, good performance in the ECG recording can still be achieved [7]. These textile electrodes are more comfortable than metallic electrodes but, in order to represent a valuable solution for smart garments, they must be robust to the typical garment stress [8]. For this reason, as in other related works [9], their performance after standard washing procedures were tested. Since the reduced contact with the skin could lead to a high skin contact impedance, causing a worse performance, their characteristics were evaluated in dry condition and adding two different electrolytes: saline solution and a solid hydrogel.

## 2. Materials and methods

In this work, textile electrodes were produced changing in a controlled way the fabric physical properties with the highly conductive PEDOT:PSS polymer [10]. This treatment involved the deposition of a conductive ink, mainly composed of this polymer (PH1000, by Heraeus Clevios) mixed with ethylene glycol and a reticulating agent, on a textile substrate, through a screen printing deposition process. This technique concerns the ink deposition on the fabric through a stencil with a mesh, allowing to control the amount of ink released on the fabric. By using a conductive ink, it is then possible to acquire ECG signals directly from the textile surface.

To increase the geometrical resolution of the deposition, this polymer solution was reduced in weight increasing the viscosity by evaporating the liquid component in oven. After the deposition, the fabric was dried in an oven at 90°C until the liquid components completely evaporated, thus stabilizing the ink on the substrate. The textile electrodes included several features, introduced to increase the comfort and the quality of the signal acquired. The electrodes presented an active area of 20 mm × 20 mm and

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a thin foam layer placed on the back of this area to improve the homogeneity of the skin-electrode contact pressure and maintain a stable humidity condition.

A channel of the same material brought the signal out from the active are to a metallic snap button, applied onto the fabric, to easily connect the electrode to a standard clinical instrumentation lead. To maintain the electrodes seamless, all these components were packed with medical adhesive tape. This tape also avoids the contact between the skin and the snap button. The screen-printed textile electrode prototype is shown in Figure 1.

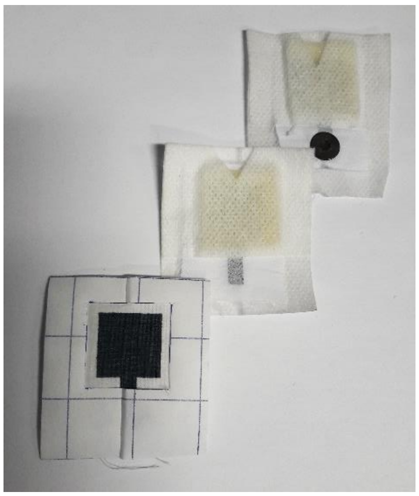

Figure 1. Prototype of screen printed textile electrode for ECG monitoring

In order to characterize the textile screen printed electrodes under stressing conditions typical of clothes everyday use, they underwent several washing cycles following the ISO 105-C10:2006 standard.

## 2.1. ECG electrode tester

The performance as passive electrodes were evaluated with the Xtratek ET-65A ECG electrode tester (Xtratek, Lenexa, Kans., USA). With this instrument it is possible to analyse, in a completely controlled way, the characteristics of coupled electrodes with different electrolytes between the surfaces. It enables the measurement of different parameters, such as noise and impedance, according with the ANSI/AAMI standard EC 12:2000 for coupled clinical gelled electrodes. The standard defines the maximum limits that the noise and the impedance could reach, for coupled Ag/AgCl gelled electrodes, as reported in Table 1. The impedance is studied with an AC signal at 10 Hz with a maximum amplitude of 0.1 mA.

By adding an electrolyte between the textile electrodes, it was possible to compare the results achieved with the standard limits. Electrode couples underwent a different number of washing cycles, from zero to 20. For each number of washing cycles, the electrodes were tested in dry conditions or with the addition of saline solution or solid hydrogel. To maintain a homogeneous coupling during the bench tests, the active surfaces of the electrodes were coupled applying a 9 N force, in dry and wet conditions, and 2 N when using solid hydrogel (already ensuring stickiness).

Table 1. ANSI/AAMI Standard EC 12:2000 Limits for impedance and noise.

| **Noise** | **AC Impedance** |
|---|---|
| Voltage (μV) | ACZ (Ω) |
| ≦ 150 | ≦ 2000 |

In order to present minimal descriptive statistics of the observed behaviors, the mean and standard deviations over six samples were computed for each testing condition.

## 2.2. Human recordings

Beyond the bench tests with the Xtratek ET-65A ECG electrode tester, screen printed textile electrodes were also tested in real ECG recording conditions. The same electrolytes used during the bench tests were adopted.

The recording on human volunteers followed the principles dictated by the Helsinki Declaration of 1975, as revised in 2000. All the volunteers gave their informed consent to the measurements. In order to obtain the homogeneity of the sample, the study population included five healthy subjects. The ECG signals were recorded at rest, exploiting the standard lead I electrodes position. No skin treatment was performed before the recording, in order to reproduce the typical application condition.

The ECG signals were recorded with a TMSI Porti7 portable physiological measurement system, using the analog bipolar input channels. The A/D converter allows a resolution of 71.5 nV (22 bits) with a noise level lower than 1 μV. A sampling frequency of 2048 Hz was set on the device. Recorded signals were exported in Matlab for digital processing.

A performance comparison with gelled Ag/AgCl electrodes (CDES000024 by Spes Medica srl) was performed not only in terms of signal quality but also in terms of skin contact impedance, measured with a 4284A LCR meter by Agilent Inc. under isolation transformer, at different frequencies ranging from 20 Hz to 500 Hz.

## 3. Results

Coupled screen printed electrodes with different electrolytes exhibited a similar trend in terms of noise and impedance when increasing the number of washing cycles (Figure 2). After 10 cycles, a stabilization of the electrodes characteristics could be observed and no further degradation was perceivable. This is relevant because the screen printed electrodes could be exposed to washing procedures if placed on smart garments. Furthermore, they could also be used in a wet condition during an athletic performance, or when covered by an electrolyte as saline solution during cardiac monitoring.

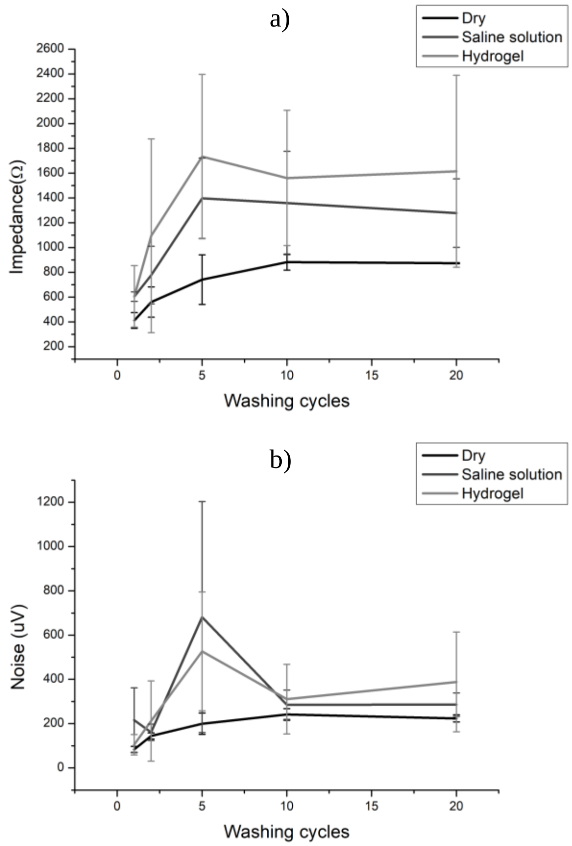


Figure 2. Impedance (a) and noise (b) measured on textile electrodes with Xtratek ET-65A in dry conditions and with saline solution and hydrogel between the active electrodes area.

Compared with the ANSI/AAMI standard EC 12:2000, the impedance value measured with the Xtratek remained under the limits even after 20 washing cycles, whereas the noise, being closer to the limit before the treatment, exceeded it after 5 washing cycles only.

The skin contact impedance measurement showed a different behavior compared to the bench tests. Since the subjects' skin was not treated for impedance reduction, in dry conditions the skin contact impedance at 20 Hz reached 16 MΩ on average, with brand new screen printed electrodes. Such a high value, incompatible with a good measurement, was due to the reduced contact pressure and the poor skin hydration. Several real recording conditions for a smart garment, such as athletes' performance monitoring or cardiac monitoring, take advantage of skin wetting. This situation was recreated by adding on the electrodes surface few drops of saline solution or applying a solid hydrogel layer used in the disposable ECG electrodes. In this case, the skin contact impedance for the screen printed textile electrodes reached 100±30 kΩ when using saline solution and 80±20 kΩ when using solid hydrogel. These results are comparable to the 70±30 kΩ impedance value measured with disposable gelled electrodes.

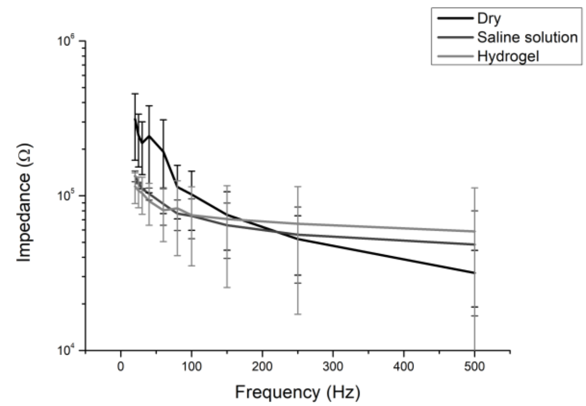


Figure 3. Variation of the skin contact impedance with the frequency for textile electrodes washed 20 times with or without electrolytes.

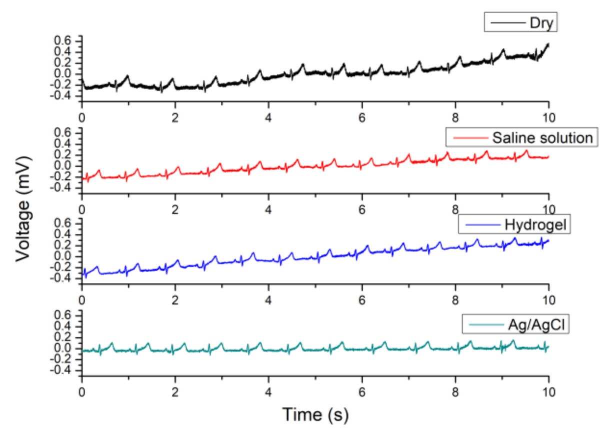


Figure 4. Comparison between the ECG signals acquired with Ag/AgCl gelled electrodes and textile electrodes with saline solution and hydrogel

In order to assess the effects associated to washing, the skin contact impedance was also evaluated with textile electrodes washed 20 times (Figure 3).

The washed textile electrodes showed a higher skin contact impedance compared to the brand new electrodes when using an electrolyte, whereas the impedance in dry conditions was lower. Thus, washed dry electrodes could be used to acquire ECG signals, which was not possible for the brand new electrodes.

Figure 4 presents typical excerpts of ECG signals acquired with disposable gelled Ag/AgCl electrodes and the proposed screen-printed textile electrodes after 20 washing cycles. Dry electrodes and electrodes with the application of different electrolytes were tested. The results with saline solution and solid hydrogel were comparable to those achieved by Ag/AgCl electrodes. Conversely, recordings performed by dry electrodes presented more noise. This was largely due to the larger skin contact impedance exhibited by these electrodes in the frequency range of the power mains interference. This was confirmed by the Power Spectral Density (PSD) analysis, presented in Figure 5.

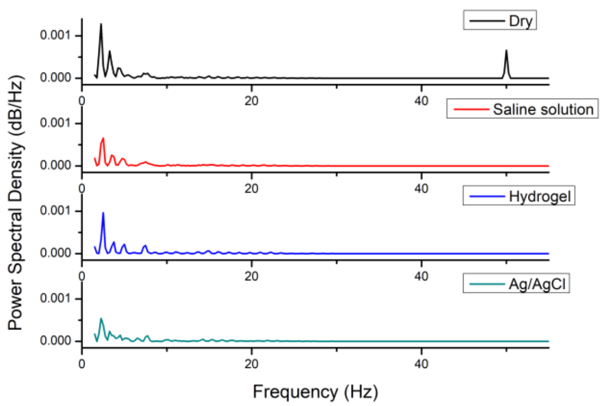


Figure 5. PSD of a recorded ECG acquired with different electrodes.

## 4. Conclusion

This work presented a screen printing process based on PEDOT:PSS organic polymer for the realization of ECG electrodes directly printed on smart garments. Since smart garments have to be able to resist to the typical stresses due to everyday use, including washing, the electrodes assessment through bench procedures and human tests were aimed at the evaluation of the textile electrodes fastness to the cleaning process.

The results revealed how these textile electrodes could be washed up to 20 times without compromising their ability to acquire the ECG signal, maintaining an acceptable signal quality comparable to that of commercial electrodes. Remarkably, washing ameliorated the skin contact impedance, allowing to exploit the dry electrodes for ECG monitoring without the addition of any electrolyte. This important result could be exploited to stabilize the electrode performance in the production phases.

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