Validation of a Novel Tattoo Electrode for ECG Monitoring

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Abstract

In this work, novel ultrathin and unperceivable Parylene C electrodes (conventionally indicated as 'tattoo electrodes') for ECG detection were comparatively assessed against off-the-shelf gelled Ag/AgCl ones. To this aim, six 60s-long single-lead ECG signals were recorded from three volunteers. Signals from Ag/AgCl and tattoo electrodes were simultaneously acquired at 2048 Hz using the TMSi Porti7 system.

Although tattoo electrodes suffered from slightly higher baseline wandering artifacts (1±1 mV) than Ag/AgCl ones (0.08±0.04 mV), they both achieved high and similar signal-to-noise ratio (33±2 dB and 34±2 dB for Ag/AgCl and tattoo electrodes, respectively) and allowed for the extraction of comparable R-R intervals. Furthermore, heartbeat morphologies extracted by the different electrodes showed high correlation (0.999±0.001).

Therefore, our findings suggest the possibility of successfully using these novel tattoo electrodes for unobtrusive ECG monitoring, ensuring high consistency with respect to gelled Ag/AgCl electrodes.

1. Introduction

The concept of tattoo electronics has been introduced in the early 2010 [1] and since then has produced an impressive variety of different devices and electronic systems that can be operated in direct contact with the skin [2]–[4]. One of the most interesting healthcare-related application of tattoo electronics is undoubtedly the recording of bio-potentials from the surface of the skin, such as surface electromyography (EMG), electroencephalography (EEG), electrooculography (EOG), and electrocardiography (ECG) [5], [6], due to the great advantage offered by the greatly improved skin conformability, which helps in maximizing the contact surface and minimizing the motion artifacts at the same time. In fact, one of the main characteristics of tattooable systems is the extreme thinness of the employed substrates [7], [8], which also allows for an optimal skin/electrode interface without the use of conductive hydrogels, thus resulting in extremely unobtrusive recording electrodes.

In this work, a novel ultrathin Parylene C-based tattoo electrode is introduced and validated for its use in ECG monitoring. The use of Parylene C, which is a well-known biocompatible, chemical inert material that has been already largely employed for the fabrication of conformable electronic devices, allows easily obtaining ultra-thin sub-micrometre layers thanks to a reliable and high-throughput chemical vapour deposition technique [9]–[11]. The performance of the proposed tattoo electrodes has been evaluated on six 60s-long ECG recordings in terms of noise content, ECG waveform morphology and measured intervals, and compared to those achievable by high-end off-the-shelf disposable gelled Ag/AgCl electrodes.

2. Materials and Methods

A prototypical tattoo electrode used in this work is shown in Figure 1. The proposed tattoo electrodes are less than 1 µm thick and present a circular sensing area with a radius of about 5 mm. Their fabrication required different steps. Firstly, spin-coating of a thin layer of polyvinyl alcohol (PVA) on a 250-µm thick polyethylene terephthalate carrier was performed. The resulting outcome was then baked on a hot plate before proceeding with a deposition onto such a substrate of a 500 nm layer of Parylene C, by chemical vapor deposition. Then, a standard photolithographic process allowed for the development of the negative pattern of the electrode. After plasma activation, to improve the Parylene C surface characteristics, a 70 nm silver layer was evaporated on the photoresist-patterned film and eventually stripped in a sonicated acetone bath. Finally, to passivate the parts of the electrode not devoted to signal sensing, a final 200 nm

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Figure 1. Examples of tattoo electrodes for ECG applied on the skin. As can be seen, they offer high skin conformability also when stretching or compressing the skin portion.

Parylene C coating was performed. As this layer has insulating properties, the electrode recording area and the end for the connection with the recording instrument were covered with a polydimethylsiloxane patch during the deposition process. At the end of the fabrication process, the electrode was moved to a piece of paper (carrier) using a small amount of deionised water.

Tattoo electrode was connected to the recording system by a passivated copper wire featuring a clip contact. The copper wire was attached to exposed back contact of the electrode thanks to two 3×5 mm silver-coated neodymium magnets, which were introduced in order to constitute an effective interface between the copper wire and the electrode film, avoiding any displacement at the connection site.

2.1. Signal acquisition setup

Recordings were performed following the principles outlined in the Helsinki Declaration of 1975, as revised in 2000. All the participants gave their informed consent. Six 60s-long ECG signals were simultaneously acquired by means of a pair of disposable gelled Ag/AgCl electrodes (BlueSensor N, Ambu A/S, Denmark) and a pair of tattoo electrodes, from three voluntary healthy participants of our research group (age: 35±11, heart rate: 65±5 bpm). In order to allow observing the most similar cardiac dipole projection, we placed the pairs of electrodes closely and at the same inter-electrode distance, as shown in Figure 2. In particular, we followed the conventional Holter placement by recording a single-lead ECG. A ground electrode (BlueSensor N, Ambu A/S, Denmark) was put on the right hip.

Before the acquisition, the selected skin portions were shaved, clean and dry. For the tattoo electrodes, a firm adhesion was guaranteed by simply moistening the paper carrier. Finally, the paper carrier was wiped away gently.

A 32-channels Porti7 portable electrophysiological

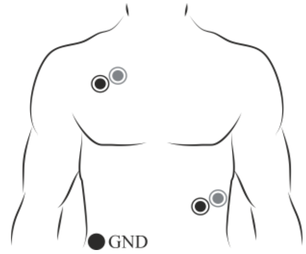

Figure 2. Electrode positioning adopted for the single-lead ECG recordings. Recording electrodes were placed as indicated by concentric circles, by using Ag/AgCl (in black) and tattoo electrodes (in grey) simultaneously, preserving the same distance between bipolar sensing electrodes.

measurement system (TMSi, The Netherlands) was used for all ECG acquisitions, which were performed at 2048 Hz. Remarkably, Porti7 system allowed recording all ECG signals by just introducing a digital decimation filter, with a cut-off frequency of 0.27 times the adopted sampling frequency.

2.2. Comparative analysis and signal processing

To carry out a quantitative comparison, different figures of merit were computed for both electrode types. However, to this end, some pre-processing stages were needed. Specifically, in order to remove the baseline wandering (BW) artefacts, raw ECG signals were pre-processed by a bidirectional 2nd order IIR Butterworth high-pass filter with a cut-off frequency of 0.67 Hz. Furthermore, powerline noise interference was removed by a bidirectional 2nd order IIR notch filter. Then, in order to identify all main ECG waveforms on the processed signals, a state-of-the-art ECG delineator was adopted [12]. Based on its annotations, the R-R intervals, the signal-to-noise ratio (SNR) and the Pearson's correlation coefficient (ρ) were computed on each recording for the signal quality evaluation and electrodes comparison.

Specifically, R-R intervals were computed in order to assess the consistency of the measurements performed with the different electrodes, to investigate the use of tattoo electrodes for heart rate variability applications, whereas SNR was introduced to evaluate how much noise affected the acquired signals.

Mathematically, the SNR was computed as:

$$\text{SNR (dB)} = 20\ log_{10}(A_{pp}/4\sigma) \qquad (1)$$

where A_{pp} represents the peak-to-peak amplitude of the median heartbeat and σ quantifies the median standard deviation of the noise, approximated as 1.4826 times the median absolute deviation of noise and computed over the third central portion of each isoelectric interval included between the offset of a T wave and the onset of the consecutive P wave.

Moreover, ρ was estimated in order to appreciate the similarity in ECG morphologies provided by Ag/AgCl and tattoo acquisitions. In this case, for each recording, the mean P-R and R-T intervals were considered to define the support for each heartbeat included in the morphological analysis. Then, the ρ metric was considered for each pair of simultaneous heartbeats detected by the two electrode types.

Finally, in order to determine the low-frequency noise amount, also the entity of the BW artefact was examined. At first, BW affecting each raw signal was extracted by subtracting the corresponding high-pass filtered ECG from it. In this way, all contributions below 0.67 Hz were included in the low-frequency analysis. For the entity quantification, the root-mean-square (RMS) value was computed on each residual.

3. Results

R-R interval mean and standard deviation of the mean were 930 ms and 77 ms respectively, for both electrode types. This finding suggests high consistency between the two measurements, which is further confirmed by the scatter plot and the linear regression model reported in Figure 3. As can be seen, the relationship between R-R intervals estimated on Ag/AgCl recordings and tattoo ones is effectively described by an identity function, thus suggesting high agreement between them. Moreover, the goodness-of-fit for the represented linear regression model is proved by its coefficient of determination, i.e. the R-squared value, which is found to be equal to one. The consistency between the Ag/AgCl and tattoo ECG acquisitions is also suggested by the SNR and ρ metrics, which are reported in Figures 4 and 5 respectively. From these results, it is clear that both electrode types offered high-quality ECG signals with very low noise content (SNR median values are 33 and 34 dB for Ag/AgCl and tattoo electrodes, respectively) and very high correlation between their heartbeat morphologies (median ρ is 0.999).

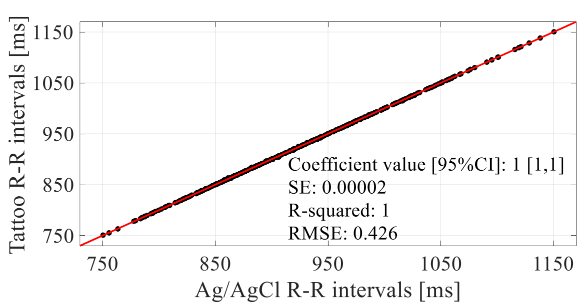

Figure 3. Scatter plot of the R-R intervals data estimated on both Ag/AgCl (x-axis) and tattoo (y-axis) ECG recordings (in black) and the linear regression model (in red) on their basis. Linear regression properties are reported on the right corner as coefficient value estimate and its 95% confidence intervals (CI), the standard error of the coefficient estimate (SE), the R-squared and the root mean squared error (RMSE) for the fitted model.

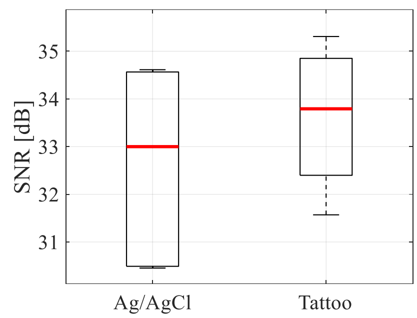

Figure 4. SNR distributions for both Ag/AgCl and tattoo ECG acquisitions.

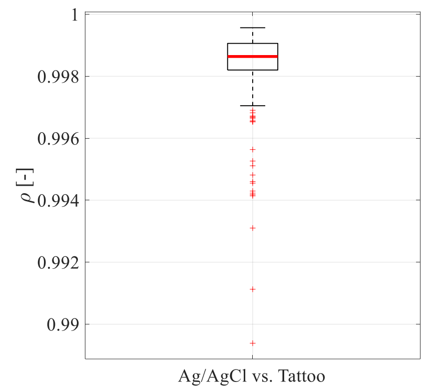

Figure 5. Pearson's correlation coefficient values computed on each pair of heartbeats acquired simultaneously by Ag/AgCl and tattoo electrodes.

However, BW artefact analysis showed that tattoo electrode recordings suffered from slightly higher low-frequency interference than Ag/AgCl ones (see Figure 6). This aspect is also evident by visually inspecting the acquired ECG signals, two examples of which are reported in Figure 7, before and after the high-pass and notch filtering stages.

4. Conclusion

In this work, a novel Parylene C-based tattoo electrode for ECG is validated and compared with disposable gelled Ag/AgCl electrodes. Our analysis included different signal quality indexes regarding not only the noise entity affecting the ECG recordings but also their timings and morphological similarity, revealing that high-quality and accurate ECG signals can be detected, which could be effectively exploited also for heart rate variability studies. Some differences can be appreciated when considering the

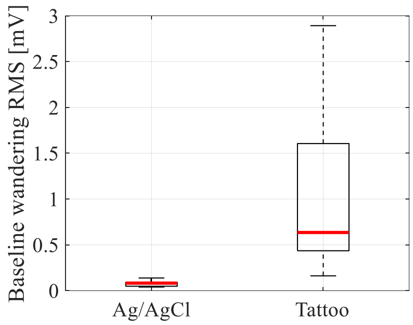

Figure 6. Amount of BW artefact computed on ECG signals acquired by both Ag/AgCl and tattoo electrodes. For Ag/AgCl acquisitions the 25th, 50th and 75th percentiles are equal to 0.05, 0.08 and 0.09 mV respectively.

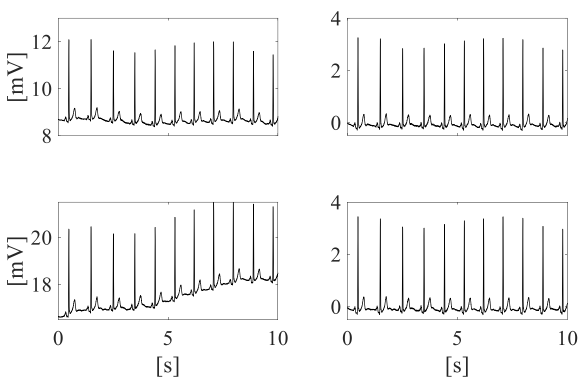

Figure 7. Examples of ECG recordings acquired by Ag/AgCl (upper row) and tattoo (lower row) electrodes, before (left column) and after (right column) the pre-processing stage. As can be seen, the tattoo recording showed greater BW artefact.

BW affecting the signals, which is slightly higher with tattoo electrodes than with Ag/AgCl ones. Although conventional ECG processing is able to correct this behavior, since it typically includes high-pass filtering stages to suppress baseline drifts, further studies are required to better characterize the limits of the proposed technology in this regard, suggesting safer application scenarios and possible electrode optimizations as ways to make the electrodes sweat-tolerant and perspirant. Moreover, despite a larger dataset is needed to confirm these conclusions, our findings revealed that tattoo electrodes could be successfully used for ECG monitoring, providing conformable skin-electrode contact devices that might be potentially useful also for different biopotential acquisition setups.

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