Concentric Ring Tattoo Electrodes for Biosignal Recordings

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Abstract: Non-invasive bioelectrical recordings utilize monopolar or bipolar disc electrodes. However, these electrodes suffer from poor spatial resolution, leading to susceptibility to physiological interferences. Concentric ring electrodes have been implemented on rigid and flexible substrates to enhance spatial resolution. The present work aims to develop an ultra-flexible and ergonomic concentric ring tattoo electrode based on PEDOT: PSS ink and check its feasibility of picking up surface bioelectric signals such as the electrocardiogram. Results reveal that it is possible to capture good quality bioelectric signals with tattoo electrodes implemented through inkjet techniques on tattoo paper substrate using PEDOT: PSS as ink. The main problem associated with this option is the cost in time of the machine for manufacturing the electrodes.

1 INTRODUCTION

The recording of electrophysiological signals in its simplest form, that is, through contact electrodes attached to the skin, is subject to continuous studies both to optimize these recordings and to search for new technologies that improve the manufacturing process.

Today, diagnosis, therapy, and health monitoring are largely based on the recording of encephalographic, cardiac, and muscle (myoelectric) signals. Even so, most recording systems for these signals continue to have a traditional approach, using monopolar disk electrodes (mainly Ag or AgCl). The use of conventional electrodes entails important limitations. On the one hand, they have limited ergonomics and comfort, and the costs of the manufacturing techniques used are also high. On the other hand, the records obtained show a low spatial resolution, which originates mainly from the smearing effect due to the different conductivities of the body volume conductor (Bradshaw et al., 2001). This fact limits the ability to localize the sources of bioelectric potential, which translates, for example, into the difficulty of using conventional electrocardiography (ECG) for the diagnosis of pathologies associated with localized alterations in the electrical conduction of the heart, as occurs in the case of ventricular ischemia, atrial hypertrophy (Macias et al., 2019), or difficulty in accurately locating epileptic foci using conventional electroencephalographic recordings (Aghaei-Lasboo et al., 2020). Addressing these issues often necessitates invasive electrophysiology, a procedure

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associated with considerable risks for the patient, and an extended diagnosis time.

In recent years, an effort has been made to search for alternative geometries and new technologies for the manufacture of contact electrodes that allow obtaining signals of better quality and/or with improved spatial resolution. In addition, the integration of the electrodes into clothing is sought, which would lead to medical control beyond the clinical work environment. To this end, the development of electrodes on flexible biocompatible substrates that provide characteristics such as lightness, high flexibility, and adaptation to the surface is sought out (Trung & Lee, 2016). Of these, screen printing is the most widely used and mature technology that has been used for decades in the manufacturing of electronic systems and, more recently, in the manufacturing of bioelectrodes.

To overcome the limited spatial resolution of bioelectric recordings obtained from conventional disk electrodes, the recording of the surface Laplacian potential has been proposed (Lu & Tarjan, 2002)(Liu et al., 2020) (Wang et al., 2023). The literature has confirmed that Laplacian recordings are capable of providing better spatial resolution of surface potential recordings, that is, they can improve the detection of bioelectric potential sources closest to the recording electrodes, rejecting the contribution of sources of bioelectric potential that are further away.

First, the surface Laplacian potential was estimated using monopolar disc electrodes and applying discretization techniques to estimate the Laplacian potential from them (Hjorth, 1975)(Tandonnet et al., 2005)(Prats-Boluda et al., 2007). Subsequently, concentric annular electrodes were designed, whose configurations (bipolar, quasi-bipolar, and tripolar) allowed obtaining a direct estimate of the Laplacian of the potential captured on the body surface. Subsequently, Laplacian potentials of ECG, electrohysterographic, and electroenterographic signals were obtained with concentric ring electrodes (CRE) implemented on rigid substrates, mainly using printed circuit boards (Lu & Tarjan, 2002) (Prats-Boluda et al., 2011) (Mas-Cabo et al., 2017)

The next step was the development of new flexible CREs (fCREs). Different printing technologies (screen printing, inkjet, gravure) and materials such as Melinex or Ultem, MEMS) were studied and compared for the development of fCREs (Wang et al., 2023)(Trung & Lee, 2016),(Wei et al., 2016). These fCREs allowed the capture of more robust signals against respiratory interference than conventional disc electrode recordings. Still, they presented greater low-frequency interference, this last observation being attributable to the fact that the recordings with fCRE were carried out dry. Therefore, despite the improvements introduced by the implementation of CREs on flexible substrates, the use of fCREs has not yet been transferred to the clinical setting.

The objective of this work was to create an ultra-flexible and ergonomic concentric ring tattoo electrode using PEDOT: PSS ink assessing its capability to capture surface bioelectric signals, specifically the ECG. With this type of recording, tools could be developed that would bring electromyography closer to clinical practice in different areas such as cardiology or obstetrics, improving and/or complementing the information provided by the non-invasive recording systems common in clinical settings.

2 MATERIALS AND METHODS

A concentric ring electrode was designed using the AutoCAD 2017 software (see Figure 1) and considering the results of previous works (Prats-Boluda et al., 2016).

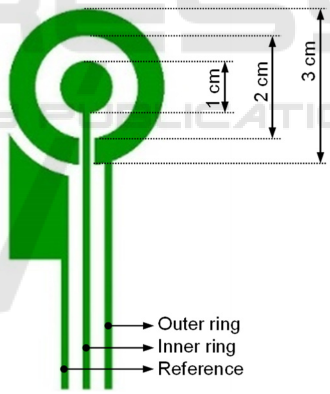

Figure 1: Diagram of the concentric ring electrode design.

The technology tested in the manufacturing of CRE tattoo prototypes was inkjet printing using the Dimatix printer available at DEALAB (Figure 2). Tattoo paper (tattoo 2.1) and commercial PEDOT: PSS conductive ink GSD9011 (Heraeus®) have been used as a substrate. Before printing the electrodes, the tattoo paper is activated by plasma (30', 100W). Likewise, the printing machine was programmed with the configuration parameters shown in Figure 2.

To ensure correct deposition of the material, a 5-layer print was made. The next step in the manufacturing of these prototypes has been allowing the extraction of signals from the tattoo electrodes. To do this, two cables have been glued to the conductive exit tracks of the electrodes prepared for this purpose, using the CW 2400 conductive glue, and the joint has been insulated and protected with Kapton adhesive. In addition, snap connectors are glued and crimped on the opposite end of the electrodes to allow their connection to the biosignal capture system available in the DEALAB, TMSI Porti 7®, see Figure 3. To cure the conductive glue it is necessary to put it in the electrode in the oven for 10 minutes at a temperature of 50º.

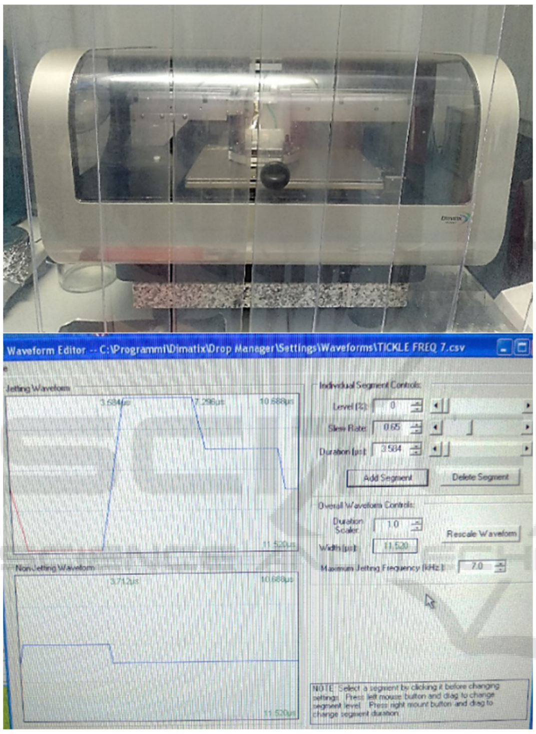

Figure 2: Inkjet printer (top panel) and the setup screen (bottom panel).

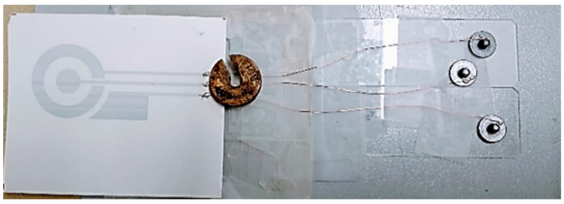

Figure 3: Output cables and connectors (at right) glued to the CRE tattoo.

Both, concentric bipolar (CRE-ECG; outer ring minus inner disc) and Lead II ECG (Lead II-ECG) signals were simultaneously recorded with the TMSI Porti7®, from DC to 500Hz, and acquired at 2048 Hz.

3 RESULTS

The capacity of this prototype of fCRE for the capture of bioelectric signals was tested. Specifically, an ECG signal was recorded. First, the skin surface where the fCRE was positioned, comparable to precordial lead V1 (CMV1), was shaved to minimize contact impedance and minimally exfoliated using Nuprep from Weaver and Company, USA. Following the subjects' skin was cleaned with alcohol. Subsequently, tattoo paper where the fCRE was printed was placed over the area to be recorded, CMV1, eliminating the “sacrificial layer”, a top transparent film that covers the printed electrode. It protects the electrode and helps transfer it onto the skin. Figure 4 shows the arrangement of the developed tattoo electrode on the chest to test its ability to record the CRE-ECG signal. Together with the CRE electrode, the Lead II-ECG was simultaneously recorded.

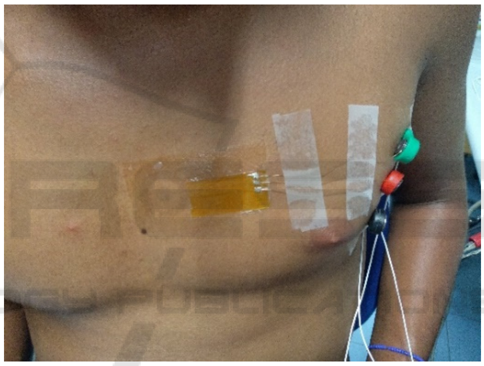

Figure 4: Placement of the CRE tattoo of PEDOT: PSS, for recording ECG signal.

Figure 5 corresponds to the simultaneous raw recordings of the Lead II-ECG with conventional commercial disc electrodes and with the PEDOT: PSS tattoo electrode printed with the Dimatix on tattoo paper. Recordings in Figure 5 demonstrate the feasibility of capturing the ECG signal with the PEDOT: PSS CRE tattoo electrodes on tattoo paper.

As expected, the amplitude of the signal captured with the CRE (ECG-CRE) is much weaker than that associated with Lead II-ECG recordings made with conventional disc electrodes. In this regard, it should be pointed out that one of the advantages of the designed CRE is the possibility of picking up the cardiac signal without using an external reference electrode located on the hip or extremities. Still, rather the tattoo electrode itself incorporates its own reference. Also, the presence of powerline noise is

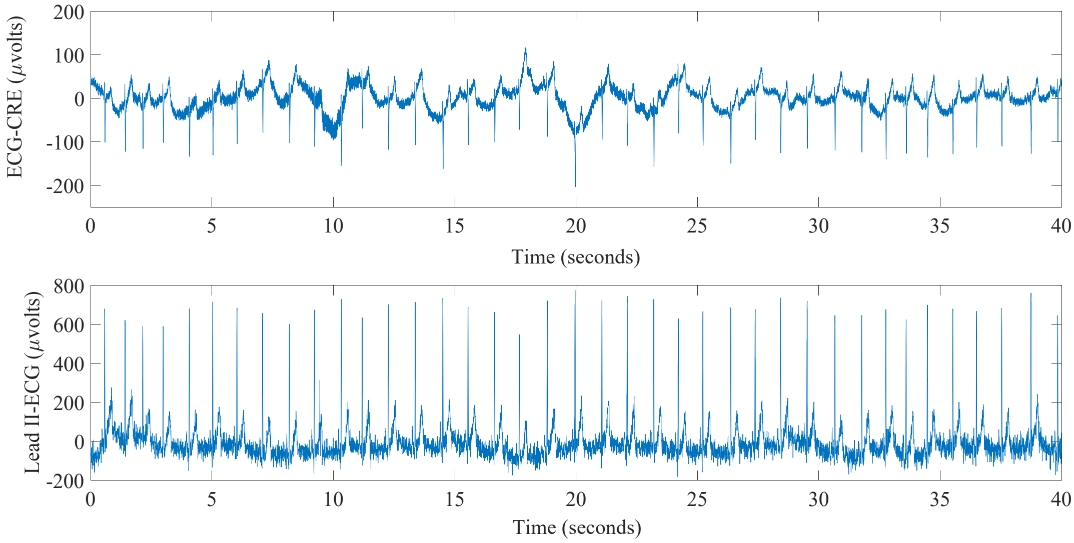

Figure 5: 40 seconds or raw signals corresponding to simultaneous recording of ECG-CRE bipolar signal captured with CRE tattoo of PEDOT: PSS printed by inkjet using the Dimatix printer on plasma-activated tattoo paper (top panel) and Lead II-ECG recording obtained with conventional disc electrodes (bottom panel).

noticeable in the recorded signals, both in the ECG-CRE recording and in the Lead II-ECG signal. Concerning this aspect, tests to check the ECG signal capture capacity with the CRE tattoos printed with the Dimatix were carried out in the laboratory, where a large number of machines and wiring are located, that is, in a very unfavorable environment for the recording of bioelectric signals.

One of the main problems with this technology is the slowness of printing, requiring 3.5 hours of machine use per electrode. That is why it is proposed in the future to carry out a study about developing tattoo electrodes using screen printing or gravure techniques, that enable the large-scale production of this type of electrodes at an industrial scale. Additionally, to enhance signal quality and facilitate extensive use, it would be advisable to incorporate additional elements such as electrolytic gel, adhesive, and connectors commonly used in the biomedical industry.

Another important aspect that needs to be addressed to bring the use of CRE electrodes into the clinical setting is to establish standard recording positions on the torso and extract patterns of normality/abnormality from the morphology of cardiac waves. In this regard, preliminary studies have been conducted using flexible concentric multi-ring electrodes in precordial positions (Prats-Boluda et al., 2016) or even mapping the torso (Besio & Chen, 2007) (Prats-Boluda et al., 2018). However, comprehensive studies are needed to validate the results and, above all, to determine biomarkers associated with pathological conditions.

As for the applicability of the developed tattoo electrode, in the present work, we have focused on ECG recording for the electrode design. Similar electrodes could be used for picking up other bioelectric signals (Estrada-Petrocelli et al., 2021) (Ye-Lin et al., 2022). The optimal TCRE dimensions will depend on the depth of the bioelectric source (the deeper the higher the electrode diameter), the required signal-to-noise ratio, or spatial resolution (Makeyev et al., 2021).

4 CONCLUSIONS

It is possible to capture good quality bioelectric signals with tattoo electrodes implemented through inkjet techniques on tattoo paper substrate using PEDOT: PSS as ink. The main problem associated with this option is the cost in time of the machine for manufacturing the electrodes. Future works will be carried out to develop tattoo electrodes by screen-printing or gravure techniques.

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