Inkjet Printed Flexible Electronic Dry ECG Electrodes on Polyimide Substrates Using Silver Ink

Mst Moriom R. Momota, Student Member, IEEE, and Bashir I. Morshed, Senior Member, IEEE, EMBS
Department of Electrical and Computer Engineering, The University of Memphis, Memphis, TN 38152, USA

Abstract—**Flexible electronic wearable device market demand is growing rapidly. In this research work, we have fabricated Inkjet Printed (IJP) flexible electronic dry ECG electrodes on polyimide substrates (50 µm thin) using silver nanoparticle ink in two shapes: circular and pentagonal. The IJP electrodes were cured at 250°C for 1 hour. We compared these IJP electrode performances against commercial gel and metal electrodes. We collected real-time ECG data using these 4 types of ECG electrodes simultaneously for 9 hours. Our IJP ECG electrodes showed very similar performances as the commercial gel and metal electrodes in terms of Signal-to-Noise Ratio, SNR (e.g. gel, metal, IJP circular, IJP pentagonal = 18.97, 18.93, 18.94, 18.96 dB, respectively) and coherence metrics. However, as the gel electrode degrades over time, after 9 hours the data was observed to be degrading while data from dry electrodes were similar as evident from the time-frequency graphs. Metal electrode suffered from higher utility line noises. Furthermore, IJP circular and pentagonal shaped flexible electrodes were superior for comfort due to being flexible compared to rigid metal electrode. Thus, the proposed IJP dry electrodes can be a viable option for long-time use, reusability, and comfort for usage in ECG wearables.**

Keywords— Dry electrodes, ECG, Inkjet printing, Polyimide, Silver ink.

I. INTRODUCTION

Electrocardiographic (ECG) is the standard procedure for the diagnosis of cardiovascular diseases (CVDs). ECG is a composite recording of all the actions potentially produced by the nodes and cells of the myocardium. ECG is a low-frequency signal, and its frequency range is 0.05-100Hz. ECG signal is a graph of voltage versus time of the electrical activity of the heart using electrodes placed on the skin. Electrodes detect the small electrical changes, which are the consequence of cardiac muscle depolarization followed by repolarization during each cardiac cycle [1]. Each wave of ECG corresponds to each heartbeat. A change in the regular ECG pattern occurs because of numerous cardiac abnormalities such as arrhythmia, angina, and atrial fibrillation.

With the evolution of technology, ECG devices have also changed considering the comfort of the patients and can also be monitor from outside hospital or clinic without affecting any routine activity. In early days, ECG monitoring devices were larger, expensive, and non-portable, as it had used vacuum tubes and water buckets [1,2]. But now, the sizes of the ECG devices are small, which makes it possible to monitor health conveniently, continuously, and remotely.

Flexible films, patches, bandage and tattoos like skin sensors are still in an experimental phase. But the demand for these flexible electronics sensors is increasing day by day [3]. For remote monitoring and earlier detection of diseases, flexible electronics sensors would be promising in terms of user comfortability and sensors reusability to make the medical service more efficient.

Among wet, dry contact and non-contact or capacitive electrode flexible electronics dry electrodes are used mostly in the ECG sensor. There are different types of dry contact electrodes are commercially available such as gel electrode, which is still clinically used standard electrode, metal electrode, cotton electrode and so on. In the gel electrode, they use a gel of Ag/AgCl for getting better skin-electrode coupling. But the gel electrode is disposable and cannot be used for a long time. Many users reported skin irritation and discomfort from the gels and adhesives that contact the skin [4]. Compared with the gel electrodes, the performance of a dry electrode usually increases over time as more moisture permeates the skin-electrode interface resulting in increased coupling [4]. Dry electrodes provide high signal to artifact ratio and reliability by meeting the following criteria: low baseline shift, high adhesion, good physical stability, large effective area and thin with high flexibility [5]. But sometimes due to proper electrode placement and lack of skin-electrode coupling dry electrode can't show the same result as the gel electrode [6]. Otherwise dry electrodes comfortability and durability could make it efficient in medical application.

Inkjet printing is a technique to print flexible electronics on surfaces. Inkjet printing technology is the best way to overcome the limitations of existing devices such as rigidity, high cost, and small area coverage of the current microelectronics fabrication process [7]. Our research lab previously fabricated flexible electronics low-cost IJP respiration sensor and ECG electrode [8]. They used three types of ink (25 % silver, 40% silver, 35 polypyrroles) and the electronics circuit developed with conductive traces on paper and polymer. An ultra-low-power inductively coupled wearable ECG Sensor was designed with Inkjet-Printed Dry Electrodes [9]. IJP electrodes were printed on a paper using Ag nanoparticle ink. Long duration IJP dry electrodes were used in this sensor for long time usability. Another work was done on IJP ECG electrodes for long term bio-signal monitoring where they used copper ink on plastic and silver ink on paper [10]

In this study, we fabricated flexible IJP ECG electrodes with different shapes one in circular and another in pentagonal with Ag B40G ink. We collected real-time ECG data using these IJP electrodes and also using the commercial gel electrode and commercial metal electrode. We have compared the performances between these four types of electrodes.

II. IJP PROCESS AND MATERIALS

A. Ag B40 Ink

The product name of the silver ink we used for our IJP electrodes is Metalon JS B40G silver ink. Novacentrix is the manufacturer of this commercial Ag B40 ink. This ink contains 30-60% silver and 0-20% Diethylene glycol monobutyl ether. The viscosity of this ink is 9.0 cp at 18^0C, specific gravity is 1.56, and the particle size (z-average by DLS) is 74 nm.

B. IJP Process

The fabrication of our IJP electrodes is performed by FujiFilm Dimatix Materials Printer (DMP-2831), which has a PC controlled application named Dimatix Drop Manager. It also has the option to visually monitor the ink-jetting and printed pattern by using the fiducial camera. The IJP cartridge has 16 nozzles at 254 µm spacing to get better deposition height control which is important for obtaining high-resolution design [11]. From Dimatix Drop Manager we can select the number of nozzles according to demand. In our case, we selected all 16 nozzles, which not only provide high-quality printing but also reduced the printing time. We used polyimide (PI) film as the substrate and Metalon JS B40G silver ink (i.e. Ag B40) as the printing ink. From the printer cartridge ink drops through the nozzles drop by drop on the substrate and the printing direction is one-directional (left to right). For 1693 dpi resolution layout printing cartridge needs to mountain at 3.4^0 angle and drop spacing will be 15 µm in this case. Fig. 1 depicts the relationship between the drop spacing and drops size for the procedure of IJP fabrication.

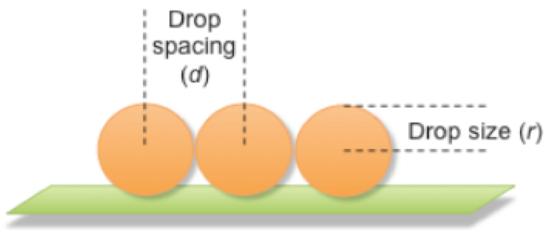


Fig. 1. Relation between drop spacing and drop size for IJP fabrication process.

C. Layout of IJP Electrodes

The layouts of circular and pentagonal shape ECG electrodes are shown in Fig. 2. We have designed these layouts using InkScape software and exported the image at 1693 dpi resolution in png format. IrfanView software converted these png files into a 24 bit-bmp format. After that, we used MS Paint software to convert these images into monochrome bmp format. The area of this circular IJP Electrode and pentagonal IJP Electrode are 314.16 mm^2 and 600 mm^2 respectively.

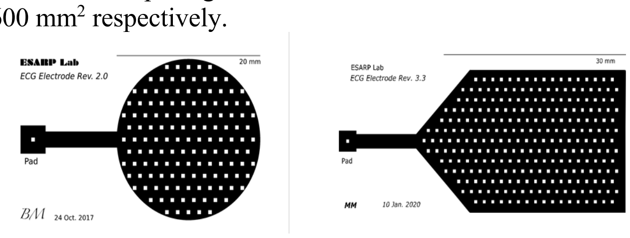


Fig. 2. Layout of ECG electrodes: circular IJP Electrode (left), and pentagonal IJP Electrode (right).

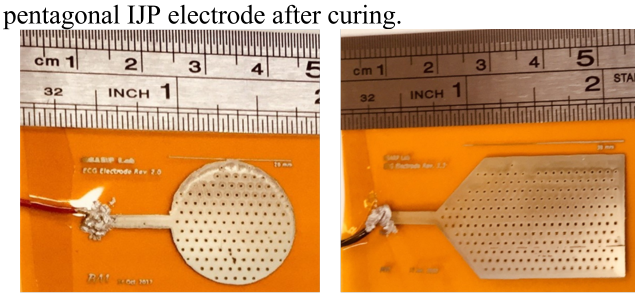
D. Fabrication Process

Fabrication was done by DMP-2831 printer (Dimatix, Fujifilm Inc.), which printed these layouts on the polyimide (PI) substrate. The PI substrate thickness was 200 nm. When the printing completed, we cured these electrodes with Thermo Scientific Heratherm Oven (Thermo Fisher Scientific Inc., MA, USA) at 250°C temperature for 1 hour. Finally, we used high conductivity silver epoxy paste (Model: 8331, MG Chemicals) to connect wires to the IJP electrode pads (2 mm x 2 mm). After applying the epoxy, we cured it at 100°C for 1 hour.

III. EXPERIMENTAL RESULTS

A. Fabricated Electrodes

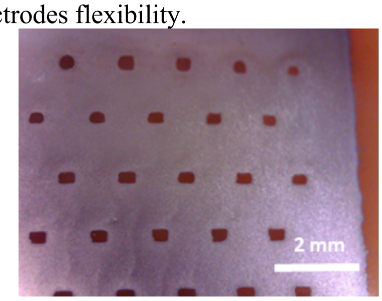
Fig. 3 depicts the fabricated circular IJP electrode and the pentagonal IJP electrode after curing.



(a) (b)

Fig. 3. Fabricated IJP electrodes: (a) circular IJP Electrode, and (b) pentagonal IJP Electrode.

The USB microscopic image is shown in Fig 4(a). We captured the image to observe the designed cavities within ink-jetting area on a polyimide substrate. These designed cavities allow anchoring of the Ag thin-films on the polyimide film leading to higher adhesion and lesser peel-off effect. Fig 4(b) shows that our IJP electrodes were held in bent formation pinched between fingers, which proofs of our IJP electrodes flexibility.



(a)

(b)

Fig. 4. (a) USB microscopic image shows designed cavities of IJP ECG electrodes. (b) The flexibility of IJP electrodes.

B. ECG Data Collection

We used 4 types of ECG electrodes for real time ECG data collection. These Electrodes are commercial gel electrodes (Red Dot Electrodes 2560, 3M, Maplewood, MN), commercial metal electrodes (SHIELD-EKG-EMG-PA – passive electrodes, Olimex), our fabricated IJP circular electrode and IJP pentagonal electrodes. Gel, metal, IJP circular, and IJP pentagonal electrodes are shown in Fig. 5.

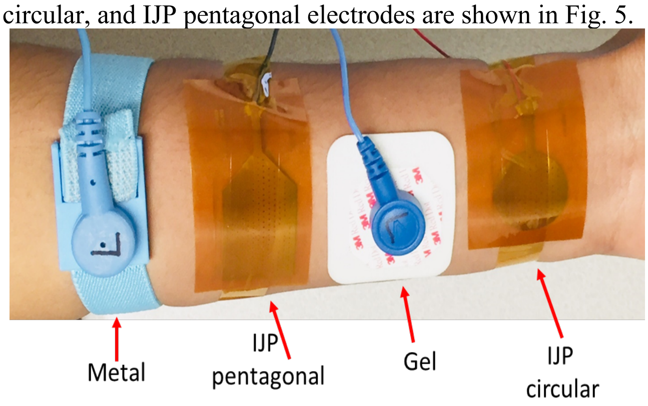


Fig. 5. Real time ECG data collection using Gel, Metal, IJP circular and IJP pentagonal electrodes.

C. Data analysis

We have used Arduino Uno and AD8232 ECG data collection board to collect the ECG data. For these data collection, we have used Lead I ECG placement. We collected these 4 types of ECG data simultaneously with four AD8232 boards, and performed this experiment for 9 hours continuously for an accurate comparison of these ECG signals.

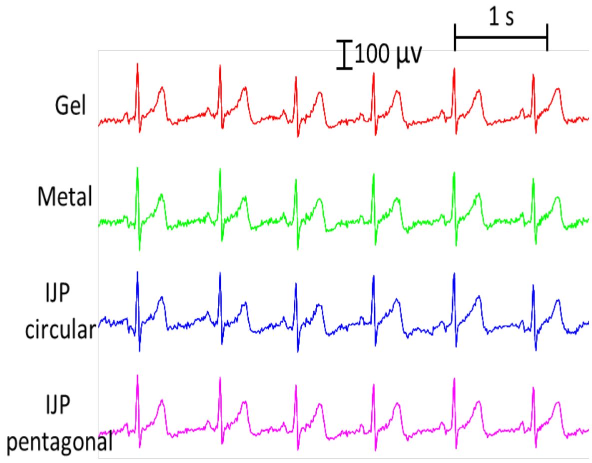
When we started collecting ECG, we noted that time as T-0. At that time captured ECG signals using these 4 types of electrodes are depicted in Fig. 6(a). We used a notch filter (60 Hz) and a low pass filter (15 Hz) to cancel noise from our raw signal. After that we subtracted the filtered signal from the raw signal to compute the noise present in the raw ECG signal. To calculate signal-to-noise ratio (SNR) of our collected ECG signal, we used the following equation:

$$SNR = 10 \log (S / N) \quad (1)$$

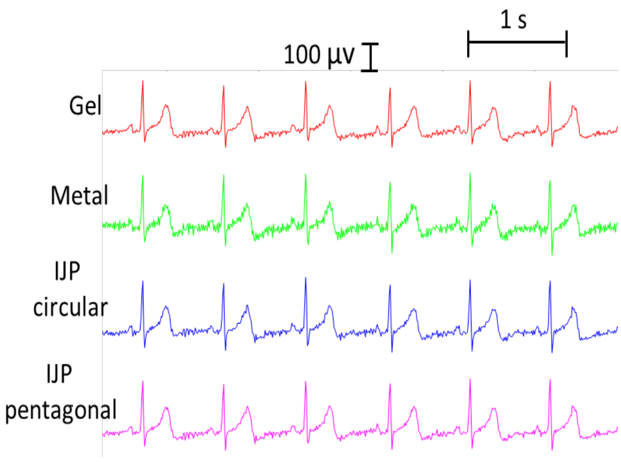
where S is the raw signal power and N is the noise power.

The SNR for gel, metal, IJP circular and IJP pentagonal were 18.97 dB, 18.93 dB, 18.94 dB, and 18.96 dB, respectively. We collected data every 1-hour interval. Data after 1 hour is noted as T-1, which is displayed at Fig. 6(b). For T-1 SNR of gel, metal, IJP circular, and IJP pentagonal were 18.94 dB, 18.83 dB, 18.91 dB, and 18.92 dB, respectively. After 9 hours collect ECG signals for these 4 types of electrodes is showed in Fig. 6(c), we considered this signal as T-9. For T-9 SNR of gel, metal, IJP circular and IJP pentagonal are 18.88 dB, 18.83 dB, 18.84 dB, and 18.87 dB, respectively.

Magnitude square coherence was calculated for analyzing the similarity between two signals over frequency. We measured magnitude square coherence for T-0 between the gel electrode and other electrodes, which is illustrated in Fig. 7 (a)-(c). We took the gel electrode as it showed the best results at the beginning of the test. Magnitude square coherence provides a result between 0 and 1. Coherence 1 is considered as the highest coherence and coherence 0 as lowest coherence. Comparing Fig 7(a), 7(b), and 7(c) it can be found that the IJP pentagonal electrode showed more coherence than metal and IJP circular electrodes. IJP pentagonal electrodes coherence was found 1 for most of the frequency. We used *mscohere* function in Matlab to implement this plot.



(a)



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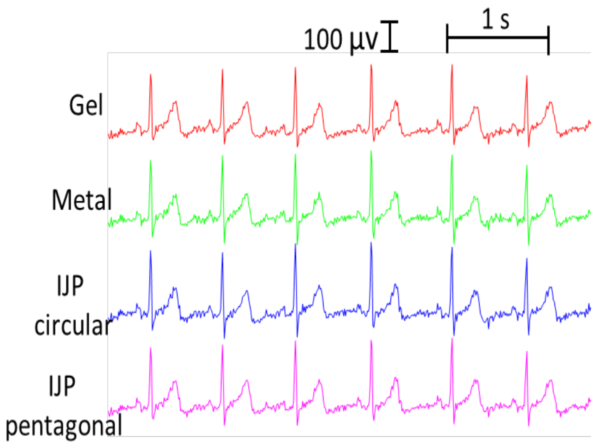
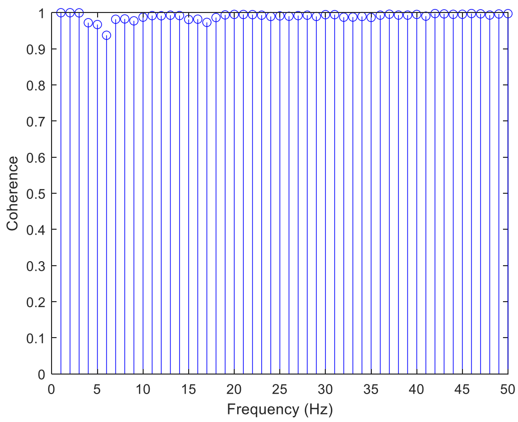
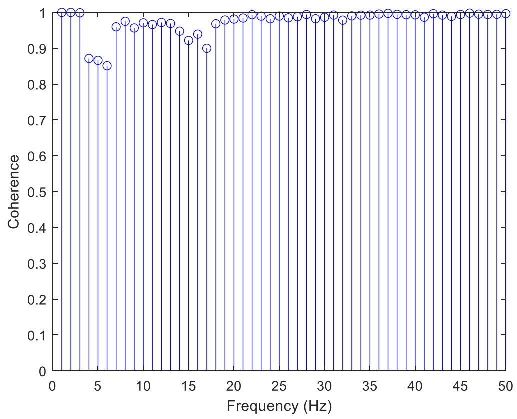


(c)

Fig. 6. Collected ECG signal, (a) at the beginning of the test (T-0), (b) after 1 hour (T-1), and (c) after 9 hours (T-9) using gel, metal, IJP circular, and IJP pentagonal electrodes.



(a)



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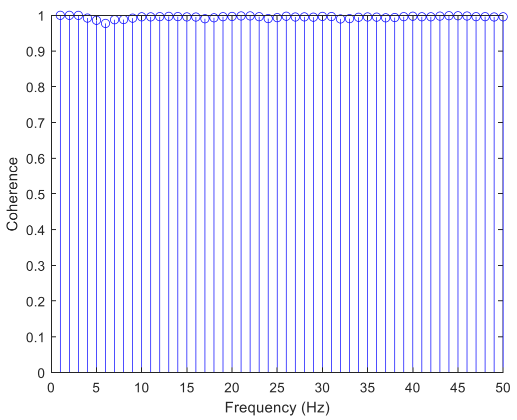
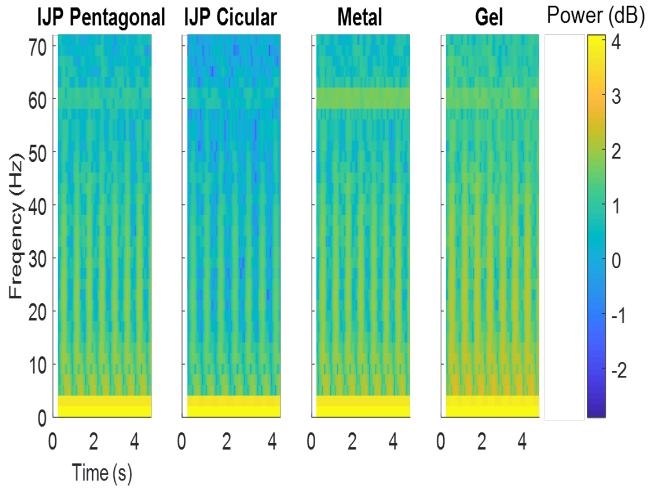


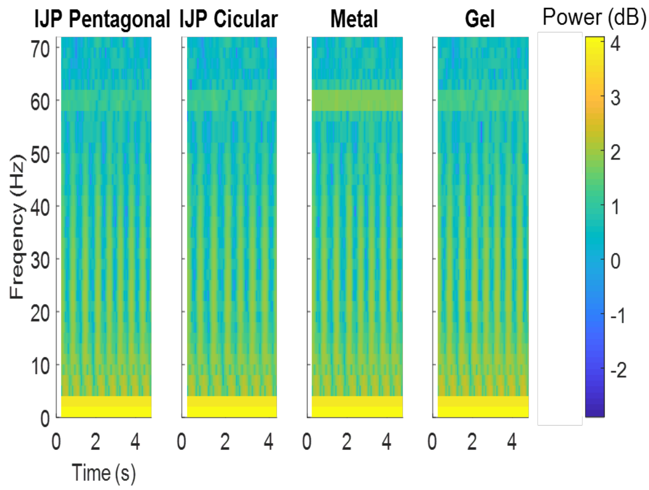
(c)

Fig. 7. Magnitude square coherence measure plot for (a) gel vs metal electrode, (b) gel vs IJP circular electrode, and (c) gel vs IJP pentagonal electrode.

The spectrograms for gel electrode are shown in Fig. 8. We plot 1000 samples of ECG signal. Fig 8(a) is the spectrogram for T-1 (1 hour after the experiment started), which shows the signal strength of ECG signal in dB. At 9 hours (T-9), the gel electrode signal strength became weaker which can be easily observed from Fig 8(b). Thus, gel electrode is not suitable for long term use. In contrast, the dry electrode data quality remains the same. Furthermore, our IJP electrodes shows lesser utility line noise and its harmonics compared to metal electrode. As there is no significant difference between the 2 IJP designs, the effect of area seems to be minimal.



(a)



(b)

Fig. 8. Time frequency plots for IJP pentagonal, IJP circular, metal, and gel electrodes at (a) 1 hour (T-1), and (b) at 9 hours (T-9).

IV. CONCLUSIONS

In this work, we fabricated flexible IJP ECG electrodes in a circular and a pentagonal shape. We have used Ag nanoparticle ink on polyimide films. We also collected real-time ECG data using our fabricated IJP electrodes and compared the data with that of commercial gel and metal electrodes. We performed the data collection simultaneously which allows accurate data comparison. Our pentagonal shaped ECG electrodes showed almost similar SNR and coherence as gel electrodes. Both circular and pentagonal IJP electrodes showed better performance than commercial metal electrodes and are more comfortable due to flexibility. Thus, these flexible IJP electrodes can be used in ECG wearables and flexible electronics that can include body-worn ECG monitoring devices.

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