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Wearable Mobile Ear-based ECG Monitoring Device Using Graphene-Coated Sensors

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***Abstract*—This work proposes the design and evaluation of a wearable mobile ear-based electrocardiogram (ECG) monitoring system using highly electrically conductive material – graphene - enabled electrodes. Prolonged physiological monitoring is important in diagnosis, monitoring chronic diseases, and improving training regimes. Current technologies for monitoring ECGs alone are acceptable to clinicians or professionals, but alien to users. Uncomfortable and unfamiliar technologies are not efficient for obtaining ambulatory data they are designed for. Smartphones and headphones are increasingly ubiquitous across generations. Here, a novel design is aimed to progress the development of an ear-based, graphene sensors with mobile connectivity producing high quality, prolonged, real-time ECG measurements in a system more familiar to the end user.**

***Keywords*—graphene; electrocardiogram; ear-ECG; mobile health; wearable sensor; ECG electrode**

I. Introduction

Chronic cardiovascular diseases significantly threaten human health and occur suddenly and unexpectedly. Periodically monitoring of heart rate and electrocardiogram (ECG) is useful both in health and disease states. It is also essential to record ECG signals for the diagnosis of the cause of dizziness and breathlessness. Traditionally two types of electrodes are used to obtain ECG signals: dry and wet type of electrode. The conventional wet type of electrode is Ag/AgCl electrode which is generally utilized in clinics and hospitals. However, the wet type of electrode is not desired in long term recording due to skin irritations and allergic reactions. The latter type of electrode (dry electrode) is conducted with several type of materials. Chlaihawi et al. [1] proposed a flexible dry electrode based on multi-walled carbon nanotube polydimethylsiloxane (MWCNT)/PDMS composite, and Varadan et al. [2] developed a textile based dry nano-biosensing electrode which was made of gold nanowire on flexible Titanium foil for long term ECG monitoring. However, the proposed dry based electrodes demonstrated higher skin-electrode contact impedance than conventional Ag/AgCl electrodes, thus the quality of recorded cardiac signals can be degraded.

Graphene (GN), a two-dimensional structure nanomaterial, exhibits exceptional electrical (highest electrically conductive material – 10^{-8} Ωm), and physical (fastest moving electrons of any material – 10^{6} m/s) characteristics that can lead the current ECG technology further [3]. Yapici et al. [4] developed a GN-based textile electrode which is suited in a medical garment for cardiac monitoring. Our group [5] also fabricated a GN-based electrode for continous ECG measurements. The results from both group demonstrated that the amplitude of obtained ECG signals using GN-based electrodes was higher than that of Ag/AgCl electrodes due to electrical characteristics of GN. Our method differs from that of Yapici's group [4] in the fabrication method of ECG electrode by deploying chemical vapour deposition (CVD) onto the target substrate.

Patient's repositioning electrodes in identical locations for prolonged recordings may be difficult for older patients. Mobile handheld recording devices do not require continous application on the chest; however, they are often inappropriately positioned by patients when recording. Furthermore, handheld mobile devices to record ECG are accessible, but do not permit the patient to move their arms freely while walking – making ambulatory recording cumbersome and often impractical for elderly patients who require co-ordinated arm movements to help with upright balance. The ears are in a standard fixed position in relation to the head. Da He et al. [6] studied in recording ECG signals from the near ear area, however, the amplitude of ECG signal was not efficient in the proposed work. In this study, a wearable continous ECG recording system is performed using ear-based GN-coated electrodes with a smartphone to display real-time measurements. The obtained results from the ear using GN-coated electrodes are compared with those obtained using conventional Ag/AgCl electrodes.

II. Sensor Design

To synthesize conductive ECG sensors, chemical vapor deposition (CVD) method is utilized for coating process where GN layers formed on silver (Ag) substrates of the targeted sensors. The modified Mattevi's method [7] was used for coating GN on Ag substrates by transferring from a copper (Cu) substrate via the CVD process. Fig. 1.a shows the whole procedure of CVD for ECG sensor design which is grown by GN. As can be seen from Fig. 1.a, the process starts with the GN growth on Cu by CVD modification and then the top side of substrate is covered by a PMMA layer with a spin coater. After that, this triple layer is placed into a bath of ammonium persulfate to etch away the Cu layer. After this happened, the PMMA/GN layer is cleaned and residues are removed by a deionised (DI) water bath. After this layer is dried it is placed onto the Ag substrate of the sensor. Finally, the proposed GN-

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based ECG electrode is produced by removing PMMA layer in an acetone solution. At the end of the fabrication process, the proposed ECG sensor is designed with a very thin GN layer (around 3.7 Å ≈ 0.37 nm) on top of Ag substrate (see Fig. 1.b).

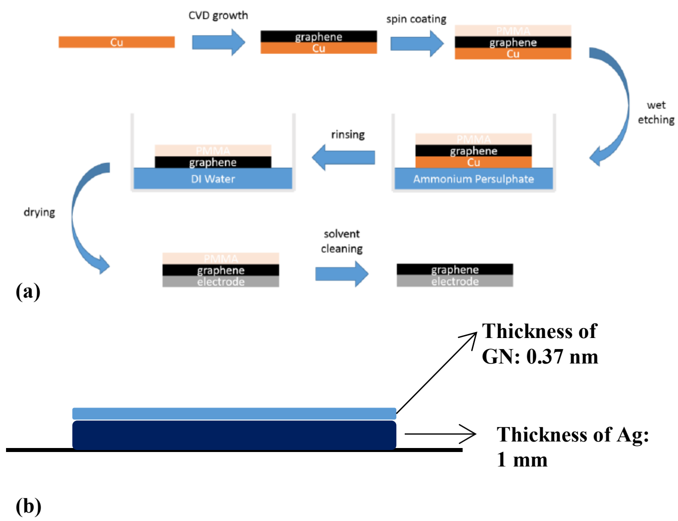
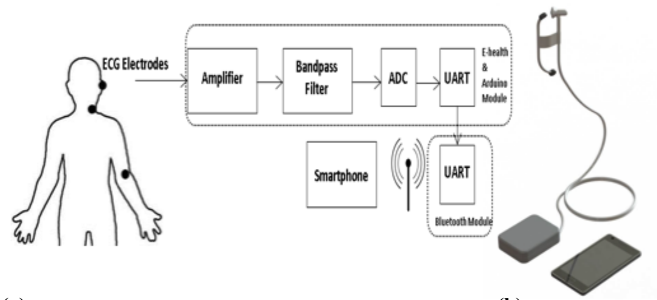


Fig. 1. (a) The process of GN-based sensor design for ECG monitoring; (b) the thickness of the proposed GN-based sensor

III. System Overview

The typical ECG monitoring systems consist of two parts which are electrodes and front-end data acquisition circuit. Three-electrode system is conducted to acquire ECG signals in this work. In three-electrode system, two active electrodes are used for differential inputs of the ECG amplifier. The third electrode is attached to have better signal quality by eliminating common mode interference. In the proposed work, two electrodes are placed on the near the ear - the one is attached just behind the ear, and another one is placed on the upper neck - and the third electrode is attached on the arm as a ground to acquire ECG signal as shown in Fig. 2.a. The electrodes are tested in a developed wearable unit (see Fig. 2.b) that sends raw ECG signals from the ear-based electrodes to measurement circuit which is placed on the arm. After digitizing, amplifying and filtering processes in the measurement circuit, the ECG data is transmitted to a smartphone via Bluetooth to be monitored continously.

To achieve a comparable ECG data from weak and small raw ECG signals, an ECG measurement circuit with high gain is needed. ECG signals were filtered by a bandpass filter between 0.5 and 100 Hz. An additional notch filter was applied at 50 Hz to eliminate powerline frequency. After that, the amplified ECG signal is digitized by a built-in, 16-bit analog-to-digital converter (ADC) of a microcontroller board with a sampling rate of 500 Hz. The commercially available microcontroller board (Arduino UNO) is also in charge of transmitting the acquired ECG signals wirelessly using HC 05 Bluetooth module to a smartphone. The system works with a lithium battery, which has a 500 mAh capacity and lasts nearly 30 hours, which depends on the use of the Bluetooth module. In this study, the size of the two different electrodes were identical and have a diameter of 24 mm and a thickness of 1 mm. The distance between two active electrodes were applied as 8 cm.



(a) (b)
Fig. 2. (a) Electrode placement and block diagram of the ECG monitoring system; (b) Prototype design of ear-based ECG monitoring system

IV. Software Design

An Android based smartphone application was developed to monitor continously the received sensor data obtained from the proposed ear-based device using both GN-based and conventional Ag/AgCl electrodes. The acquired ECG signals were displayed in real-time wirelessly using Bluetooth communication. The software algorithm has also extra benefits over monitoring ECG data continously, e.g. calculating heart rate (HR), and storing the received data. The algorithm was developed in the Android Studio software tool using Java programming language. The developed software was implemented onto an Android based based smartphone not only to receive, display and save ECG data from a subject, but also to transmit the critical signs periodically to a clinical server, so that transmitted biopotential can be monitored by a clinician at a distance.

Furthermore, a stored ECG sequence can be analyzed to identify specific health issues, which are defined in the software algorithm by looking up a database for matching process, such as Tachycardia or Vertigo. Hence, when a critical sign is detected, the ECG monitoring system can alert the person with HR information.

V. Experimental Results and Discussion

A. *ECG Signal Quality*

Two different type of electrodes (Graphene and Ag/AgCl based) were used in this study to analyse the acquired ECG signals in terms of ECG signal quality and skin-electrode contact inmpedance. ECG measurements were performed on a healthy -29 year old- subject using a commercial data acquisition system (e-Health platform) in order to evaluate the performance of the two-type of the electrodes. Firstly, the conventional Ag/AgCl electrodes were used to perform ECG measurements. Subsequently, the ECG signal was measured using the proposed GN-coated electrodes from the ear-based device. Eventhough only QRS complex was identified using conventional Ag/AgCl electrodes, all critical signs of an ECG waveform (P-wave, QRS complex and T-wave) were detected using GN-coated electrodes, as can be seen in Fig. 3. It is clearly observed that the amplitude of QRS complex for the GN-coated electrodes was higher than that of Ag/AgCl electrodes. A comparison is made that the ECG signal obtained by the Ag/AgCl electrodes was less reliable than that of the proposed GN-based electrodes. It is also clear in Fig. 3 that the acquired ECG signal of the proposed GN-coated electrode has smaller distortion and fluctuation.

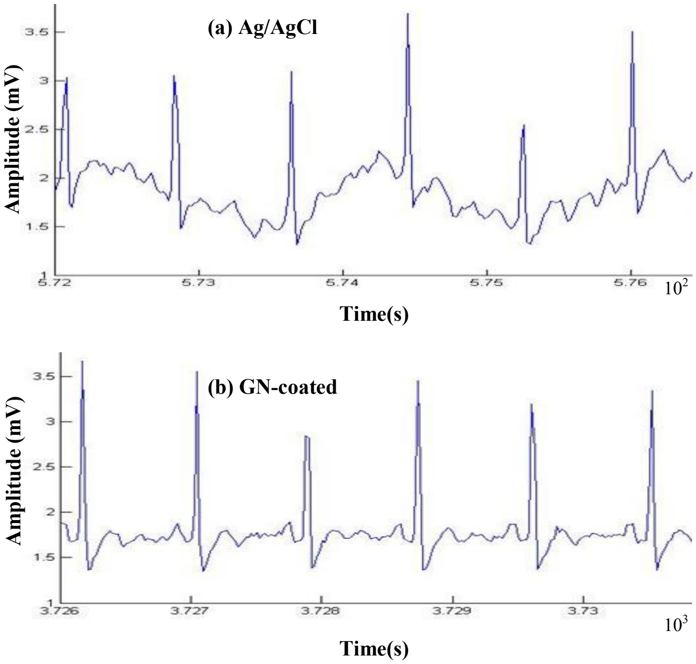


Fig. 3. Acquired ECG signals from ear-based device using (a) conventional Ag/AgCl electrodes; and (b) the proposed GN-coated electrodes

B. *Performance Evaluation of Mobile Device*

Fig. 4 shows the comparison of the real time ECG monitoring application on a smartphone using Ag/AgCl and GN-coated electrodes. It is clearly evident that the ECG signals were improved by GN-coated electrodes when compared to Ag/AgCl electrodes. It is obvious that the ECG signals using GN-coated electrodes have better ECG signal quality and are able to display P-QRS-T. In fact, again only QRS complex was identified in mobile ECG signals using Ag/AgCl electrodes.

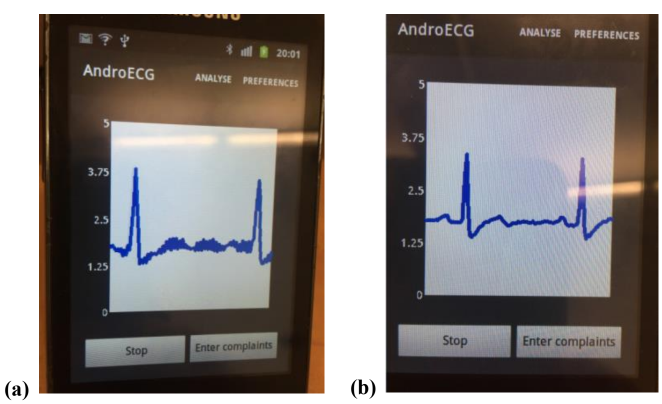


Fig. 4. Mobile ECG monitoring by (a) Ag/AgCl and (b) GN-coated sensors

C. *Skin-Electrode Contact Impedance Evaluation*

To validate whether the proposed system is suitable for high quality signal acquisition with minimal noise, then skin-electrode contact impedance needs to be small and stable. Fig. 5 illustrates the log-log scale of the average impedance values of Ag/AgCl and GN-coated electrodes in the frequency range of 20 Hz to 1 kHz. The impedance results were varied from 448 kΩ to 14 kΩ, and from 76 kΩ to 5.5 kΩ, for Ag/AgCl and GN-coated electrodes respectively.

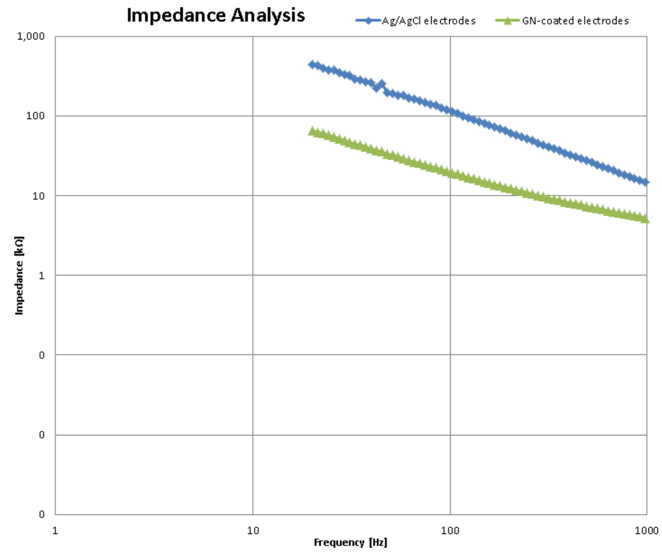


Fig. 5. Plot of the skin-electrode contact impedance for Ag/AgCl and GN-coated electrodes in log-log scale

VI. Conclusion

In summary, an ear-based graphene-coated sensor system was developed for continuous mobile ECG monitoring application. The experimental results clearly showed that the proposed GN-based electrodes exhibited better performance than conventional Ag/AgCl electrodes in terms of ECG signal quality and skin-electrode contact impedance. It is proved that GN-coated electrodes enable good quality recording of ECG signals from the ear area, thus motion artefact is minimized.

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