





# Performance Evaluation of Biomedical ECG Suction Electrodes with Different Materials

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## Abstract

A suction electrode is often used as a precordial electrode in clinical electrocardiograms. It can be used frequently and has no need for adhesive or a strap. Higher source impedance since the contact area is small. The present study aims to 1) design and implement biomedical suction electrodes with different types of materials (Copper and Aluminum) and determine the dimensions of each electrode, 2) apply these constructed electrodes on subjects in hospitals and laboratories to extract their electrocardiogram waveform, and 3) finally, make a comparison between these constructed electrodes (Copper and Aluminum) with the standard electrode made from Ag/AgCl. The results obtained indicate that the best material for a construction electrode after the Ag/AgCl material is the Copper material, which gives the same electrocardiogram signal with high efficiency and accuracy. In addition, Copper material is less expensive than silver, so it is desired to use it in the reading of electrocardiogram signals. While Aluminum material was never used in the electrode construction, this was obtained from the reading of its electrocardiogram signal.

**Keywords:** ECG; Chest electrode; Suction electrode; Ag/AgCl electrode; Copper electrode.

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## 1. Introduction

The electrical activity of the heart's cardiac muscles produces a temporally changing bio-potential signal known as an electrocardiogram (ECG) [1]. The most common cause of death worldwide is due to cardiovascular disease, resulting in millions of deaths annually [2]. The ECG signal is most frequently utilized in clinical examinations. In addition to diagnosing heart-related conditions such as atrial and ventricular hypertrophy, rapid beats, and atrial fibrillation, it can reflect normal cardiac electrical activity [3].

Electrodes are necessary parts that allow electrophysiological signals to be recorded and analyzed [4]. An electrode is a device that transforms ionic potentials generated by muscles, glands, or nerves in the body into electrical potentials within the electronic instrument. It's a small metal plate attached to a subject's skin to record underlying bioelectrical signals, often using a gel or electrolyte-soaked pad to maintain contact [5, 6, 7]. At the interface between the electrode and electrolyte, an electrochemical reaction occurs, creating a voltage difference between the electrolyte and the metal. This

process allows voltages to be generated at the electrode site regardless of the body's bioelectric activity. Consequently, it becomes possible to record the desired physiological signal alongside any unwanted voltages produced by the electrodes [8, 9].

Based on the findings of previous research indicating the strong electrical performance of copper-based electrodes and the inconsistent behavior of aluminum-based electrodes, the present study aims to:

1. Design and fabricate suction-type ECG electrodes using two alternative materials (Copper and Aluminum) with dimensions comparable to standard Ag/AgCl electrodes.
2. Evaluate the performance of the constructed electrodes on human subjects and extract ECG signals under realistic clinical and laboratory conditions.
3. Compare the obtained ECG signals with those produced by standard Ag/AgCl electrodes in terms of signal quality, stability, noise level, and correlation.

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4. Identify the most suitable low-cost material for manufacturing reusable ECG suction electrodes based on the experimental results.

Biomedical electrodes are used in a variety of biomedical applications, such as [10]:

- (i) Detecting bioelectrical activities like the electrocardiogram.
- (ii) Applying therapeutic impulses to the body, such as defibrillation and transcutaneous electrical nerve stimulation.
- (iii) Delivering electrical potentials to aid the transdermal delivery of ionized molecules for both local and systemic therapeutic effects.

The ECG electrode is a metal disk with conducting electrode gel covering it, which is adhered to the subject's skin by an adhesive flange. The electrode gel minimizes the electrical resistance at the skin's interface, ensuring the impedance is as low as feasible to prevent signal attenuation [11]. Silver-silver chloride (Ag/AgCl) material is the most frequently utilized material for ECG electrodes, and may typically provide an electrode with a high electrical performance [12].

In (2007) S. Jang et al. [13] developed electronic textiles that had a small, film of Copper (Cu) applied to their surface. The electrical resistances were then measured, their effectiveness as ECG (electrocardiogram) electrodes were evaluated, and the ECG signal was compared with that measured using standard AgCl electrodes. The results showed that the ECG signals from copper-sputtered electrodes demonstrated great potential as textile-based electrodes because they differed little from those of AgCl electrodes, which are widely used.

In (2021), Y. Maithani et al. [14] developed self-adhesive dry electrocardiogram electrodes using polydimethylsiloxane (PDMS) embedded with silver nanorods (AgNRs). The designed electrode performs better than the traditional wet electrode and is more skin-compatible.

In (2022), A. Alsharif et al. [15] introduced the use of a copper-based filament with the best-recorded conductivity ( $0.006 \Omega \cdot \text{cm}$ ) in medical applications. This article presents the process for creating 3D-printed, semi-flexible, wearable dry electrodes to monitor electrocardiogram (ECG) signals. The results of this study confirmed that various electrode structures and printing configurations have a substantial impact on the conductivity, functionality, and impedance evaluations of electrodes. The concentric and flat dry electrode constructions made of copper material showed the best performance.

The rest of this paper is organized as follows: Section 2 describes the materials and methodology used to design and construct the suction electrodes. Section 3 presents and compares the ECG results obtained from the Copper, Aluminum, and Ag/AgCl electrodes. Section 4 concludes the study and provides recommendations for future work.

Finally, ethical approval statement is illustrated in section 5.

## 2. Methodology

This part describes the materials used in this study and the methodology for constructing electrodes. The study initially involved only two subjects; future work will include a larger cohort to improve validity. This study was performed over six months. It was applied in Al-Kindeg Teaching Hospital and Biomedical Engineering Laboratory at Al-Nahrain University in Baghdad. Cu and Al were selected in this study due to their high electrical conductivity, low cost, and wide availability compared to the Ag/AgCl electrodes. The following steps were followed to construct the ECG suction electrode with Cu and Al materials:

1. A shaft of copper material was chosen to construct three samples of copper suction electrode, as shown in Fig 1. Copper is a chemical component and is comprised of only a single type of atom. With an atomic number of 29, the copper atom has 29 protons in its atomic nucleus. Its symbol is Cu.



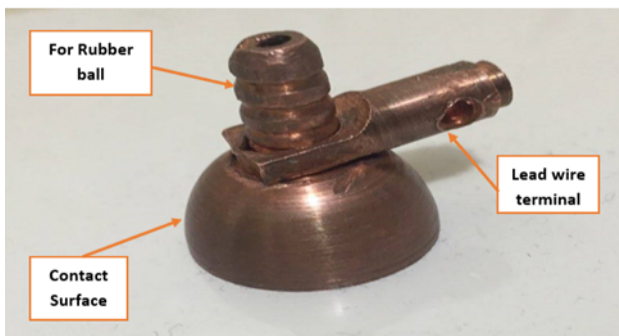
Fig. 1 Shaft of Copper Material

2. A shaft of Aluminum material was chosen to construct three samples of Aluminum suction electrode, as shown in Fig 2. Aluminum is a chemical element, silvery-white metal of main Group 13 (IIIA, or boron group) of the periodic table. Its symbol is Al.

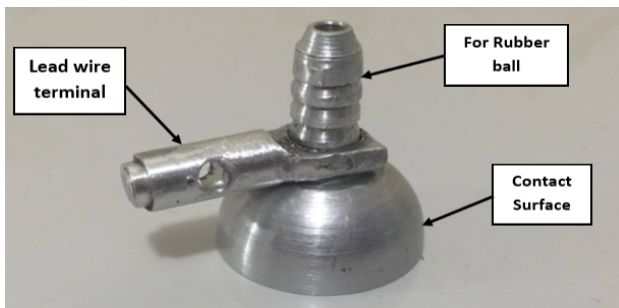


Fig. 2 Shaft of Aluminum Material

3. The main workshop machines (lathe machine, milling machine, and some tools) were used for manufacturing Copper and Aluminum electrodes.
4. The Autodesk Inventor software (mechanical design software) was used for measuring the dimensions of Copper and Aluminum suction electrodes. The suction electrodes were designed with a diameter of 24 mm, depth of 10 mm, and contact area of  $4.9 \text{ cm}^2$ . The suction electrodes from Copper and Aluminum materials were constructed, and their surfaces were mechanically polished to a mirror finish ( $R_a < 0.2 \mu\text{m}$ ) and cleaned with ethanol before use, as shown in Fig 3. and Fig. 4.

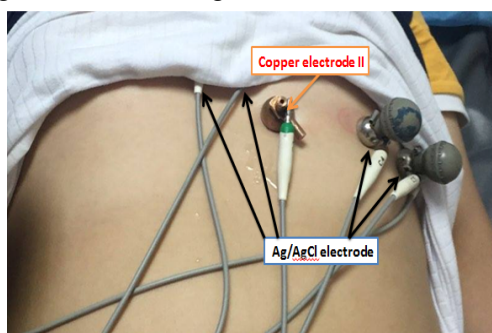


**Fig. 3** Copper suction electrode



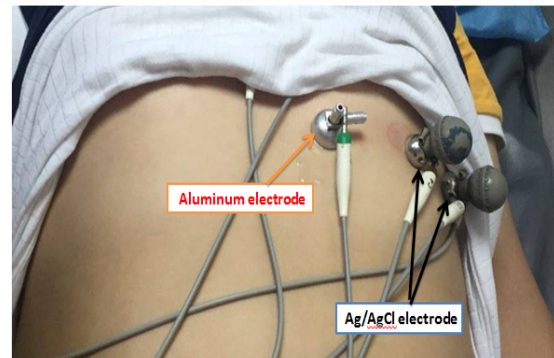
**Fig. 4** Aluminum suction electrode

5. An ECG machine (Bionet Cardio7) was used to read the ECG signals of the Subject. ECG signals were recorded using a Bionet Cardio7 ECG system, with a sampling rate of 500 Hz, bandwidth 0.05–150 Hz, and 60 Hz notch filter enabled to remove powerline interference.
6. A liquid gel electrode was used and placed above the skin for prices and fast ECG signal pickup and for improve conductivity. Each electrode was disinfected with 70% isopropyl alcohol before and after every use to ensure safety and hygiene.
7. In the present test, five suction electrodes (standard electrode from Ag/AgCl) were applied to the subject's chest under realistic conditions, and four other electrodes were connected to his arms and legs to determine his ECG signals to compare with the electrodes that are constructed from Copper and Aluminum materials.
8. The copper electrode was connected to the C3 lead in the ECG machine with five suction electrodes (standard electrode from Ag/AgCl) to obtain his ECG signal, as shown in Fig 5.



**Fig. 5** Applied a copper electrode to the subject's chest

9. The test was repeated by replacing the Copper suction electrode and connecting the Aluminum suction electrode instead of it to obtain the ECG signal of the subject, as shown in Fig 6.



**Fig. 6** Applied an aluminum suction electrode to the subject's chest

The same procedures were repeated in the laboratory by connecting the constructed electrodes to another subject and reading his ECG signals.

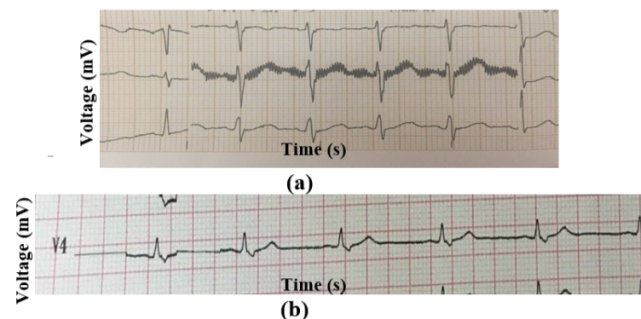
### 3. Results

The electrode materials were selected based on research and references. The ECG signal formed the basis for the comparison of electrode materials. ECG signals were obtained from electrodes of different materials (Copper and Aluminum) and compared these signals with the ECG signal of standard electrodes made from Ag/AgCl material to obtain the best material for electrode construction.

#### 3.1 ECG signals of the standard (Ag/AgCl) suction electrode

ECG signals were obtained from two normal subjects by using an ECG device with an Ag/AgCl suction electrode, as shown in Fig 7 (a) and (b).

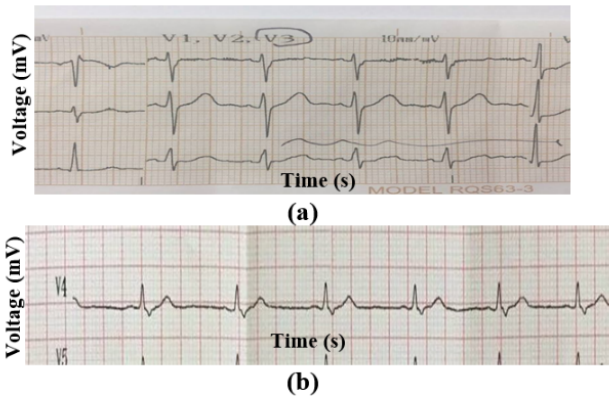
In Fig 7. (a) ECG signals were obtained from the first subject using Ag/AgCl suction electrodes in the hospital, while in Fig 7. (b) signal of ECG was obtained from the second subject using Ag/AgCl suction electrodes in the laboratory. Ag/AgCl suction electrode is used as a standard electrode to make comparisons with the other electrodes manufactured from different materials.



**Fig. 7** Extracted ECG signals of Ag/AgCl electrode  
 a. Subject<sub>1</sub> (age: 15 years, sex: male) from hospital  
 b. Subject<sub>2</sub> (age: 23 years, sex: male) from laboratory

### 3.2 ECG signals of the Copper electrode

ECG signals were obtained from the copper electrode that has the same dimensions as the standard Ag/AgCl electrode, as shown in Fig 8 (a) and (b). These signals are very analogous to those obtained from the Ag/AgCl signals, this indicates that the copper material is one of the best materials that may be used in constructing electrodes with high efficiency and much lower cost than the Ag/AgCl electrode. Results also showed that the copper electrode has SNR = 32.3 dB and  $r = 0.95$ .

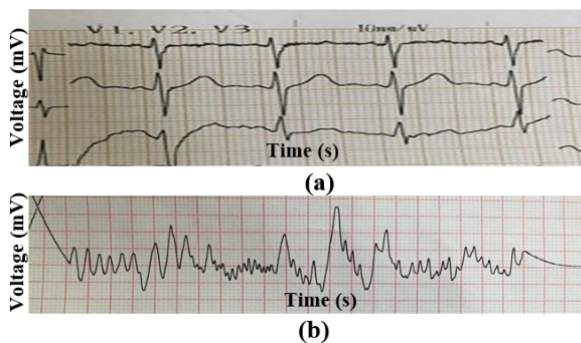


**Fig. 8** Extracted ECG signals of copper electrode

- a. Subject1 (age: 15 years, sex: male) from hospital
- b. Subject2 (age: 23 years, sex: male) from laboratory

### 3.3 ECG signals of the Aluminum electrode

ECG signals were obtained from the Aluminum electrode that has the same dimensions as the standard Ag/AgCl electrode, as shown in Fig 9 (a) and (b). The signal obtained by this electrode is not similar to that obtained by the Ag/AgCl electrode and has high noise. This indicates that the Aluminum material is not one of the materials that may be used in constructing electrodes, and this electrode is not used to obtain ECG signals. Results also showed that the aluminum electrode has SNR = 18.5 dB and  $r = 0.59$ .



**Fig. 9** Extracted ECG signals of Aluminum electrode

- a. Subject<sub>1</sub> (age: 15 years, sex: male) from hospital
- b. Subject<sub>2</sub> (age: 23 years, sex: male) from laboratory

### 4. Conclusions

The conclusions of the present study are concluded: the Ag/AgCl electrodes are the most widely used electrodes and the best-performing of all electrode materials. Ag/AgCl suction electrodes are considered essentially non-polarizable; this behavior creates a very stable electrode for

use in biopotential recordings. Copper (Cu) is the best material for manufacturing electrodes instead of Ag/AgCl due to its excellent electrical conductivity and corrosion resistance. Copper is second to silver in terms of bulk electrical conductivity. Copper has more strength than silver, but offers inferior oxidation resistance. Copper is a common base metal for electrical contact and electrode applications. It is a low-cost material and is less expensive than silver, so it is desired to use it in the manufacturing and reading of ECG signals. Preliminary results suggest that copper electrodes exhibit comparable ECG performance to Ag/AgCl electrodes. Aluminum material cannot be used in the electrode construction, and this is determined from the reading of its ECG signal, scientifically, its tendency to form a non-conductive oxide layer, which introduces high impedance and noise, and its instability in the biological environment.

### 5. Ethical Approval

This study was approved by the Institutional Review Board (IRB) of Al-Nahrain University (Approval No. BME-2025-001). Written informed consent was obtained from all participants prior to data collection.

### Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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