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Evaluation of CNT/MOSFET Based Active Electrode with ECG, EMG, and EEG Signals

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Abstract

In this study, the electrical circuit equivalents of the previously designed novel CNT/MOSFET based active electrode and commonly used wet electrode are simulated by applying different biopotentials. Responses of the electrode models are compared within the certain skin surface circumstances. Fourier transforms and total harmonic distortion calculations of obtained biopotentials are examined to assess the electrodes. The simulation results demonstrate that the CNT / MOSFET based electrode predominates the wet electrode and can measure biopotentials with high quality.

Keywords: CNT, MOSFET, Biopotential electrodes, Fourier transform, Total harmonic distortion

KNT/MOSFET Tabanlı Aktif Elektrotun EKG, EMG, EEG İşaretleri ile Değerlendirilmesi

Öz

Bu çalışmada, önceden tasarlanmış olan özgün KNT/MOSFET tabanlı aktif elektrotun ve yaygın olarak kullanılan ıslak elektrotun elektrik devresi eşdeğerlerine, farklı biyopotansiyeller uygulanarak benzetimleri gerçekleştirilmiştir. Elektrotların giriş sinyallerine verdiği yanıtlar, belirli cilt yüzeyi koşullarında karşılaştırılmıştır. Elektrotları değerlendirmek için elde edilen biyopotansiyellerin Fourier dönüşümleri ve toplam harmonik bozulmaları incelenmiştir. Simülasyon sonuçları, KNT/MOSFET tabanlı elektrotun ıslak elektrottan daha iyi sonuçlar verdiğini ve biyopotansiyelleri yüksek kalitede ölçebileceğini göstermektedir.

Anahtar Kelimeler: KNT, MOSFET, Biyopotansiyel elektrotlar, Fourier dönüşümü, Toplam harmonik bozulma

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1. INTRODUCTION

Many organs and tissues in the human body exhibit their health states or functions with electrical signals called biopotentials. The signals obtained from the activities of the heart (electrocardiogram), brain (electroencephalogram), or muscle (electromyogram) are examples of biopotentials. These electrophysiological signals or the other biopotentials measured from the human body enable the identification of the diseases.

Biopotentials are small-amplitude signals in the microvolts or millivolts, and their frequencies are between DC to several hundred hertz [1]. The quality of the measuring electrode is crucial to acquire these small amplitude signals from the skin surface with high precision [2]. Artefacts and noises on a biopotential signal generally depend on the measuring electrodes as well as the skin surface. The surface of the human skin contains a high number of dead cells and hairs, leading to increased resistivity and decreased contact surface area with the measuring electrode [3]. Therefore, the surface of the skin must be prepared before performing the measurement. Abrasion of the outermost stratum corneum layer decreases the contact resistivity arising from dead cells. Besides, applying a conductive electrolytic gel on the skin surface also decreases the resistivity and increases the surface area between the electrode and skin. The electrolytic gel between the skin surface and electrode, diffuses into the skin and enables forming a highly conductive layer.

Although the self-gelled skin electrodes present good performance for short duration measurements, signal deterioration occurs on long-duration records, since the gel dries out over a period of time. Besides, the conductive gel is allergenic. Gel-free dry electrodes are a promising alternative for long-duration recordings [4]. There are various dry electrodes, from a pure disk metal to silicon-based microfabricated electrodes containing on-chip amplifiers [5,8]. However, the absence of conductive gel in dry electrodes causes high electrode-skin impedance, high interface potential, and low signal quality problems [9,10].

In the literature, dry electrode designs involve carbon nanotubes to decrease high contact impedance as an alternative to metallic needle electrodes [11,12]. Researches show that the vertically aligned carbon nanotube electrodes have low electrode-skin impedance and can increase the measurement quality according to dry and wet electrodes. Since CNT utilizing electrodes do not contain electrolytic gel, which negatively affects the signal quality over time, it maintains the signal quality even in long-term measurements. Although CNTs increase the quality of the measured signal, they should not be designed long enough to reach nerve cells when attached to the skin [13].

In this work, previously designed novel CNT/MOSFET based active electrode [14] is simulated and evaluated in terms of signal quality for ECG, EMG and EEG signals. The input biopotential signals are selected randomly from the Massachusetts Institute of Technology Beth Israel Hospital database. The biopotential signals are also applied to the circuit equivalents of commonly used wet electrodes for comparison. Simulations are performed for two different skin surface cases. The first case is prepared skin and the second case is unprepared skin surfaces. The simulations of previously designed electrode are performed under the worst skin case specifications. The obtained biopotential signals and their Fourier transforms are compared. Additionally, total harmonic distortions of obtained signals are calculated. The simulation results indicate the high performance and feasibility of the CNT/MOSFET based active electrode for clinical applications.

2. MATERIAL AND METHOD

2.1. The CNT/MOSFET Based Electrode

The novel CNT/MOSFET based electrode increases the electrode-skin contact surface area by utilizing CNTs. CNTs constitute a robust interface contact that leads to reduce motion artifacts. Additionally, the electrode does not require conductive gel and abrasion process since it penetrates the skin surface. The mentioned multi-walled, metallic CNT arrays are grown on the gate of depletion type n-channel MOSFET. MOSFET in the electrode converts biopotentials from voltage to current form and provides high dielectric insulation between the skin and instrumentation unit. Besides, the MOSFET device amplifies the measured signal with low-noise as reported previously. [14]. Figure 1 shows the CNT/MOSFET based active electrode model.

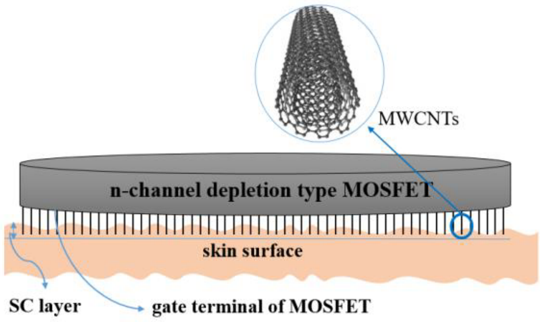

Figure 1. Schematic of CNT/MOSFET based electrode

As shown in the figure vertically aligned brush-like CNT arrays are grown on the gate terminal of the n-channel depletion type MOSFET. CNTs penetrate the outermost layer of the skin. The electrode provides stable contact and decreased contact resistance since the CNTs bypassed the dead skin layer. Figure 2 shows the AC equivalent of the electrode. As shown in the figure, circuit equivalent model of individual CNT in contact with the gate terminal of the MOSFET is given at the left hand side. Small signal AC equivalent of the n-channel depletion type MOSFET is located at the right hand side. When the electrode attached to the skin surface, CNTs acquire biopotentials and transfer to the MOSFET. The MOSFET converts the sensed biopotential to a current flowing between source and drain terminals.

The electrode contains several numbers of CNT/MOSFET hybridized cells in an array manner. All drain and source terminals in individual measuring cell are electrically connected to each other as shown in Figure 3. Thus, biopotentials from different sites of the skin acquired simultaneously.

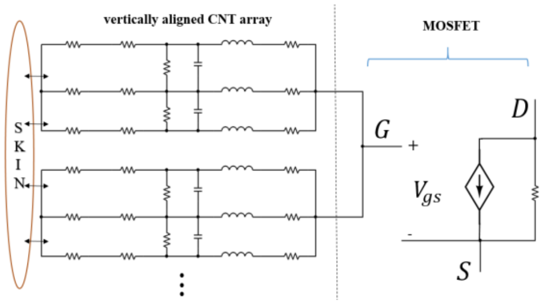

Figure 2. AC equivalent circuit of CNT/MOSFET based electrode

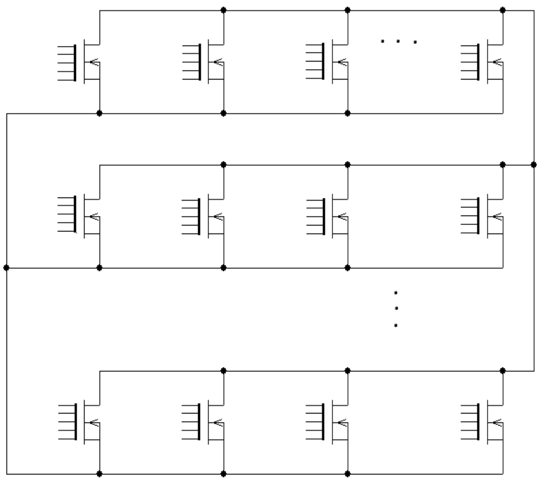

Figure 3. The complete circuit diagram of the CNT/MOSFET based electrode

2.2. The Electrode-Skin Interface

The skin-electrode interface is in fact a RC network. The circuit equivalent model of a skin-wet electrode interface is given in Figure 1 (ref), in which the model for popular Ag/AgCl electrode is used. In Figure 1, R_d and C_d are the resistance and capacitance associated with the electrode-electrolyte interface, respectively. R_s is the effective resistance related with the interface effects of the electrolytic gel between electrode and the skin. E_{se} potential arises from the ionic concentration difference across epidermis. Epidermis layer also behave as an electrical impedance represented by a parallel RC circuit, $R_p \| C_p$. The subcutaneous tissues can be characterized by a pure resistance, R_m.

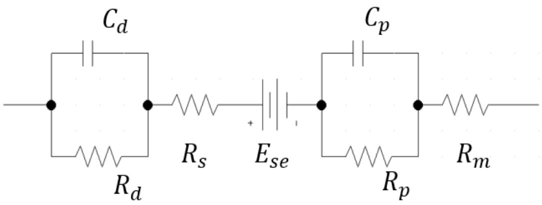

Figure 4. Circuit model of wet electrode-skin interface

The values of resistances and capacitances shown in Figure 4 depend highly upon skin condition and preparation. Type of electrode itself and electrolytic gel, attachment status of the electrode to the skin surface define the numerical values. Experimentally proven typical values of these parameters are given in Table 1 [15].

Table 1. Typical values of skin-electrode interface parameters

For unprepared skin	$R_d = 1M\Omega$ $C_d = 40nF$ $R_u = 120\Omega$ $R_s = 100\Omega$
For well prepared skin	$R_d = 10k\Omega$ $C_d = 10nF$ $R_u = 120\Omega$ $R_s = 100\Omega$
Well attached electrode	$R_p = 500\Omega$ $C_p = 100nF$ $R_s = 100\Omega$
Poor attached electrode	$R_p = 2k\Omega$ $C_p = 20nF$ $R_s = 100\Omega$

Figure 4 shows the electrical equivalent of electrode-skin interface in the case of wet electrode is used for recording biopotentials. However, if the CNT/MOSFET based electrode is used, the electrode-skin interface equivalent is reduced much simpler form since the CNT penetrated and bypassed the outer layer of the skin. The parameters associated with electrode-electrolyte interface (R_d, C_d, R_s, E_{se}) are then eliminated. In this case, only $R_p \| C_p$. pair and R_m resistance are remain to exist in the electrode-skin interface. Therefore, a decrease is reasonably predictable in the contact interface impedance and artifacts due to dead cell containing stratum corneum layer.

2.3. Fourier Transform and Total Harmonic Distortion

The Fourier transform is a mathematical tool to represent a function or a waveform into the frequency domain. All waveforms are the sum of sinusoids at different frequencies. The discrete Fourier transform (DFT) is obtained by decomposing a sequence of values into elements of different frequencies. Thus, DFT is an extremely useful operation for signal analysis. The DFT of a finite-length signal of length N is given in Equation 1.

$$F_k = \sum_{n=0}^{N-1} x_n W_N^{kn} \qquad for\, k = 0,1,...,N-1 \tag{1}$$

where $W_N = e^{-j(2\pi/N)}$ and $j = \sqrt{-1}$.

The Fourier transform of a waveform gives the fundamental frequency components, harmonics as well as the relative amplitudes. Therefore, analyzing the Fourier spectrum of an electrode's signal output provides information about the related electrode quality.

The total harmonic distortion (THD) can be calculated by the ratio of the sum of the harmonic component powers to the fundamental frequency power. Considering a biopotential electrode, lower distortion in an acquired biopotential lead to a more accurate measurement. The biopotential obtained as a result of the measurement must be free of noise. Since undesired signals mainly appear by depending on the measuring electrode, THD calculation of obtained biopotential presents the electrode quality. The THD of a signal can be defined as Equation 2.

$$THD = \frac{\sqrt{\sum_{n=2}^{N} V_n^2}}{V_1} \tag{2}$$

where V_n is the RMS voltage of the n^{th} harmonic and n=1 for fundamental frequency. THD values are usually expressed in percent. In this work, THDs of each obtained biopotentials for the electrodes within all cases are calculated. THD values are listed in Table 2.

3. SIMULATION RESULTS

In this work, simulations are performed on simulation program for integrated circuit emphasis (SPICE). Plotting Fourier transforms and THD calculations are done in the MATLAB environment. The obtained biopotentials from the circuit equivalents of the CNT/MOSFET based active electrode and the commonly used wet electrode circuit model are compared. Two cases of skin condition are taken into consideration for comparison. These are prepared and unprepared skin cases. The typical numerical values of skin, gel, and electrode parameters are given in Table 1. In any case, measurements with dry electrodes are noisier, and they contain more artifacts with respect to wet and CNT/MOSFET based electrodes. Thus, a comparison with dry electrode measurement is not performed.

Before evaluating the electrodes with considering biopotentials, circuit equivalent model responses of the CNT/MOSFET based electrode on unprepared skin, wet electrode on prepared skin with gel and wet electrode on unprepared skin with gel are simulated. Figure 5 shows the simulation results of the three electrode models to the 2 Hz, 100 mV sinusoidal wave. Bypassing the dead stratum corneum layer with CNT/MOSFET based electrode has great effect on signal amplitudes as obvious in the figure. Signal amplitude obtained from the CNT/MOSFET based electrode model maintains the 93.27% of the input signal, whereas the signal amplitudes taken from wet electrodes on prepared and unprepared skin surfaces retain their input amplitudes 48.26% and 0.99%, respectively.

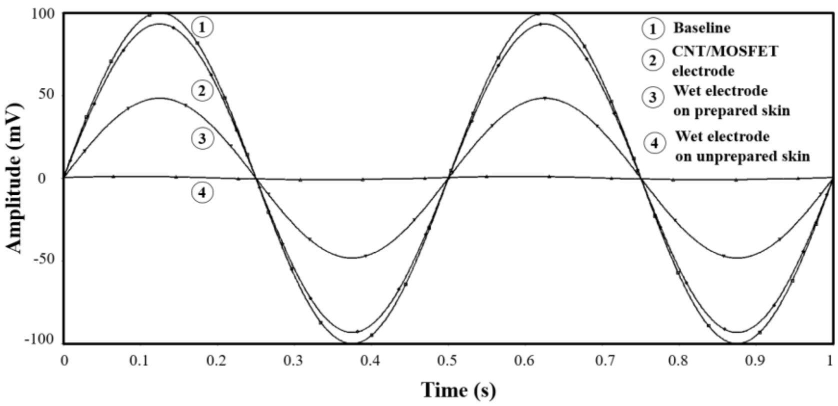

Figure 5. Responses of electrode circuit equivalents to the sinusoidal signal

ECG, EMG and EEG signals given in Figure 6 are also applied to electrodes in order to observe their effects on the signals. The EMG signal is taken from a healthy person with a 4000 Hz sampling frequency, whereas the EEG signal is obtained by the 10-20 electrode system with 500 Hz sampling frequency. The EEG signal, given in the Figure 6 (c), is the pre-frontal (Fp1) recording. Fourier transforms of the input signals are also given in Figure 6.

Signal responses of the CNT/MOSFET based electrode, as well as wet electrodes in two cases, to the ECG, EMG and EEG inputs, are shown in Figure 7, Figure 8 and Figure 9, respectively. Figure 7 shows the captured signal waveforms of the CNT/MOSFET based electrode and the wet electrode models for ECG signal in certain cases. The simulation results, shown in Figure 7, are the CNT/MOSFET based electrode on unprepared skin (a), wet electrode on prepared skin (b), and wet electrode on unprepared skin (c), respectively. Figure 7 (b) is the first case where the skin is well prepared, and the electrolytic gel is applied. The results show that the amplitude of the input signal is reduced to approximately half of the baseline shown in Figure 6 (a). In the second case, the skin is not cleaned from hairs and stratum corneum layer, the signal quality is quite distorted, and the amplitude of the signal is reduced one-tenth of the baseline.

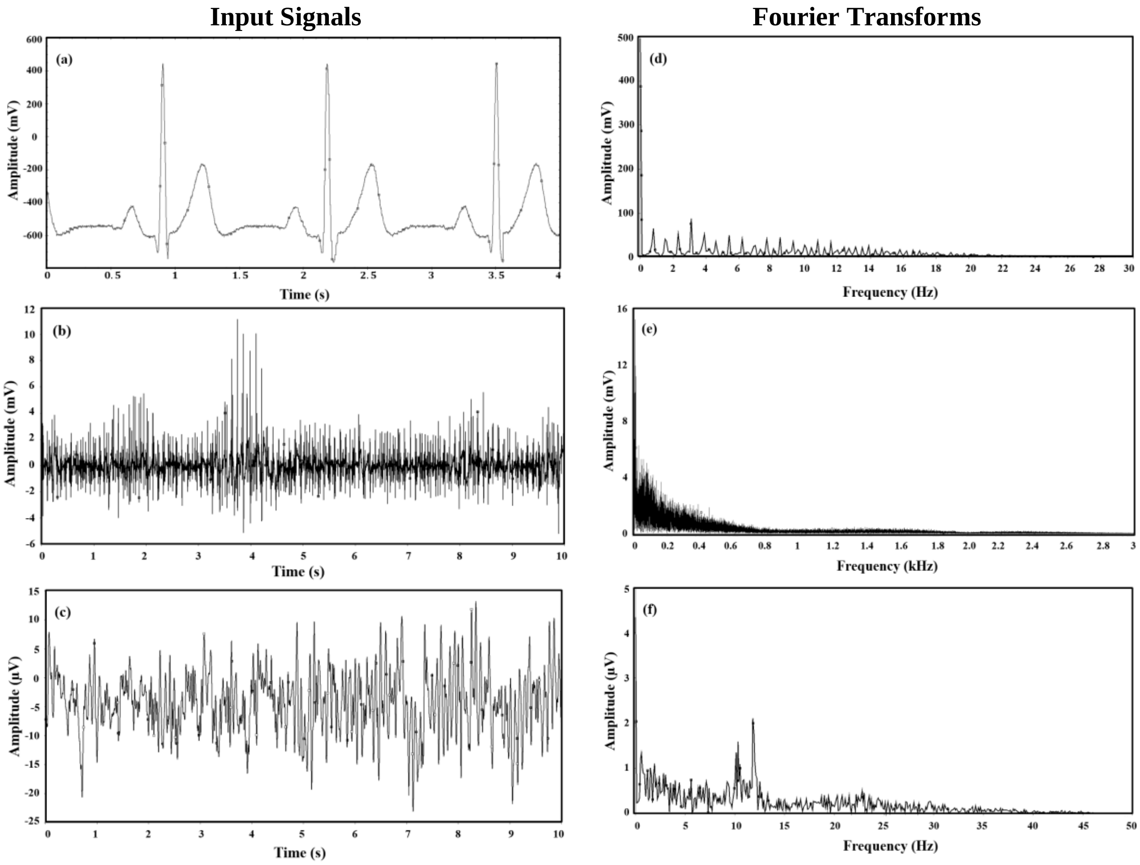

Figure 6. Input biopotential signals (a) ECG, (b) EMG, (c) EEG and their Fourier transforms (d), (e), (f), respectively

Biopotentials obtained from the wet electrode model for the second case show approximately ~480 mV half-cell potential, whereas half-cell potential of the first case is ~290 mV. The amplitude of the signal obtained by the CNT/MOSFET based electrode is attenuated slightly and maintains the baseline amplitude at approximately 93%. Additionally, the CNT/MOSFET based electrode model presents the smallest half-cell potential (~30 mV).

In Fıgure 8 (a), the EMG signal obtained from the CNT/MOSFET based electrode remains the amplitude of the input signal, whereas the amplitude of the signal, taken from the wet electrode on the prepared skin surface with the presence of conductive gel, is decreased approximately 60% as given in Figure 8 (b). Moreover, the signal acquired from the wet electrode on the unprepared skin is reduced considerably, as shown in Figure 8 (c).

Similarly, when the EEG signal is applied to the three electrode models, comparable results are obtained with that of ECG and EMG inputs. The signal output from the CNT/MOSFET based electrode almost does not show voltage drop in contrast with the wet electrodes, as given in

Figure 9 (a). The simulation results show that the CNT/MOSFET based electrode has much lower contact impedance and obtain biopotentials with high-quality. Although skin preparation and/or gel application are performed in the both wet electrode acquisitions, the electrophysiological signal qualities are much less than that of the CNT/MOSFET based electrode, as shown in Figure 9 (b) and (c).

The Fourier transforms of obtained biopotential signals prove the abovementioned considerations. Figures 7 (d), 7 (e) 7 (f), 8 (d), 8 (e) 8 (f) and 9 (d), 9 (e) and 9 (f) show the Fourier transforms of the simulation outputs for ECG, EMG and EEG signal inputs. The figures annotated with (d) show the Fourier transforms for the CNT/MOSFET based electrode model, whereas (e) and (f) give the Fourier transforms for the wet electrode on prepared skin and the wet electrode on the unprepared skin, respectively. Figures 7 (d), 8 (d) and 9 (d) exhibit almost the same Fourier transform with respect to that of original signals given in Figure 6 (d), (e) and (f). Fourier transforms for wet electrode at the case-2 show considerable decrement on the amplitude of principal frequency components as given in Figure 7 (e), 8 (e) and 9 (e). It is obvious from the Fourier transforms for the wet electrode at case-1, the signal amplitude is extremely reduced. Additionally, amplitudes of noise components are increased considerably, as shown in Figure 7 (f), 8 (f) and 9 (f).

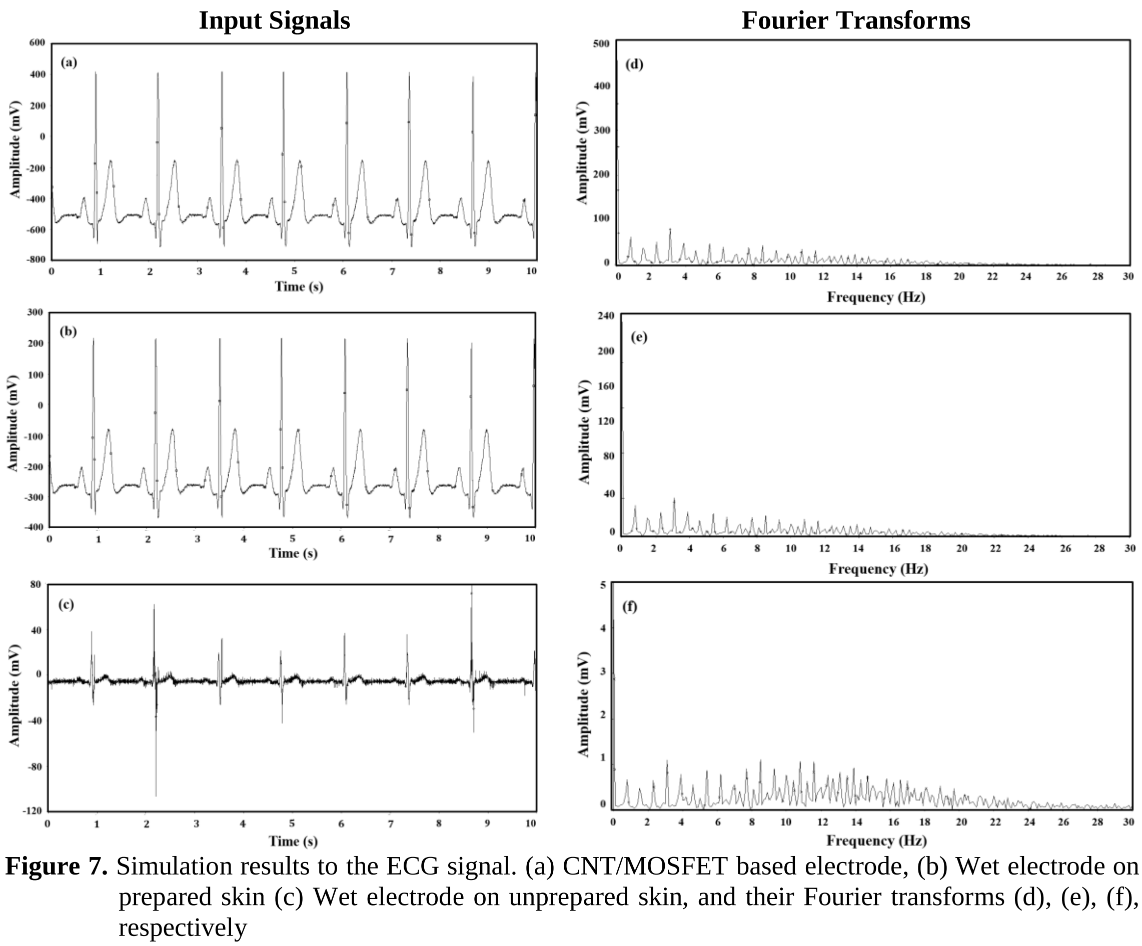

Figure 7. Simulation results to the ECG signal. (a) CNT/MOSFET based electrode, (b) Wet electrode on prepared skin (c) Wet electrode on unprepared skin, and their Fourier transforms (d), (e), (f), respectively

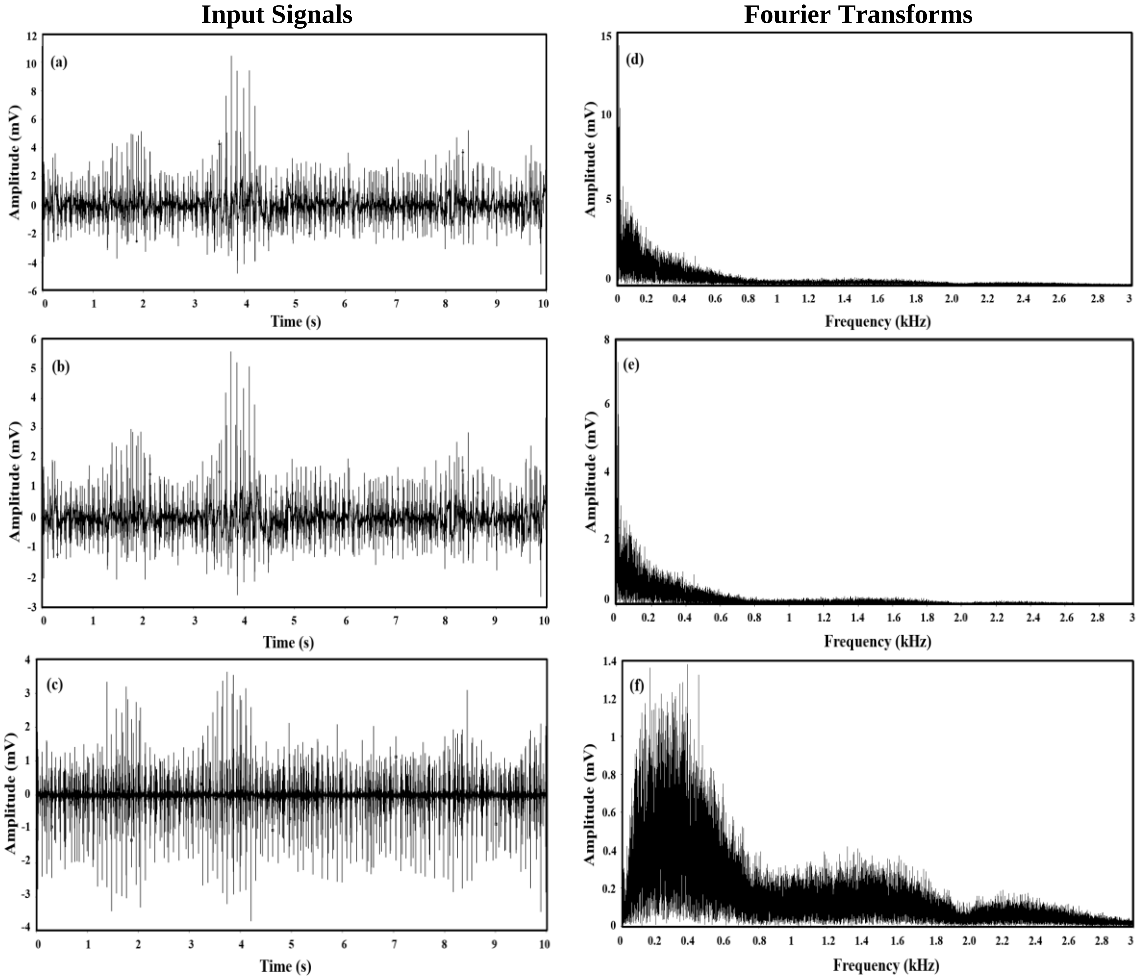

Figure 8. Simulation results to the EMG signal. (a) CNT/MOSFET based electrode, (b) Wet electrode on prepared skin (c) Wet electrode on unprepared skin, and their Fourier transforms (d), (e), (f), respectively

THD calculations of the obtained biopotentials from each electrode model are given in Table 2. As shown in the table, CNT/MOSFET based electrode exhibits THD around 6.7% for ECG, EMG, and EEG signals, whereas THD for wet electrode on prepared skin is around 51.5%. The impedance value of dead cells containing the stratum corneum layer of the skin depends on signal frequency, as stated before. Since the stratum corneum layer remains to exist in unprepared skin, it affects the THD calculations for different biopotentials with different frequencies. The value of THD for the wet electrode on unprepared skin is 67.09% for EMG signal, whereas 98.66% and 97.29% for ECG and EEG signals, respectively. THD values of the wet electrode on unprepared skin is more than that of CNT/MOSFET based electrode and the wet electrode on prepared skin, as it is expected. However, THD values of CNT/MOSFET based electrode are small and stable for all biopotentials, since the stratum corneum layer is bypassed employing CNTs. THD calculations prove the feasibility of the CNT/MOSFET based electrode on biopotential measurements.

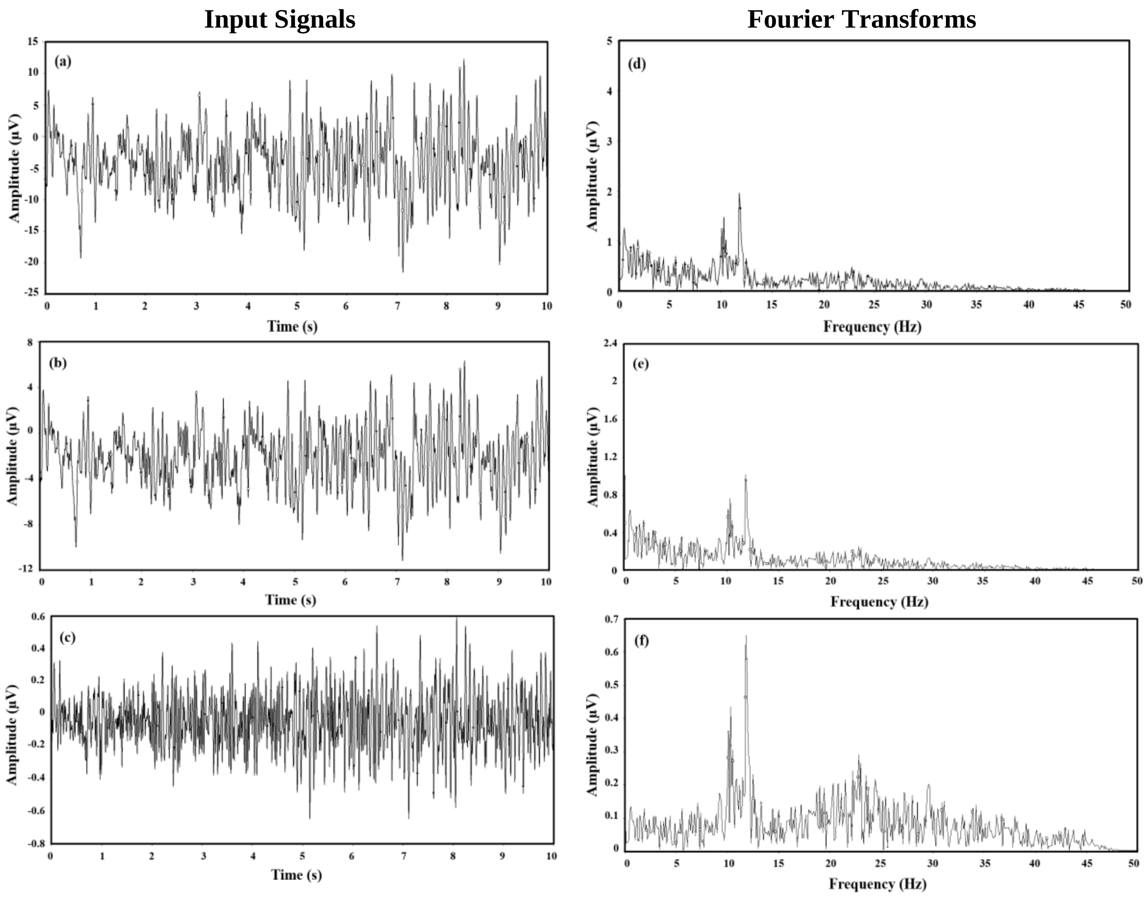

Figure 9. Simulation results to the EEG signal. (a) CNT/MOSFET based electrode, (b) Wet electrode on prepared skin (c) Wet electrode on unprepared skin, and their Fourier transforms (d), (e), (f), respectively

Table 2. THD values of the biopotentials obtained from the electrodes

	THD Values		
Electrode Type	**ECG**	**EMG**	**EEG**
CNT/MOSFET Based Electrode	6.72%	6.69%	6.72%
Wet electrode on prepared skin	51.73%	51.27%	51.68%
Wet electrode on unprepared skin	98.66%	67.09%	97.29%

4. CONCLUSIONS

The stratum corneum layer of the skin consisting of dead cells has negative effects on the biopotential signal acquisition such as noise and increase in the electrode-skin contact impedance. To improve the obtained signal quality, the negative effects of this layer must be reduced with either the electrode itself or applying the conductive gel. The conductive gel applied to the skin surface dries up in long-term measurements and causes noise on the obtained biopotentials. Besides, it may cause allergic reactions.

In this work, previously designed novel CNT/MOSFET based active electrode is simulated and evaluated in terms of signal quality for ECG, EMG and EEG signals.

The effects of stratum corneum layer and the conductive electrolytic gel on the obtained biopotentials are shown in the simulation results. SC layer on the human skin exhibits resistive/capacitive medium properties that lead to a voltage drop at the output of the electrode. Comparison of simulations for prepared and unprepared skin conditions prove this phenomenon. Although conductive gel reduces the significant decrease in signal amplitude, it cannot completely prevent the distortion and noise on the signal, since it cannot completely eliminate the effect of the SC layer. In contrast with the wet electrode cases, the CNT/MOSFET based electrode simulated for unprepared skin without conductive gel. Although it is simulated at the worst case specifications, the CNT/MOSFET based model obtained the highest quality signals. As shown in the Fourier transforms of the biopotential signal outputs, the signal to noise ratio of the CNT/MOSFET based electrode is higher than that of the wet electrodes. THD calculations of the obtained biopotentials also indicate the great effect of measuring electrode on the signal quality. The simulation results demonstrate and prove the efficiency of the CNT/MOSFET based electrode.

The CNT/MOSFET based electrode has advantages such as recording biopotentials with high signal to noise ratio, eliminating the negative effects of the stratum corneum skin layer, providing robust, stable skin contact, no need to both conductive electrolytic gel usage and skin abrasion process. The simulation results prove the efficiency and importance of the previously designed electrode. This electrode can be used for clinical measurements even for long-term measurements without biocompatibility problems.

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