Rejection of Common-Mode Voltages in ECG Signal by Removing the Ground Electrode

Nabil Hamza, Lazhar Khriji, Rached Tourki

Abstract—Common mode voltages rejection in ECG signal becomes a crucial issue. The identification and minimization of these common voltages is necessary to acquire such signal since its level is low (few millivolts) compared to these undesirable common voltages generated by the surrounding environment. We investigate different sources of common voltages coupled to an ECG signal and analyze techniques to reject and mitigate their effects. We propose the elimination of the ground electrode and study its efficiency to reduce common-mode voltages and improve the rejection ratio of the bioamplifier. We provide a qualitative ECG signal acquisition with a sophisticated analog front-end architecture resulting on an accurate ECG signal detection and an improved Common-Mode and Isolation-Mode Rejection: CMR and IMR.

Index Terms—ECG signal; biopotential amplifier; power line interference; displacement current; electrical and magnetic coupling; common-mode interference; isolation-mode rejection; common-mode rejection.

1 Introduction

BIOPOTENTIAL signals, known as biosignals, are acquired as potentials, voltages, and electrical field strengths generated respectively by heart's contraction: Electrocardiograph (ECG), brain nerves activities: Electroencephalograph (EEG) and muscles' contractions: Electromyograph (EMG). The measurement of these biosignals involves voltages at low level typically ranging between some few microvolts (EEG signal) and few hundred millivolts (EMG signal). Since ECG signal, in particular, is of the order of few millivolts, it is then susceptible to sources of interference including induced signals from power lines and electric wiring, RF from transmitters, magnetically induced currents in lead wires generated by electric motors and other surrounding appliances, Fig. 1, [1].

These sources of noise can affect the recording of the ECG signal by coupling high level interference signals [2]. This interference can seep in by power line coupling either with leads or patient, which can be seen in Fig. 2. As a consequence, capacitive coupling may completely mask the ECG signal. Therefore, it needs to be amplified in order to make it acquirable by medical devices such as displays, recorders, or A/D converters for computerized equipment [3]. Amplifiers adequate to acquire this signal have to satisfy very specific requirements. They have to provide amplification selective to the ECG signal, reject superimposed noise and interference signals, and guarantee protection from damages through voltage and current surges for both patient and electronic equipment. Amplifiers featuring these specifications are known as biopotential amplifiers. The ratio of the amplification of the required differential signal to the amplification of common mode signal is termed the common mode rejection ratio. For biopotential recording a high common mode rejection ratio is absolutely necessary. Improving that ratio is crucial in ECG signal acquisition [4].

Figure 1. Identifying various interference sources coupled to an ECG signal [16]

We propose to study different types of common voltages superimposed to an ECG signal, followed by analyzing methods and remedies to mitigate their effects. After discussing different types of common voltages superimposed to an ECG signal and remedies to mitigate their effects, we study the case of eliminating the ground electrode and its effect on the quality of the ECG trace. The final section in this article describes how the removal of the ground electrode makes the bioamplifier reliable and increases its immunity against high level common mode voltages leading to an optimal design of an ECG acquisition system.

2 Identification of Various Common Voltages Coupled to an ECG Signal

The main external contributions to interference come from displacement currents coupled into the patient body and currents coupled to the electrodes, Fig.2. Huhta and Webster [1] identified the four basic ways by which interference can enter

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ECG recordings obtained by an earth-grounded amplifier: a) magnetic induction, b) displacement currents into the electrode leads, c) displacement currents into the body, and d) conversion from common-mode into differential-mode interference at the input of the amplifier. The input signal to the amplifier consists of five components: (1) the desired biopotential, (2) undesired biopotentials, (3) a power line interference signal of 50 Hz and its harmonics, (4) interference signals generated by the tissue/electrode interface, and (5) noise.

Proper design of the amplifier provides rejection of a large portion of the signal interferences. The main task of the differential amplifier is to reject the line frequency interference that is electrostatically or magnetically coupled into the patient. The desired biopotential appears as a voltage between the two input terminals of the differential amplifier and is referred to as the differential signal. The line frequency interference signal shows only very small differences in amplitude and phase between the two measuring electrodes, causing approximately the same potential at both inputs, and thus appears only between the inputs and ground and is called the common mode voltage. Strong rejection of the common mode voltage is one of the most important characteristics of a biopotential amplifier [5].

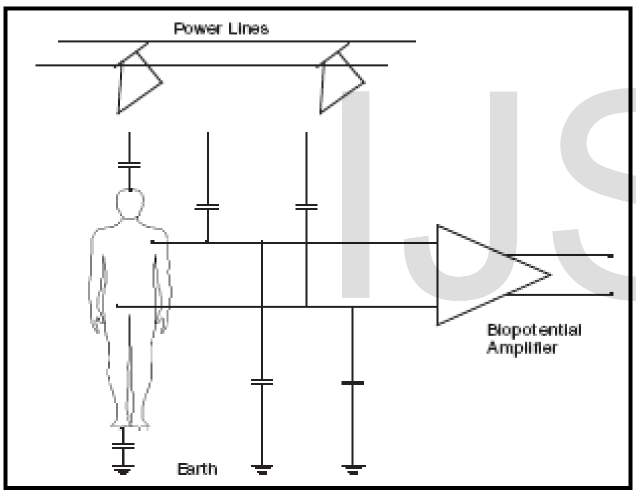

Figure 2. Capacitive coupling to electrode leads and patient [14]

3 A MODEL FOR COMMON MODE VOLTAGES COUPLED TO AN ECG SIGNAL

A typical front-end for the measurement of an ECG signal is shown in Fig. 3. Three electrodes, two of them picking up the biological signal and the third providing the reference potential, connect the subject to the amplifier. The mission of the differential amplifier is to amplify the signal between the measuring electrodes while rejecting any unwanted signals, either other biopotentials or external sources of interference [6].

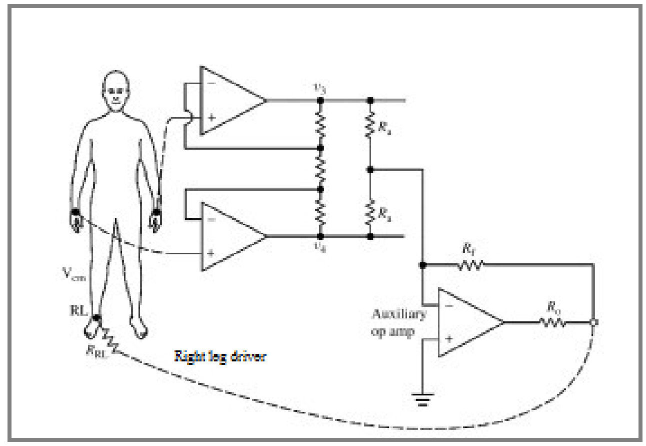

Figure 3. A typical hardware configuration of an ECG Front-End [3]

In Fig. 4, Vd represents biopotential to be measured that with these configurations appears as a differential voltage, while Vcm represents the voltage that appears in both inputs, known as common-mode voltage. This voltage is normally produced as interference by the power lines surrounding the measurement system as well as interference from nearby instruments and even interference from other biopotential signals. Ideally, the output of the biopotential amplifier could be represented as:

$$V_O = A_d V_d \qquad (1)$$

where VO is the output of the amplifier, Vd is the differential voltage, that is, the biopotential to be measured and Ad is the differential gain of the biopotential amplifier.

From (1) it can be seen that for an ideal biopotential amplifier, the output is totally independent of the interfering voltage and only responds to the biopotential to be measured as differential input. It is necessary to mention that strictly speaking, not any differential amplifier can be used as a biopotential amplifier. Only those differential amplifiers with high input impedance can be used as biopotential amplifiers. These differential amplifiers are commonly known as Instrumentation Amplifiers.

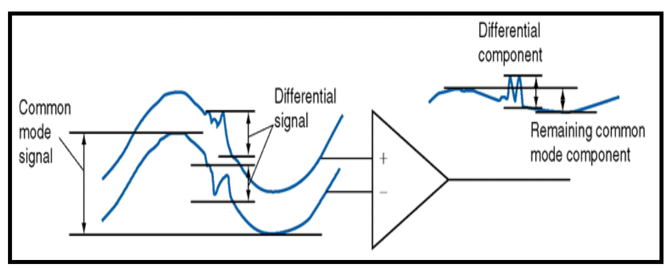

Figure 4. A simplified model for a biopotential amplifier [15]

With real electronic devices, however, this ideal situation is never achieved [7]. Equation (2) shows more realistic representation of the voltage at the output of the differential biopotential amplifier:

$$V_O = A_d V_d + A_{cm} V_{cm} \qquad (2)$$

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where Vcm is the common-mode voltage at the input of the differential amplifier, and Acm is the common-mode gain for the amplifier.

4 Remedies to Reduce Common Mode Voltages: Case Study of the Ground Electrode Removal

When using three electrodes, amplifiers supplied by batteries or by isolated power supplies (whose signal ground is independent from earth ground), reduce the common mode voltage with respect to signal ground [8]. Two-electrode amplifiers have a larger common-mode voltage with respect to earth ground. However, the rejection of that voltage, properly termed isolation-mode rejection ratio, is usually very high for three- and two-electrode systems [9].

Hence, the elimination of the reference electrode leads to two-electrode configuration at which the common mode interference current must flow via the same electrodes used for the signal sensing. As a consequence, the electrode impedance imbalance is converted to a differential input voltage and is amplified together with the useful signal. Because the common mode voltages are generated mainly from power-line interference, the main disadvantage of two-electrode approach is the higher level of the power-line interference at the amplifier output. Therefore a differential amplifier with high common-mode rejection (CMR) is absolutely necessary in the acquisition of biopotential signals.

Nowadays, all biosignal acquisition devices are highly isolated and have an analog-to-digital conversion, which allows the application of efficient algorithms for power-line interference suppression. Thus the problem of reducing a power-line noise in two-electrode approach is practically eliminated [1] and [2]. In addition, implementing a low common mode input impedance approach, makes the amplifier operation reliable and increases its immunity against high-level common mode interference, [8] and [9]. That is why in the case of ECG processing, there are no reasons for usage of three-electrode amplification technique in future designs.

5 Experimental Design and Discussion

We have designed and implemented a ground-free two electrodes ECG front-end system as an improvement of the previously designed prototypes, [10], [11], [13] and [17]. An AD622 from Analog Device with high CMR (120 dB) is chosen to meet the common-mode rejection ratio specified by the Association for the Advancement of Medical Instrumentation (AAMI) which is 89 dB minimum for a clinical ECG and 60 dB for an ambulatory ECG [12]. Electrodes were connected to the amplifier by coaxial shielded and twisted cables to reduce electrical and magnetic coupling.

We successfully recorded an ECG trace from two standard disposable electrodes stuck to the right and left wrists of a 35 years-old adult volunteer (myself) with no ground-electrode, Fig. 5. Trace (a) illustrates a raw ECG acquisition (an unfiltered recording at the output of the instrumentation amplifier). We can note the presence of high amplitude 50-Hz (mains) noise due to the removal of the ground-electrode. Trace (b) is a band-pass (0.1 to 40 Hz) filtered version of the raw ECG trace: the coupled 50-Hz noise is reduced significantly.

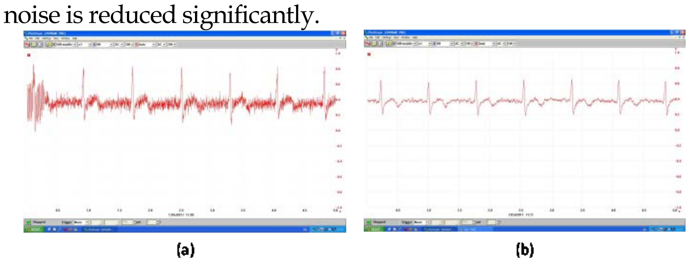

Figure 5. Raw ECG trace with 50 Hz mains noise (a), denoised ECG (0.1- to 40-Hz bandpass filtered) (b).

This trace was compared to an ECG sample acquired on the same volunteer using an approved ECG Monitor Machine in collaboration with Farhat Hachad Hospital of Sussah in Tunisia as shown in Fig. 6. Both signals were shown to a cardiovascular doctor from the same hospital. She approved the authenticity of both signals and gave a certificate of conformity as a proof of concept.

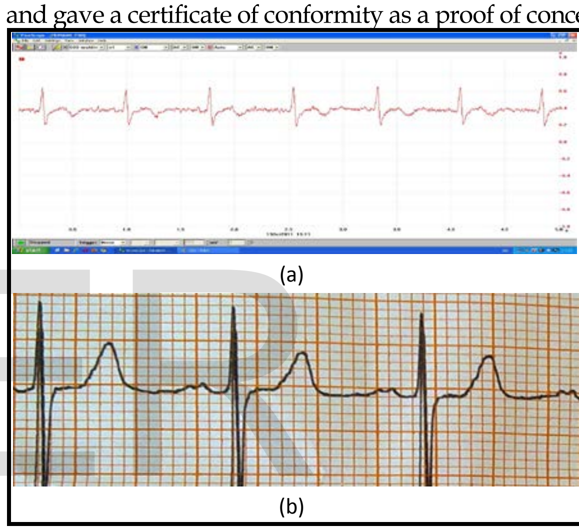

Figure 6. Comparison of ECG traces recorded by a grounded monitor machine in (b) and by the proposed design in (a).

In summary, the experimental results show that eliminating the ground-electrode reduces common-mode voltages and does not affect the ECG waveform. There is no static voltage problem seen and no 50-Hz interference is observed. This model can be applied to any ECG recording equipment giving security and safety to patient and keeping him away of any risk of an electrical chock.

6 Conclusion

We have analyzed and identified sources of common-voltages that can be coupled to an ECG signal. We provided a qualitative model that depicts these sources. We gave an overview about different techniques to reject and mitigate their effects. As a remedy, we proposed the removal of the ground-electrode and proved its effectiveness to reduce common-mode voltages and improve the rejection ratio of the bioamplifier. We provided a qualitative ECG signal acquisition with a sophisticated analog front-end architecture resulting on an accurate ECG trace.

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