Reference Electrode Placement in EOG-based Systems Design

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***Abstract*—The recording of eye movement biopotential is called electrooculogram (EOG). This technique is applied as a diagnostic method in ophthalmology to investigate the human oculomotor system and to control different assistive systems. The first step for developing an EOG-based system is to know in depth the possible sources of interference and the placement of the electrode, especially the reference electrode. They affect the recording of the EOG and pose a challenge to analog signal acquisition. This paper presents a novel study conducted to analyze the influence of these issues in the design of an EOG-based system. To estimate the noise level at each of the reference electrode placements, signal-to-noise-ratio (SNR) and percent root-mean-square difference (PRD) parameters were calculated.**

Keywords—Electrooculogram (EOG), Electromyogram (EMG), interference; reference electrode, signal acquisition

I. INTRODUCTION

Electrooculography detects and analyzes eye movement based on electrical potentials measured using electrodes placed around the eyes. This technique is based on the behavior of the eye as a dipole with the cornea as a positive pole and the retina as the negative one. When the eye rotates the potential´s dipole change proportionally between limits [1]. The electrooculogram (EOG) is the recording of that potential along the time. This signal can be used in different types of applications such as eye disorders [2], sleep studies [3], Ataxia SCA-2 diagnosis [4], electrical wheelchair [5], robots controlled by eye movements [6], etc.

The level of the EOG signal is typical between 0.05 to 3.5 mV and the bandwidth of DC to 50 Hz [7]. The main sources of interference are electrode-skin interface, electric coupling, and electromyographic potential. The electric coupling of the powerline with the patient is, without a doubt, the principal source of interference as it is with any recorded biopotential [8]. Besides, the choice of instrumentation amplifier (IA) and its common-mode rejection ratio (CMRR) will be another important concern. Fig. 1 is a big picture of this issues. It is usual to place an auxiliary electrode at a reference potential that is proportional to the common-mode voltage (V_{cm}) of the subject and the opposite sign to remove it from the acquired EOG signal, as is shown in Fig. 1 [9].

The first element to consider is the electrode´s position. They act as transducers, converting the ionic currents into electric currents [10]. The reference electrode plays a special role. This electrode aims to pick up any unwanted signals that are also present on the active electrodes to compensate for them in the acquired signal. So, a well-placed reference electrode can reduce noise and artifacts. The reference electrode should be placed in a well-conducting medium close to or some distance away from the active electrodes.

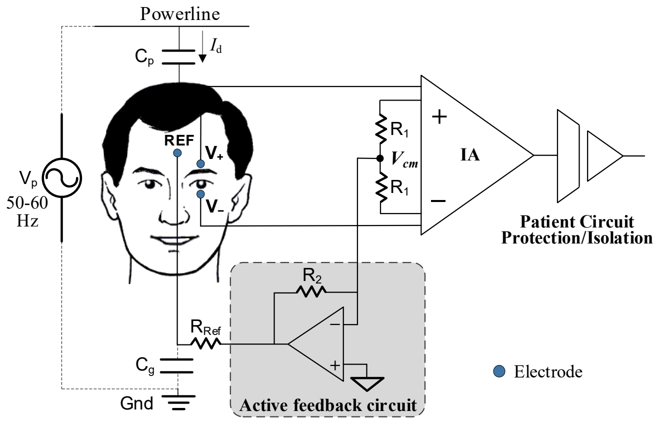

Fig. 1. Electric interference induced by the displacement current I_d from the powerline. The active feedback circuit uses negative feedback into the reference electrode (REF) to reduce the effective common-mode voltage V_{cm}.

In the literature there does not seem to be an established pattern or rigorous analysis regarding the placement of the reference electrode, as there is with the recording of other biosignals as the electrocardiogram (ECG), electroencephalogram (EEG), or electromyogram (EMG). In this sense, Gamble et al. made a comparison of the standard 12-lead ECG by placing electrodes on the wrist and ankles to exercise electrode placements [11]. Choi et al. also carried out a critical study to estimate the optimal location of EEG reference electrodes for the design of brain-computer interfaces [12]. More recently, Day considered a variety of reference electrode placements to obtain the best accessory and axillary nerve conduction studies [13]. Their results showed a significant influence on the signal morphology due to the placement changes and inter-electrode distance. Following this idea, our work aims to evaluate the influence of locating the reference electrode in each of the locations identified in the literature considering the main sources of interference. To estimate at which location the most noise is recorded, two parameters were calculated: signal-to-noise-ratio (SNR) and percent root-mean-square difference (PRD).

The remainder of this work is structured as follows. Section II explores the main sources of interference around the signal acquisition by surface electrodes. The experimental results are presented in Section III. Finally, Section IV contains our conclusion.

II. Sources of Interference in EOG Acquisition

In this section we present the three main sources of interference that condition the EOG measurement by surface electrodes are presented.

A. Powerline Interference

The electric coupling of the powerline with the patient is the most relevant interference. The human body can be considered a volumetric conductor separated by air from the conductors of the powerline. In this way, a voltage divider is formed which causes the user to be at a voltage with respect to the ground of several volts. Furthermore, these capacitive interferences cause the appearance of displacement currents between the powerline and the body, closing by body capacity to ground as shown in Fig. 1. Displacement currents can vary with frequency. They are given, in peak-to-peak values, by (1). This also causes a common-mode voltage expressed as (2) that can be amplified and appear as an interference.

$$|I_d| = 2\sqrt{2}V_p \frac{C_d C_g}{(C_p + C_g)} \quad (1)$$

$$V_{cm} = \frac{I_d R_{Ref}}{1 + 2R_2/R_1} \quad (2)$$

where I_d is the displacement current with a typical value of 0.2 µA, V_p is the powerline voltage, C_p and C_g are the capacities between the user, the powerline, and the ground, and R_{Ref} is the resistance of the reference electrode.

50/60 Hz powerline interference can be modeled as sinusoids and a combination of sinusoids (see Fig. 2a). The amplitude and frequency content of the signal are generally consistent for a given measurement.

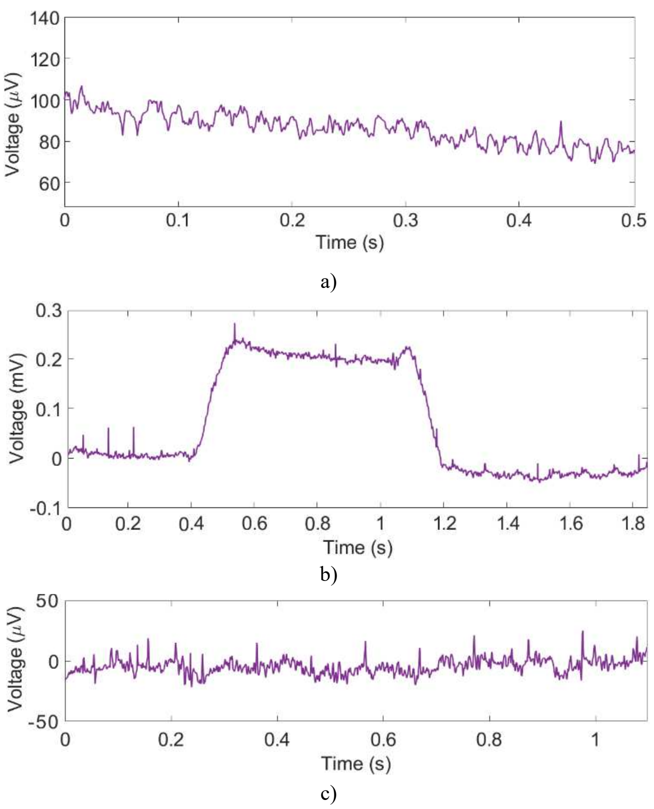

Fig. 2. EOG signal influenced by: a) powerline interference; b) electrode motion artifact, and c) electromyographic noise.

B. Electrode-skin Interface

To avoid the charging effect the impedance of the electrode-skin interface must be as low as possible [14]. Any movement between the skin and the electrode will cause an imbalance in the distribution of charges. This is a very low-frequency interference named motion artifact. Fig. 2b shows the EOG signal influenced by the electrode motion artifact caused by loss of contact between the electrode and skin. This transient interference can be permanent or be manifested as intermittent spikes when a loose electrode is brought in and out of contact with the skin because of movements and vibration.

Fig. 3 shows the electrical model of the electrode-skin. An analysis of the anatomy of human skin reveals three distinct layers: epidermis, dermis, and the subcutaneous fat layer. In the outermost part of the epidermis lies the stratum corneum or corneal layer, which can be considered as a membrane semipermeable to ions. Therefore, if there is a difference in concentration of ions along with the corneal layer, there is a potential difference. In Fig. 3 this potential difference is denoted as E_{ep}. Conductive gel is used to soften the stratum corneum and to facilitate the capture of the impulses. Moreover, it is necessary to rub the skin with gauze moistened with acetone or alcohol to eliminate part of this layer. The epidermis is represented by the circuit formed by R_{ep} and C_{ep}, which in Fig. 3 appears parallel to the $R_s C_s$ network. This reveals the action of the sweat glands and the K^+, Cl-, and Na^+ ions that sweat contains [15], [16]. The frequency band of interest, 0.05−40 Hz, E_e has an approximate value of 220 mV, and the impedance of the electrode normally varies in the range of 5−20 kΩ [17].

The effectiveness of the electrodes can be checked by measuring the resistance on the skin. The resistance is of the order of 3−4 MΩ. Once the electrodes are placed, however, the resistance decreases to about 40 kΩ [9].

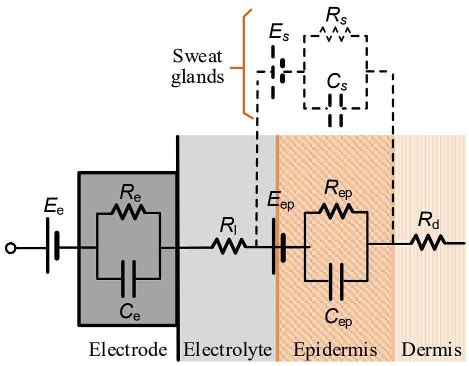

Fig. 3. Electrical model of the electrode-skin interface considering the sweat glands [9]. E_e=half-cell potential, C_e=electrode capacity, R_e=electrode resistance, R_l=electrolite equivalent resistance.

C. Electromyograpghic Biopotential

The electromyographic biopotential is generated by the muscle's activity. It represents an important source of interference, but there is no way to eliminate it because it covers the entire EOG signal spectrum. The subject must have their muscles as relaxed as possible and avoid movements during the recording of the signal. The electrodes must be positioned properly in places where this interference is minimal, for example, on the bones, in the orbital rim, or at the base of the orbital cavity. In these places there is almost no muscle presence, so the EMG is not as relevant as the EOG. The muscle contraction signals (Fig. 2c) are transitory and

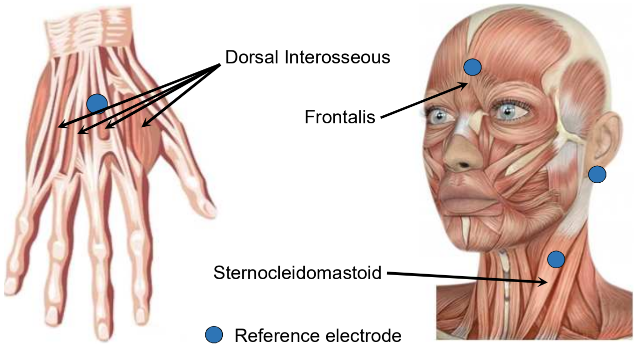

Fig. 4. Different options for placing the reference electrode: back of hand, head, and neck. Muscles are shown in reddish brown and tendons in white.

have a very low level, so they cannot be considered.

The reference potential should be placed over a supposedly electrically quiet or inactive location. It is taken typically from the forehead, but also possible are the earlobe the back of the hand, or the neck [5], [18]–[20]. The electrodes should adhere to the subject's skin so that they do not move. To reduce motion artifacts and EMG interference, the reference electrode should be placed over the bony structure, as shown in Fig. 4. In the frequency domain, interference due to the movement of the electrodes can be easily discriminated. This is because most of the time they introduce high-frequency components and, considering that the EOG signal has a low-frequency range, they can be eliminated by low-pass filters.

III. Measurements

A. Electrode Placement

According to the literature, there are four main electrode placements which condition the position of the reference electrode [21]. In Fig. 5a there are only three active electrodes. The reference electrode is placed in the earlobe. More accurate measurements can be obtained using the electrodes configuration in Fig. 5. In this case, the reference electrode is placed on the forehand, and vertical and horizontal eye movements can be considered independently. Fig. 5c shows a very accurate configuration, but due to the high number of electrodes, it is only recommended for medical and research purposes [18]. Finally, in Fig. 5d both signals can be recorded simultaneously by channel 1 (X_{1+}-X_{1-}) and channel 2 (X_{2+}-X_2). As in the first alternative, the forehead cannot be considered as a possibility due to the presence of active electrodes.

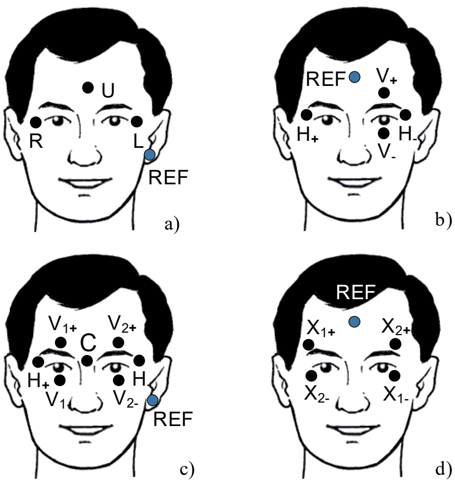

Fig. 5. EOG signal acquisition with: a) four electrodes; b) five electrodes; c) eight electrodes, and d) two cross-channels.

The main alternative is to place the reference electrode on the earlobe. Placing the reference and active electrodes as close as possible gives the lowest input impedance to the measurement system. Large impedances will result in the current flow's being minimal, and hence the potentials cannot be picked. Therefore, the reference electrode should be placed on a low-impedance surface with less mismatch for the active electrodes. Thus, common-mode rejection works more effectively, and the signal-to-noise ratio increases, which can be achieved using a differential amplifier.

The electrolyte-skin interfaces are difficult to characterize because they depend on the characteristics of the skin. The impedance of the electrolyte-skin interface has been measured by [22], [23], and it has been possible to verify that for the same subject the impedance has variations depending on the area of the body where the electrode is applied, the time elapsed since its application, the electrolyte composition, and the condition of the skin and its preparation. However, it is well-known that the eccrine sweat glands, the largest in the human body, are found in higher density in the palm and the soles of the feet, then on the head (mainly on the forehead), and to a lesser extent on the torso, armpits, and extremities. Therefore, the forehead may present a greater stratum corneum and impedance, charging the analog-front-end stage and increasing the common mode. Proper cleaning and preparation of the skin surface before disposing of the electrodes is especially important in this case.

The reference electrode should be placed in an electrically noiseless location, in which any electrophysiologic potential is registered. As can be seen in Fig. 4, there is less muscle activity susceptible to generate interference by electromyographic signals in the earlobe and on the forehead. If the electrodes are placed close to a muscle, any artifacts arising from muscle activity are picked up by them. If the reference electrode is close to the active electrode, the artifact to be compensated in the IA would be more similar and therefore the signal would be less contaminated. Wide separation between reference and active electrodes makes that different artifact generated mainly by the muscle fibers immediately under the electrode or heartbeat be acquired by both types of electrodes.

B. Experimental Tests

We recorded the EOG using a commercial bio amplifier that provided two differential channels and a reference input [24]. Our electrode model was the Ambu® Neuroline 700. This is an Ag/AgCl surface electrode that provides an impedance less than 3 kΩ. The configuration we followed for the active electrodes was that shown in Fig. 5b and the reference electrode place was changing. In all cases, we prepped the electrode locations by using a gauze cloth with alcohol to reduce electrode impedance. After preparing the skin, we placed the active surface electrodes over the bony area of the eye socket and the reference electrode on the forehead, on the right hand, on the right earlobe, and on the right side of the neck.

Fig. 6 shows the EOG signal acquired by placing the reference electrode in the four positions in the same volunteer, who was thirty-four years old with no known pathologies. The user was seated with his hands on his calves and remained immobile during the tests. The electrode leads were twisted to minimize the inductive interference generated by the magnetic field produced by them. We instructed the volunteer as

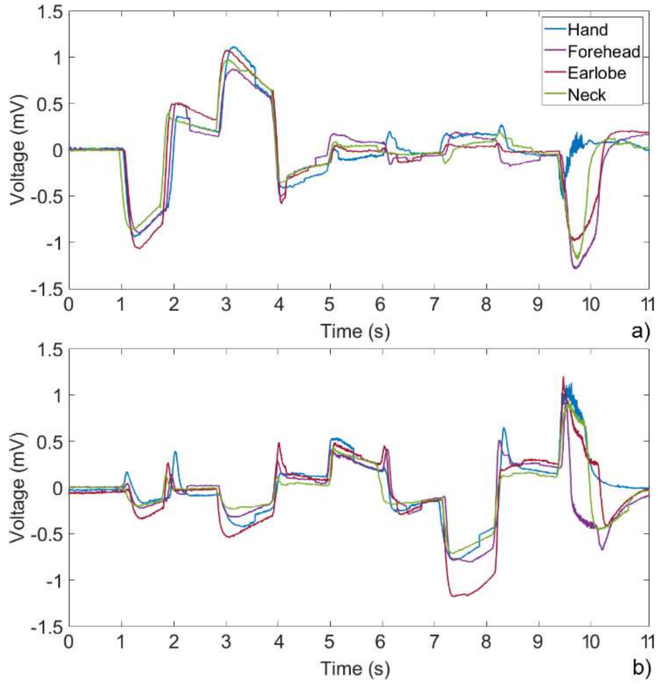

Fig. 6. a) Horizontal and b) vertical channels acquired by placing the reference electrode in back of the hand, forehead, earlobe, and neck.

follows in measuring the signals: look ahead, turn the gaze to the left, look ahead, turn the gaze to the right, look ahead, turn the gaze upward, look ahead, turn the gaze downward, look ahead, blink, and turn to look ahead again for one second in each position. We applied a high-pass Bessel filter with a cutoff frequency of 0.1 Hz to the signals shown. This filter allowed us to remove the DC component and centered the signal at 0 V.

To compare the measured signals and estimate at which location the most noise is recorded, two parameters were used: SNR and PRD. These parameters are defined as follows:

$$SNR = 10\,log\frac{\sum_{n=1}^{N}(x_i)^2}{\sum_{i=1}^{N}(x_i-\hat{x}_i)^2} \qquad (3)$$

$$\text{PRD }(\%) = 100 \times \sqrt{\frac{\sum_{i=1}^{N}(x_i-\hat{x}_i)^2}{\sum_{\text{i}=1}^{\text{n}}(x_i)^2}} \qquad (4)$$

where $\hat{x}_i$ and x_i are the samples of the recorded signal and original signal, respectively, and N is the number of samples. The original signal was estimated by filtering the recorded signal by an infinite impulse response low-pass filter with a 40 Hz cutoff frequency.

Table I shows the SNR and PRD values obtained for the different reference electrode placements considered. As can be noticed, the signal recorded when placing the reference electrode on the hand contains a greater noise component while placing it in the earlobe, the best SNR and the lowest PRD were obtained with respect to the filtered signal. The values obtained by placing the reference electrode on the forehead and neck were almost similar and slightly worse than those obtained when placing it on the earlobe. However, as can be seen in Fig. 6, the waveforms obtained were very similar in the four places considered. The amplitude of the potential also remained relatively constant when the position of the reference electrode was changed.

TABLE I. SNR AND PRD VALUES FOR DIFFERENT PLACEMENTS OF THE REFERENCE ELECTRODE

Placement	Channel	SNR (dB)	PRD (%)
Hand	Vertical	29.30	3.43
	Horizontal	29.43	3.38
	Mean	**29.36**	**3.40**
Forehead	Vertical	30.76	2.90
	Horizontal	32.19	2.46
	Mean	**31.48**	**2.68**
Earlobe	Vertical	31.57	2.64
	Horizontal	32.33	2.42
	Mean	**31.95**	**2.53**
Neck	Vertical	31.21	2.75
	Horizontal	32.01	2.51
	Mean	**31.61**	**2.63**

IV. CONCLUSION

From the experimental results, we can conclude that: 1) the closer the reference electrode was to the active ones, the compensatory effect of the interference would be greater because the signal recorded by the reference electrode was more like the active ones. Therefore, placing the reference electrode on the forehead would be the most appropriate despite presenting a more stratum corneum. 2) Smooth friction of the epidermal skin can considerably reduce skin resistance and skin potential and thereby reduce motion artifact. Another option, although less effective, is to clean the skin surface. For Ag/AgCl electrodes the quality of gels helps to reduce the junction potentials. This effect is more pronounced the greater the contact time between the electrode and the skin, so it is advisable to leave the maximum time interval between the placement of the electrodes and the recording of the signal. 3) Capacitive coupling with the patient can be reduced by using electrodes with low impedances and the least possible imbalance. Besides, the choice of IA and its CMRR is very important. 4) It is possible to easily reduce interference due to muscle activity mainly present in the 50−150 Hz band using a low-pass filter with a 40 Hz cutoff frequency. This also reduces powerline interference.

The analysis of the source of interferences—as well as the instrumentation principles we describe in this paper—may be useful for the signal acquisition and design of EOG-based systems that typically use Ag/AgCl surface electrodes.

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