Reduction of Power Line Interference using Active Electrodes and a Driven-Right-Leg Circuit in Electroencephalographic Recording with a Minimum Number of Electrodes

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Abstract—**Unwanted power line interference is one of the most common problems in electroencephalographic recording. This paper examines how the use of active electrodes together with a driven-right-leg circuit can significantly improve interference reduction, even when the same electrode is used for common and reference which is attractive because it saves an electrode. General conclusions about the active electrodes and the driven-right-leg circuits were obtained thanks to a prototype that uses the same electrode for both common and reference. Measurements were performed both on a subject and on an electrical equivalent model.**

Keywords—**Active electrode, bioelectric recording, driven-right-leg, reference electrode.**

I. INTRODUCTION

Unwanted power line interference in electroencephalographic (EEG) recording is one of the most recurrent problems in hospitals. Capacitive coupling between line, ground and cables is one of the major sources of line interference [1].

Although some papers have previously been written on active electrodes (e.g. [2], [3] and [4]), and on driven-right-leg circuits (e.g. [5]), none of them seem to have published figures on quantitative tests on subjects.

This paper examines how the use of active electrodes together with a driven-right-leg circuit can significantly improve interference reduction. Quantitative information about parasitic voltage on measurement and common electrodes was also deduced from measurement and can be generalized to all kinds of EEGs. The measurements were performed both on an electrical model and on a subject.

In a traditional EEG, the *common* electrode is connected to the differential amplifiers' common. The differential amplifiers amplify the signals of the measurement electrodes with respect to the *reference* electrode. Using two different electrodes for reference and common helps to reduce common-mode interference using the well known three-op-amps instrumentation amplifier configuration.

Our prototype uses the same electrode for common and reference which is attractive because it saves an electrode. This is particularly important for application with a low number of electrodes (typically 8 for a portable "holter EEG").

Our approach was to build a two-channel battery powered prototype able to record an EEG signal simultaneously with and without an active electrode and able to switch from the driven-right-leg circuit to the traditional common electrode circuit. The prototype enables the comparison of those systems and the benefits from active electrode and driven-right-leg circuits were quantified.

The results are in good agreement with theory and simulations.

II. THEORETICAL APPROACH AND SIMULATIONS

The prototype is presented in Fig. 1. It is composed of two measurement channels. The only difference between the two channels is the location of the pre-amplifier : while the pre-amplifier of the second channel is traditionally placed next to the amplifier (passive electrode), the pre-amplifier of the first is placed next to the electrode (active electrode). This way, it is possible to record simultaneously with and without an active electrode. It is also possible to switch the common electrode from the amplifiers common to the driven-right-leg circuit.

Stray capacitances produce interference in the measurement and common wires that are nearly current sources because the impedances of the stray capacitances are much larger that those of the electrodes and the body.

In a system without a driven-right-leg circuit (switch connected on common) the parasitic currents are lower in the measurement electrodes (Im1 and Im2) than in the common electrode (Ic) because the parasitic currents are nearly stopped by the pre-amplifiers' high impedance and can only flow through the subject. So, a large parasitic current flows through the common electrode impedance and is the main cause of common-mode voltage.

The driven-right-leg circuit drives the subject to the common average voltage of the input signals, reducing the

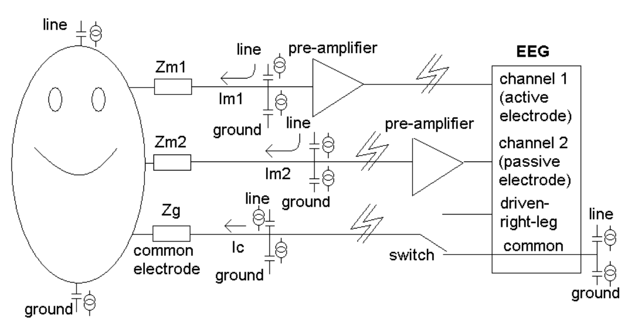

Fig. 1. EEG system.

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common-mode voltage by a factor of G+1, where G (typically 300 at 50 Hz [1]) is the driven-right-leg voltage gain [5].

A drawback of the system is that the signal is amplified with respect to the average of the input signals, and therefore any noise on this average influences all channels. Hence, if some measurement electrodes pick up a lot of interference the use of the driven-right-leg circuit induces interferences on all channels.

This problem does not arise if all measurement electrodes only pick up a low level of interference, which is likely to happen with active electrodes. The active electrode is placed as close as possible to the electrode; that way it can improve signal quality by reducing the two stray capacitances (ground-wire and line-wire), and therefore also by reducing the parasitic current (Im1 on Fig. 1) flowing in the measurement electrode.

The use of active electrodes in conjunction with a driven-right-leg circuit can reduce the interference even if (measurement and common) electrode impedances are high, due to careless placing or gel drying.

Fig. 2. shows the comparison between the traditional system with a three-op-amps instrumentation amplifier (Fig. 2a), and a simple inverter amplifier system used in our prototype (Fig. 2b). Both systems can be inserted in Fig. 1.

The main difference between the two systems is that in system (b) the signal is amplified with respect to the common electrode, while in system (a) it is amplified with respect to the measurement channel chosen as reference so that the common-mode voltage is rejected by the amplifier.

For both systems, it can be seen in Fig. 2 that the parasitic currents in the measurement or reference wires see the amplifier input on the right and a measurement electrode on the left. The parasitic current in the common wire sees the amplifier common or the driven-right-leg circuit on the right and the common electrode on the left. Therefore, parasitic currents see the same impedance for a system with or without separated reference electrode and so are equal.

III. Experimental Approach

A. Circuit Description

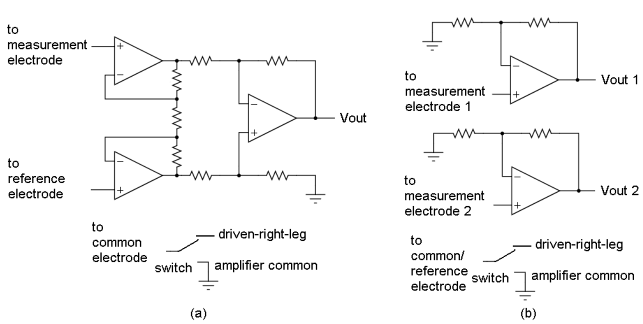

Fig. 2. EEG channel (a) traditional (b) common and reference together.

The noise of the system in a typical EEG bandpass (0.16 Hz to 70 Hz) is lower than 4.2 µV peak-to-peak.

The measurements were made in a nearly humless room (the picked-up hum is typically 1 µV peak-to-peak). A test hum source was made with a typical 4m line (220 Vrms, 50 Hz) cable (section=1.5 mm²) placed horizontally and straight at 1m from the subject and at 1m height. No current goes through the cable, so the interference is only due to capacitive coupling.

The signal is recorded simultaneously in both channels, the FFT is computed and the component at 50 Hz (line frequency) is extracted.

The electrodes used are typical sponge foot electrodes with a diameter of 1cm placed with gel (Parker Signa).

B. Electrode and head impedance evaluation

The parasitic current flowing in the cable goes through the electrode-gel-skin impedance (often called “contact impedance”) and through the head tissues before returning to ground through the subject [1]. It is therefore important to quantify the total impedance which produces the parasitic voltage.

The contact impedance of the electrodes is typically 20 kΩ showing typical 50% variation [1] and can go up to 100 kΩ for sponge electrodes with dried gel [6]. The impedances of the head tissue between two electrodes can be estimated using computer simulations, and a value ranging from 300 Ω to 500 Ω has been found for electrodes with a diameter of 1cm depending upon the distance between the electrodes and the choice of skull conductivity [6]. From now on, we shall simply call “electrode impedance” the sum of the contact impedance and the head tissue impedance.

Since the electrode impedances vary with time, because of the gel drying [6], they were measured both before and after each recording. The average of the two measurements was considered. The measurements were made at 50 Hz (line frequency) with the Waynekerr 6425 precision component analyser.

The model chosen for the subject electrical equivalent circuit (active, passive and common electrodes are considered) consists of three resistors in star configuration.

The values of the electrode impedances in star configuration are deduced from the measurements of the impedances performed on the subject.

C. Experimental tests on an electrical equivalent of a subject

Measurements were first made on the three resistors model. This provides a better reproducibility since the geometry of the whole system corresponds to a fixed configuration of subject, cable and electrode placement, and since the electrode equivalent impedances are kept constant.

Fig. 3 shows the parasitic input signal due to line interference as a function of common electrode impedance with and without a driven-right-leg circuit. Measurement electrode impedances are kept to zero.

For the system without a driven-right-leg circuit, it appears clearly that the parasitic current of the common electrode induces a voltage proportional to the impedance. The interference voltage for the system with a driven-right-leg circuit is remarkably lower for the whole range of common electrode impedance (up to 90 kΩ).

Fig. 4 shows the parasitic input signals with and without a driven-right-leg circuit when the passive electrode impedance varies. The impedance of the active electrode is kept to zero and the impedance of the common electrode is kept constant at a value of 20 kΩ. The average of the input signals was calculated (and is shown with stars).

For the system without a driven-right-leg circuit, it appears again clearly that the parasitic current of the passive electrode induces a voltage proportional to its impedance.

The figure illustrates what can happen if the driven-right-leg circuit is used without resorting to active electrodes : interference becomes substantial on all channels when impedance of one or more measurement electrode varies. For example, although the active channel only has a constant interference due to the common electrode in a system without a driven-right-leg circuit, it picks up interference from the passive electrode in a system with a driven-right-leg circuit. The level of interference measured (arrow A on Fig. 4) is approximately the difference between the active channel and the average of the input signals (arrow B on Fig. 4) because the driven-right-leg circuit amplifies with respect to the average of all electrodes.

This problem does not appear when it is the active electrode impedance that varies, as shown on Fig. 5. Here, the impedance of the passive electrode is kept to zero and the impedance of the common electrode is kept constant at a value of 20 kΩ.

It can be seen that the parasitic current of the active electrode is small enough to produce no visible change in parasitic voltage for the whole range of active electrode impedance (up to 90 kΩ). Therefore, the driven-right-leg circuit effectively reduces the interference from the common electrode without being disturbed by the interference from the measurement electrode.

Some practical considerations should be kept in mind. If an electrode were unstuck from the skin a great noise would result from that electrode (even if active electrodes are used) and would affect all channels. The noise could be strong enough to saturate the amplifier (the problem would arise both in our prototype or in a traditional EEG). It would therefore be interesting to use a switch and to disconnect any channel that shows abnormal amplitudes from the driven-right-leg circuit.

D. *Experimental tests on a subject*

Tests were then carried out on a subject and measurements corresponding to the electrical model (Figs. 3, 4 and 5) are shown in Figs. 6, 7 and 8. Ten measurements were made (mean, maximum and minimum values are displayed) for each electrode placement. To make comparison possible, when electrode impedances were kept to zero for a subject electrical model, they were made small (electrodes were applied carefully with gel) and constant (gel was constantly added to prevent it from drying). In Figs. 7 and 8 the common electrode impedance was kept relatively constant but it was observed in Fig. 6 that even small fluctuations of its impedance induced large interference fluctuations. To produce significant changes in the electrode impedance, the electrode was applied with

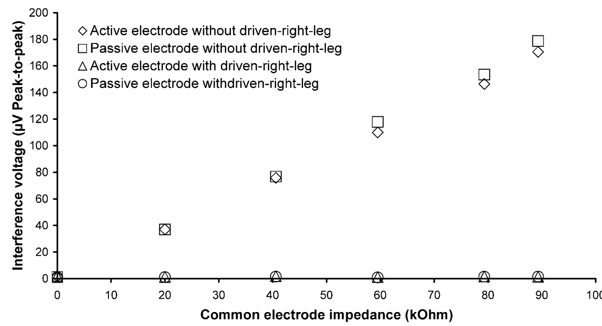

Fig. 3. Variation of interference as a function of common electrode impedance.

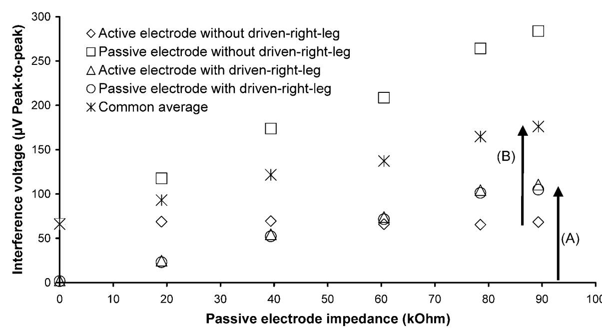

Fig. 4. Variation of interference as a function of passive electrode impedance.

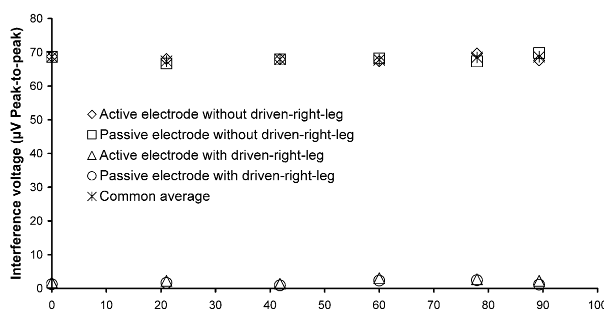

Fig. 5. Variation of interference as a function of active electrode impedance. The signals for a system without driven-right-leg circuit are superimposed on the top of the graph and those for a system without driven-right-leg circuit on the bottom.

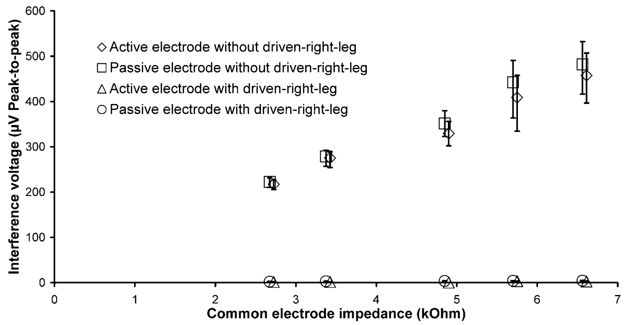

Fig. 6. Variation of interference as a function of common electrode impedance.

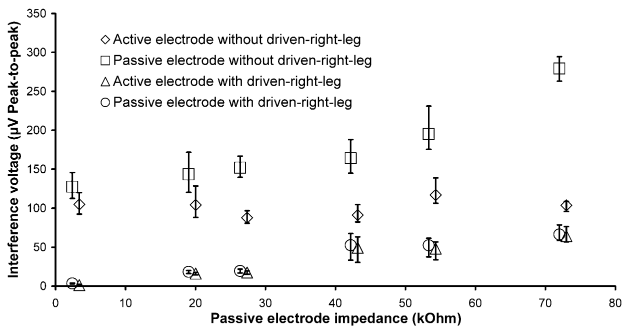

Fig. 7. Variation of interference as a function of passive electrode impedance.

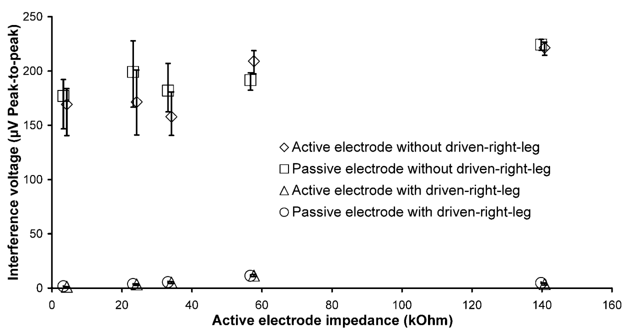

Fig. 8. Variation of interference as a function of active electrode impedance.

varying degrees of care and with or without gel.

Results are similar to those found on the electrical model. The main difference is that common electrode parasitic voltage found on the subject is much larger (about 35 times). This is certainly due to the fact that the two stray capacitances of the body (earth-body and line-body) were not included in the electrical three resistors model, resulting in a lower parasitic current flowing between the electrodes and the subject. We can simulate these stray capacitances by connecting someone's body to the node point of the three resistors equivalent circuit. Those capacitances are then added and values similar to the ones found on a subject are found. The reproducibility of the model, however is reduced.

Some quantitative results can be deduced from the three figures above. In Fig. 6, since the measurement electrode impedances are kept small, the graph corresponds to the parasitic voltage on the common electrode of a traditional EEG. The parasitic current can be deduced from the slope of the graph. For a system without a driven-right-leg circuit it equals about 70 nA peak-to-peak (similar to the 50 nA peak-to-peak found in [1]) whereas it is nearly zero for a system with a driven-right-leg circuit. In Fig 7, the difference between the active and passive electrode in the graphs for a circuit without driven-right-leg corresponds to the interference on the measurement wires for a traditional EEG. Since the impedance of the common electrode is kept constant, the parasitic current of the passive electrode can be deduced from the slope and equals about 2 nA peak-to-peak (lower than the 10 nA peak-to-peak found in [1]). With the same reasoning, it can be seen in Fig. 8 that the parasitic current equals zero for the active electrode.

IV. Discussion and Conclusion

In this paper, the reduction of interference on the common electrode and on the measurement electrodes due to a driven-right-leg circuit and active electrodes was quantified for the prototype and can be generalized for other kinds of amplifiers.

We can conclude that using a combination of active electrodes and a driven-right-leg circuit significantly reduces the sensitivity to the electrode impedance, even when they are high due to the duration or to the quality of electrode placement.

Moreover, we can obtain good quality EEG even if we use the common electrode as reference.

Acknowledgment

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