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Can Driven-Right-Leg Circuits Increase Interference in ECG Amplifiers?

J. Gomez-Clapers, *Student Member*, *IEEE*, E. Serrano-Finetti, R. Casanella, *Member*, *IEEE* and R. Pallas-Areny, *Fellow*, *IEEE*

***Abstract*—The Driven-Right-Leg (DRL) circuit has been used for about 50 years to reduce interference due to common-mode voltage in biopotential amplifiers in scenarios that range from fixed equipment supplied from power lines to battery-supplied ambulatory monitors, and for systems that use gelled, dry, textile, and capacitive electrodes. However, power-line interference models predict that for isolation amplifiers, currently mandated by safety standards, power-line interference can often couple mostly in differential mode rather than in common mode. In this work we analyze the effect of the DRL circuit in different ECG leads to elucidate its actual effect on power-line interference reduction. It turns out that that the DRL circuit, which effectively reduces common-mode interference, affects differential-mode interference in an unpredictable way and can increase interference.**

I. Introduction

POWER-LINE interference coupling in biopotential recordings has received attention for years because it can easily mask relevant signal features. Digital filtering can eliminate residual power-line interference but amplifiers must still be designed to minimize that interference as it could saturate analog front ends. Huhta and Webster [1] identified four ways for electric and magnetic interference to couple into biopotential recording systems: 1) Variable magnetic fields; 2) Capacitive coupling to electrode leads (and to the electrodes themselves); 3) Capacitive coupling to the body; and 4) Common-mode voltage that results from currents that flow to earth, usually along the reference ("right leg") electrode connected to amplifier common. Meting van Rijn et al. [2] added a fifth coupling way: Current injected to the body through the reference electrode because of the finite capacitance between power lines and amplifier common, part of which can be attributed to capacitive coupling between the primary and secondary windings of the power supply transformer [3].

Variable magnetic fields induce voltage in the loop formed by electrode leads and also inside the patient's body, but the intensity of magnetic fields in common environments is small enough for the resulting differential voltage to be negligible if electrode leads are short or if they are twisted when they are long.

Displacement currents coupled to the electrodes, to their leads, and to the patient because of variable electric fields flow through the patient to earth, because power lines are earth grounded. As a result, there is a drop in voltage between the two recording electrodes (differential-mode voltage) and also a drop in voltage between the patient's body and amplifier common (common-mode voltage). In three-electrode differential voltage amplifiers, where the reference electrode is connected to amplifier common, the common-mode voltage is the drop in voltage across the impedance of this electrode plus the drop in voltage across the internal impedance of the body between the recording electrodes and the reference electrode (Z_{t2}). In Fig. 1, if the voltage dividers formed by each recording electrode (Z_{e1}, Z_{e2}) and the common-mode input impedance (Z_{c1}, Z_{c2}) of the respective input of the differential amplifier are imbalanced, that common-mode voltage results in a voltage difference at the input of the amplifier, hence, differential-mode interference across Z_d [4]. It follows that for a given imbalance of the Z_e/Z_c impedance ratio, the output interference will decrease if the common-mode voltage is reduced, and for a given power-line current that flows to earth along the reference electrode, a method to reduce the common-mode voltage is by reducing the impedance Z_{e3} of this electrode.

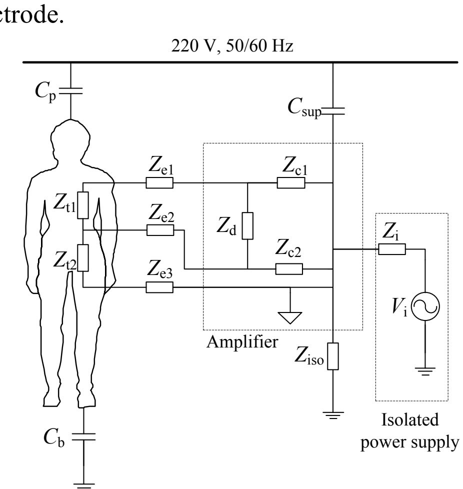

Fig. 1. Circuit model for power-line interference coupling in amplifiers supplied by an isolated power supply.

To effectively reduce that impedance below the limits of a good physical contact, a driven-right-leg (DRL) circuit was already in use in 1962 [5] which fed back into the body the

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J. Gomez-Clapers, E. Serrano-Finetti, R. Casanella, and R. Pallas-Areny are with the Instrumentation, Sensors and Interfaces Group, Department of Electronic Engineering EETAC-UPC, 08860 Castelldefels, Barcelona (Spain) (phone: +34-93-413-7096; fax: +34-93-413-7007; e-mail: {joan.gomez-clapers, ernesto.serrano, ramon.casanella, ramon.pallas} @upc.edu).

common-mode voltage derived from the two recording electrodes. By reducing that impedance, the common-mode voltage decreased and the possible impedance ratio imbalance was no longer a major problem. By 1967, however, concerns about patient's electrical safety mandated amplifier common and earth ground to be electrically isolated [5]. Therefore, the drop in voltage between the patient and earth was no longer equal to the drop in voltage across the reference electrode, that for earth-grounded amplifiers could be larger than 1 V. Rather, the larger the isolation impedance Z_{iso} between signal common and earth (Fig. 1), the smaller the common-mode voltage. By considering that to protect the patient the isolation impedance should be larger than 20 MΩ, it can be easily found that for an isolation amplifier the peak-to-peak common mode voltage due to currents capacitively coupled to the body seldom exceeds 2.5 mV in normal condition [2] [6]. Therefore, an effective CMRR of 60 dB would be enough to attenuate that voltage below system's resolution. In fact, if high-isolation devices with C_{iso} around 1.6 pF are used [7], the drop in voltage between the body and earth because of power-line currents coupled to the body is determined by C_p (1 to 4 pF) and C_b (100 pF to 1 nF), regardless of the impedance of the reference electrode. Then, less than 1.6 % of the displacement current coupled to the body (< 1 μA) flows along the reference electrode, and the drop in voltage across it, hence the common-mode voltage due to displacement currents is negligible even if the contact impedance of that electrode is as high as 100 kΩ. However, currents coupled to the electrodes and their leads, and power-line currents from the internal power supply (V_i, Z_i in Fig. 1) and direct coupling from power lines to amplifier common (C_{sup}) often result in larger common-mode voltages.

Nevertheless, in spite of the reduced common-mode voltage in amplifiers with isolation much higher than that required by safety standards, systems from legacy ECG monitors [5] to system-on-chip circuits for wearable sensor nodes [8] use the DRL circuit to "mitigate the supply line interference effect." Some time ago, we demonstrated that the pervasive differential-mode interference identified in [1] can become the predominant power-line interference source in ECG amplifiers [9]. Because this interference depends on the actual path of power-line currents coupled throughout the body, this work aims to describe the possible effect of the DRL circuit on differential-mode interference by 1) Comparing the interference level for each lead of a three-lead ECG standard measurement when using a commercial class II medical-grade power supply, and 2) Controlling the point where power-line interfering currents leave the body, to gain a deeper insight into the effect studied.

II. Materials and Methods

A. ECG Amplifier

Fig. 2 shows the custom-built ECG amplifier used in our experiments, which is based on the circuit in [10] but includes two input voltage buffers to ensure high input impedance. The DRL circuit was designed according to [2]. The differential gain was 1000 from 0.05 to 100 Hz and the measured common-mode gain at power-line frequency (50 Hz) was 0.06, which results in CMRR = 86 dB. A resistive network allows for common-mode voltage (V_c) sampling from the input stage of the instrumentation amplifier (INA121). The reference electrode could be connected to either the output of the DRL circuit or to amplifier common.

The amplifier was supplied by a class II medical-grade power supply (KMT15-51515, TDK-Lambda, USA). The ECG signal was acquired by a 12 bit, 10 V full-scale data acquisition system (μDAQ Lite, Eagle Technology). All measurements were performed with LabVIEW® running on a battery-supplied laptop PC. Therefore, the isolation impedance between amplifier common and earth ground was determined by that of the transformer inside the power supply. The record length was 15 s and the sampling frequency 1 kHz.

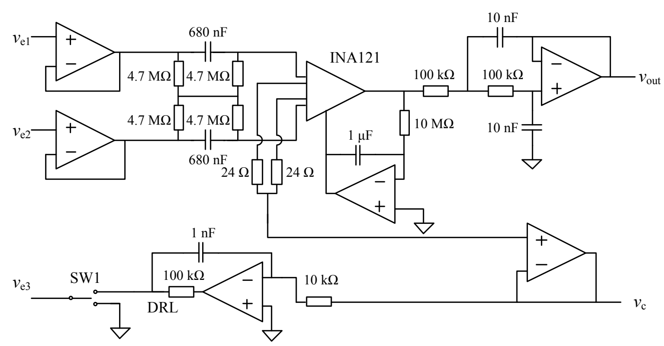

Fig. 2. Custom-made ECG amplifier to analyze the effect of the DRL circuit on power-line interference.

B. Experimental setup for power-line interference assessment

As shown in Fig. 1, the interference sources considered are displacement currents directly coupled to the body through C_p and C_b, and currents coupled from power-supply lines to amplifier common, either directly (C_{sup}) or through the medical-grade power supply (V_i, Z_i) [3]. Note that whereas internal interference current flow through the reference electrode (Z_{e3}) when this is connected to signal common, C_p and C_b are distributed capacitances and therefore currents flowing through them will follow a path to ground different from that followed by power-line currents coupled through the amplifier. Displacement currents coupled to electrode leads and to the recording electrodes themselves add to those currents directly coupled to the body. The interference model includes Z_{t1} which is the impedance of the body segment between the two recording electrodes; the closer the electrodes, the smaller Z_{t1}. Any drop in voltage across Z_{t1} because of power-line currents becomes differential-mode interference. Electrode leads were twisted to reduce magnetic interference.

The input common-mode voltage and total output power-line interference have been assessed for standard ECG leads I, II and III by placing two pre-gelled electrodes on the upper thorax next to the arms and a third electrode on the left leg. The reference electrode was connected to the right leg and switch SW1 allowed us to connect it to either amplifier common or the DRL circuit. A fast Fourier Transform was applied to each 15 s record from which the estimates for the power-line frequency component (50 Hz) were obtained for V_c and V_{out}, renamed to $V_{out,pl}$. The difference between $V_{out,pl}$ and the output predicted from the measured V_c and the common mode gain (0.06) can be attributed to differential-mode interference. All measurements were performed on the same (seated) subject along several sessions in a laboratory full of electronic equipment, but all results presented here belong to the same session.

III. Experimental Results and Discussion

Table I summarizes the input common-mode voltage V_c and the output power-line-frequency voltage $V_{out,pl}$ for each lead in consecutive measurements.

TABLE I
POWER LINE INTERFERENCE IN LEADS I, II AND III

Reference electrode connected to	Amplifier common		DRL circuit	
Lead	V_c/V	$V_{out,pl}$/V	V_c/V	$V_{out,pl}$/V
I	0.855	0.081	0.001	0.216
II	0.865	1.311	0.001	1.414
III	0.887	1.411	0.004	1.560

When the reference electrode is connected to amplifier common, V_c is about the same for all leads and its value far exceeds what can be expected from only currents coupled to the body, the electrodes or their leads. If the power supply is replaced by batteries, V_c reduces to less than 10 mV, which confirms the relevance of power line coupling through the power supply, whose isolation is intended to guarantee safety, not to minimize interference. Further, because the common-mode gain is 0.06, the output voltage attributable to V_c in Table I is about 40 to 50 mV. For lead I, an output almost twice larger is obtained whereas for leads II and III it is more than 25 times larger. This can be attributed to differential-mode interference larger than 1 mV (say, 1 µA across 1 kΩ.

When the reference electrode is connected to the DRL circuit, the common-mode voltage becomes negligible, as expected, but the power-line component of the output voltage increases for the three leads measured. This can be explained by an increase in differential-mode interference. In [1] it was already observed that relocating the reference electrode affected the interference in spite of the common-mode voltage being about the same. In particular, interference decreased when the reference electrode was symmetrically placed with respect to the recording electrodes. Here, even in the absence of any noticeable common-mode voltage when using the DRL circuit, the power-line interference at the output can be comparable to the R wave.

The increase in differential-mode interference when using the DRL circuit as compared to connecting the reference electrode to amplifier common can be explained by considering that the path to earth ground followed by power-line currents coupled to the body is quite different in both cases. If the reference electrode is connected to signal common, some current coupled through C_p (Fig. 1) and almost all current coupled through the power supply will flow along the reference electrode. When applying to this electrode the common-mode voltage (DRL circuit), there is a redistribution of power-line current throughout the body. If most of this current flow to earth ground through an area close to one of the recording electrodes, the differential-mode interference will increase.

To verify this hypothesis, a new experiment was performed intended to control, to some extent, the place where interfering currents leave the body. Given that the body-to-ground impedance, as determined by stray capacitance C_b, can be about 20 MΩ [2] [6], we used a fourth electrode in series with a 100 kΩ resistor to successively connect one of three different areas of the body to earth ground, as shown in Fig. 3. We expected most power-line current to flow to ground along the 100 kΩ resistor rather than the distributed capacitance C_b. Lead I was recorded, both using the DRL circuit and without it, in four different conditions for the fourth electrode: not connected (NC) and connected to the right leg (RL), left leg (LL) and right arm (RA). Table 2 shows the results.

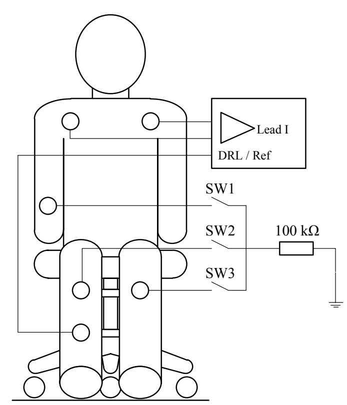

Fig. 3. A grounded electrode additional to those used to record ECG, is a preferred path to ground for power-line currents coupled to the body

TABLE II
POWER LINE INTERFERENCE IN LEAD I

Reference electrode connected to:	Amplifier common		DRL circuit	
Fourth electrode	V_c/V	$V_{out,pl}$/V	V_c/V	$V_{out,pl}$/V
NC	1.157	0.200	0.004	0.268
RL	2.117	0.199	0.007	0.015
LL	2.113	0.220	0.005	0.015
RA	1.982	0.685	0.008	0.721

By comparing with the results for lead I in Table I, we see that when the body is earth grounded, the common-mode voltage V_c increases, as expected, and it does not depend much on the placement of the grounding electrode. When the body is not earth grounded, V_c is only a bit larger than that obtained for lead I in Table I. The DRL circuit always reduces V_c, as expected.

The power-line component of the output voltage in no case can be explained from only the common-mode voltage and common-mode gain. Rather, it must be attributed to differential-mode interference. Its maximal value is obtained when the right arm is connected to earth, which is consistent with a large fraction of the current flowing through the segmental impedance of lead I (LA to RA). If power-line currents leave the body mostly from areas in the legs, the fraction of them flowing between LA and RA is about one third of that when RA is earth grounded.

On the other hand, the effect of the DRL circuit on displacement currents is unpredictable. Table II shows that when the DRL is used, the worse interference is also obtained when the earth grounded area is close to RA, and it is even larger than that when the DRL circuit is not used. However, when the areas connected to earth are LL or RL, interference decreases by a factor larger than ten if the DRL circuit is used. This cannot be attributed to the reduced common-mode voltage, as this is now insignificant. This reduction can be better attributed to a beneficial redistribution of power-line currents when the earth-grounded area is far from the recording electrodes. Anyway, because earth grounding is forbidden by safety regulations, the overall benefit of the DRL circuit is dubious.

IV. Conclusion

The role of the DRL circuit in reducing power-line interference has been assessed for leads I, II and III corroborating its remedial properties to reduce common-mode voltage. However, ECG signals show power-line interference even when the common-mode voltage is minimal. This is an undisputable evidence of power-line interference coupled in differential mode. However, in spite of its relevant role, differential-mode interference has received far less attention than common-mode interference, to the point that the DRL circuit sometimes seems to be used as the sure solution for power-line interference, together with amplifier isolation.

By comparing power-line interference in ECG leads I, II, and III when the reference electrode is either connected to signal common or to the DRL circuit, and simultaneously measuring the actual common-mode voltage, we have found that power-line interference can increase when the DRL circuit is used (Table I). This result can be explained by realizing that the path to earth ground followed by power-line currents coupled to the body is less controllable in isolation amplifiers than in legacy earth-grounded amplifiers. An ad hoc experiment wherein that path has been controlled by using an earth- grounded electrode additional to the recording and reference electrodes has shown that the DRL circuit affects that path to ground in an unpredictable way so that interference can increase or decrease (Table II). This result also implies that experimental interference analysis where the body is earth grounded to consider a worst-case scenario because of the larger common-mode voltage, may in fact benefit from reduced differential-mode interference as compared to signals recorded with isolation amplifiers. Further, the isolation provided by these amplifiers is often intended just to reduce power-line currents in first-fault condition, which implies isolation impedances that do not help much in reducing interference.

Finally, from the point of view of amplifier design, it is important to know if the DRL circuit is strictly necessary because large common-mode interference can be expected. Otherwise, given the dubious overall benefit of the DRL circuit, it may be better not to include it to save power and space, for example in an ambulatory scenario where the energy budget has severe restrictions.

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