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Amplifier Input Impedance in Dry Electrode ECG Recording

Cédric Assambo and Martin J. Burke

Abstract—**This paper presents a novel approach for designing the front-end of instrumentation amplifiers for use in dry electrode recording of the human electrocardiogram (ECG). The method relies on information provided by the characterization of the skin-electrode interface and the analysis of low frequency ECG criteria defined by international standards. Marginal measurements of capacitive elements of the skin-electrode interface as small as 0.01 μF, suggest values of input impedance in the order of 1.3 GΩ. However, results in 99% of the data analyzed indicate that a recording amplifier providing an input impedance of 500 MΩ should ensure clear signal sensing without distortion.**

I. INTRODUCTION

Progress made in bio electrode technologies in recent years has enabled the development of new applications of long-term physiological monitoring. Particularly, there has been increasing interest in the recording of the human electrocardiogram (ECG) using dry or un-jelled electrodes. Dry electrode recording does not require preparation of the electrodes before or after application, enabling the electrode system to be re-used. In addition, the use of dry electrodes eliminates toxicological concerns such as allergic reactions or other forms of skin irritation, commonly associated with electrolyte gels [1]. It has long been established that the skin-electrode interface introduces a phase shift into the received signal which can result in serious distortion of the ECG waveform [2, 3]. Furthermore, the dc polarisation potential of dry electrodes can be much higher than is the case with conventional electrodes and is best eliminated by using dc blocking capacitors, in series with the electrodes. This can give rise to further phase distortion of the ECG signal if the input impedance of the amplifier is not high enough. Consequently, characterization of the impedance of the skin-electrode interface provides essential information for the correct design of the amplifier for faithful reproduction of the ECG signal morphology.

The authors present a method for optimizing the impedance of the front end of bio potential recording amplifiers used with dry electrodes. The method initially relies upon the measurement of the parameters of a two-time-constant based model of dry conductive electrodes. The authors then use International standards requirements to determine the input impedance requirement of the amplifier front-end stage.

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II. BACKGROUND

A physical model of the skin-electrode interface and its equivalent electrical model are shown in Fig. 1. It can be seen that there is one resistor-capacitor network associated with the skin-electrode contact and one associated with the epidermal layer of the skin itself. There are also associated polarisation potentials which are treated as dc voltage sources.

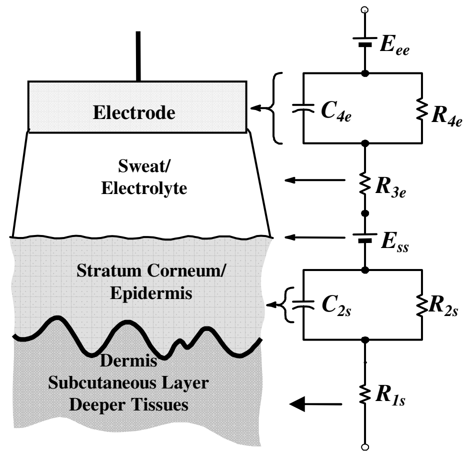

Fig. 1 Skin-electrode interface and its electrical equivalent circuit [4].

Measurements taken in previous studies returned values of resistance ranging from 23kΩ to 1850kΩ and of capacitance ranging from 0.01μF to 65μF, while the values of the time constants $C_{2s}R_{2s}$ and $C_{4e}R_{4e}$ varied from 0.02s to 7.2s [5, 6].

International standards defining the performance criteria for recording systems to ensure accurate ECG reproduction published by the European Union and the American Heart Association (AHA) were considered. The European Committee for Electrotechnical Standardisation (ECES) states that a 300 μVs impulse shall not produce an offset on the ECG record from the isoelectric line greater than 100 μV, and should not produce a slope greater than 250 μV/s in a 200ms region following the impulse and a slope of 100 μV/s anywhere outside the region of the impulse [7]. The AHA recommends that a 1mVs impulse input should not generate a displacement greater than 0.3 mV. The slope of the response outside the region of the impulse should nowhere exceed 1mV/sec. In addition, the AHA specifies that the amplitude response of the high-pass filter should be flat to within ±6% (0.5 dB) over a frequency range of 1 to 30Hz. Besides, the 3dB points should be less than or equal to 0.67Hz and greater or equal to 150Hz. A note from the AHA indicates that a system that meets the amplitude response criterion and also has phase linearity at least equal to that of a linear 0.05 Hz, single-pole high-pass filter is likely to meet the impulse response criteria [8].

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III. Materials and Methods

A. ECG measurement

A set-up, showing the detection of an ECG signal from the body using two electrodes and a differential amplifier is illustrated in Fig. 2.

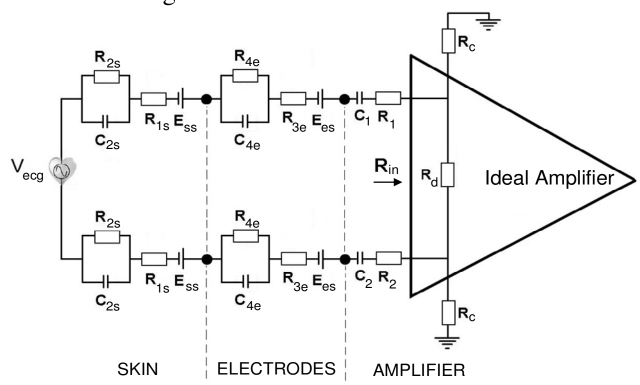

Fig. 2 Measurement of the ECG using two identical Electrodes and a differential amplifier.

The common-mode input resistances, R_c, are the equivalent resistances of both inputs of the differential amplifier with respect to ground while the differential input resistance, R_d, is the equivalent resistance between the two inputs. C_1 and C_2 act as dc blocking capacitors. In addition, resistors R_1 and R_2 are introduced in series with the electrodes to limit transient current spikes or the current due to fault conditions which may reach the subject. When R_c and R_d taken as purely resistive, the transfer function of the combined skin-electrode-amplifier network as measured at the amplifier input is given as:

$$H(s)=\frac{R_{in}}{R_{in}+2\left(Z_i+R_1+\frac{1}{sC_1}\right)} \tag{1}$$

with:

$$R_{in}=R_d\,//(2R_c) \tag{2}$$

$$Z_i=R_{1s}+R_{3s}+\frac{R_{2S}}{1+sR_{2s}C_{2s}}+\frac{R_{4e}}{1+sR_{4e}C_{4e}} \tag{3}$$

It can be shown that H(s) is also equal to:

$$H(s)=R_{in}C_1\,\frac{s^3\tau_2\tau_4+s^2(\tau_2+\tau_4)+s}{as^3+bs^2+cs+1} \tag{4}$$

where:

$$\tau_2=R_{2s}C_{2s} \tag{5}$$

$$\tau_4=R_{4s}C_{4s} \tag{6}$$

$$R_0=R_{in}+2(R_{1s}+R_1+R_{3e}) \tag{7}$$

$$a=R_0C_1\tau_2\tau_4 \tag{8}$$

$$b=[R_0(\tau_2+\tau_4)+R_{2s}\tau_2+R_{4s}\tau_4]C_1+\tau_2\tau_4 \tag{9}$$

$$c=R_0C_1+2(\tau_2+\tau_4) \tag{10}$$

Fig. 3 shows a bode plot comparing the frequency response of the skin-electrode-amplifier combination with 0.05Hz single-pole high-pass filter.

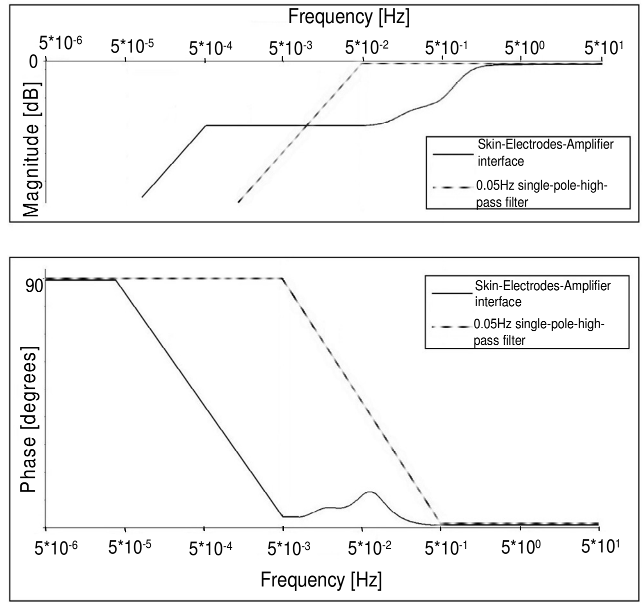

Fig. 3 A Bode plot of the magnitude and phase

B. Phase response criteria

The recommendations of the American Heart Association on the performance of ECG recording equipment [7] require that the amplifier should introduce no more phase shift into the signal than that which would be introduced by a linear 0.05 Hz, single-pole filter, as indicated in Fig. 3. The phase introduced by a single-pole high-pass filter is given as $\Phi(\omega)=\mathrm{Arctan}(2\pi f_c/\omega)$ and the phase $\varphi_H(\omega)$ of the skin-electrode-amplifier can be derived from eq. (4):

$$tan(\varphi_H(\omega))=$$
$$\frac{2\tau_2\tau_4\begin{bmatrix}(R_{2s}\tau_2+R_{4e}\tau_4)C_1\\+\tau_2\tau_4\end{bmatrix}\omega^4+\begin{bmatrix}\tau_2\tau_4+2(\tau_2^2\tau_4^2)\\+2(R_{2s}\tau_4+R_{4e}\tau_2)C_1\end{bmatrix}\omega^2+1}{R_0C_1\tau_2^2\tau_4^2\omega^5+\begin{bmatrix}R_0(\tau_2^2+\tau_4^2)\\+2(R_{2s}\tau_2^2+R_{4e}\tau_4^2)\end{bmatrix}C_1\omega^3+\begin{bmatrix}[R_0+2(R_{2s}+R_{4e})]C_1\\+(\tau_2+\tau_4)\end{bmatrix}\omega} \tag{11}$$

It can be shown that the requirement $\varphi_H(\omega)<\Phi(\omega)$ is met when:

$$\begin{aligned}&\tau_2\tau_4[2\pi f_cR_0C_1\tau_2\tau_4-2[(R_{2s}\tau_2+R_{4e}\tau_4)C_1-\tau_2\tau_4]]\omega^4\\&+\left[2\pi f_c\begin{bmatrix}R_0(\tau_2^2+\tau_4^2)\\+2(R_{2s}\tau_2^2+R_{4e}\tau_4^2)\end{bmatrix}C_1-\begin{bmatrix}\tau_2\tau_4+2(\tau_2^2+\tau_4^2)+\\2(R_{2s}\tau_4+R_{4e}\tau_2)C_1\end{bmatrix}\right]\omega^2\\&+2\pi f_c[[R_0+2(R_{2s}+R_{4e})]C_1+\tau_2+\tau_4]-1>0\end{aligned} \tag{12}$$

The polynomial represented in eq. 12 is always positive if the coefficient of the highest power of ω is positive and if there is no positive root. All roots must be complex or negative. Whith f_c=0.05Hz, the phase requirement is then satisfied when the input impedance is chosen as:

$$R_{in}>max\left[\frac{20}{\pi}\left(\frac{R_{2s}}{R_{4e}C_{4e}}+\frac{R_{4e}}{R_{2s}C_{2s}}+\frac{1}{C_1}\right)\right] \tag{13}$$

C. Impulse Response requirements

The low frequency criteria for ECG signal reproduction are more precisely defined in terms of the system impulse response: the response to a rectangular pulse x(t) of amplitude V_m and duration T is limited to a maximum offset and a maximum slope. Fig. 4 illustrates the impulse response requirement defined by the European Committee for Electrotechnical Standardisation [8].

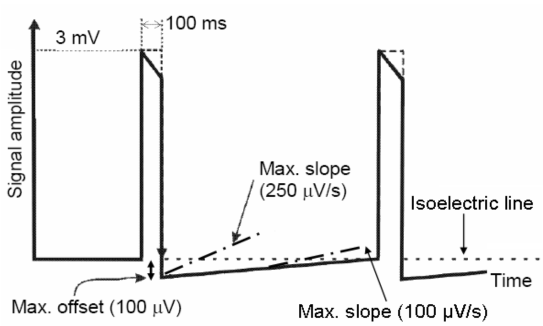

Fig. 4: Impulse response requirements (modified from [8]).

The response y(t) of the skin-electrode-ampliflier network to the pulse x(t) and its derivative y'(t) can expressed as:

$$x(t)=V_m[u(t)-u(t-T)] \quad (16)$$

$$y(t)=V_m R_{in} C_1 \tau_2 \tau_4 \begin{bmatrix} \left(Ae^{-p_0 t}+Be^{-p_1 t}+Ce^{-p_2 t}\right)u(t) \\ -\left(Ae^{-p_0(t-T)}+Be^{-p_1(t-T)}+Ce^{-p_2(t-T)}\right)u(t-T) \end{bmatrix} \quad (17)$$

$$y'(t)=V_m R_{in} C_1 \tau_2 \tau_4 \cdot \begin{bmatrix} \left(p_0 Ae^{-p_0(t-T)}+p_1 Be^{-p_1(t-T)}+p_2 Ce^{-p_2(t-T)}\right)u(t-T) \\ -\left(p_0 Ae^{-p_0 t}+p_1 Be^{-p_1 t}+p_2 Ce^{-p_2 t}\right)u(t) \end{bmatrix} \quad (18)$$

Where u(t) is the Heaviside unit step function.
The terms τ_2, τ_4, p_0, p_1, p_2, A, B and C are functions of the skin-electrode-amplifier network components. The problem consists of finding the minimum value for R_{in} for which the recording system meets the pulse response requirements. A numerical resolution testing the criteria for successive values for R_{in} was implemented in Matlab.

IV. Results and Discussion

Data collected from two hundred and sixty eight measurements of the skin-electrode interface were analyzed using the proposed method. Measurements were taken on seven subjects, using seven different types of dry electrodes, under variable conditions of contact pressure, electrode settling time and current level.

A. Phase response criteria

Fig. 5 shows the frequency response of the skin-electrode interface when eq. (13) is used for R_{in}. For all measurements the input impedance requirement varies from 21 MΩ to 750 MΩ. The maximum value of R_{in} is obtained for: R_{2s}=1.76 MΩ, C_{2s}=0.01 µF, R_{4e}=1.85 MΩ, C_{4e}= 0.1 µF and C_1= 0.33 µF. It can be seen that both magnitude and phase requirements are satisfied in all cases.

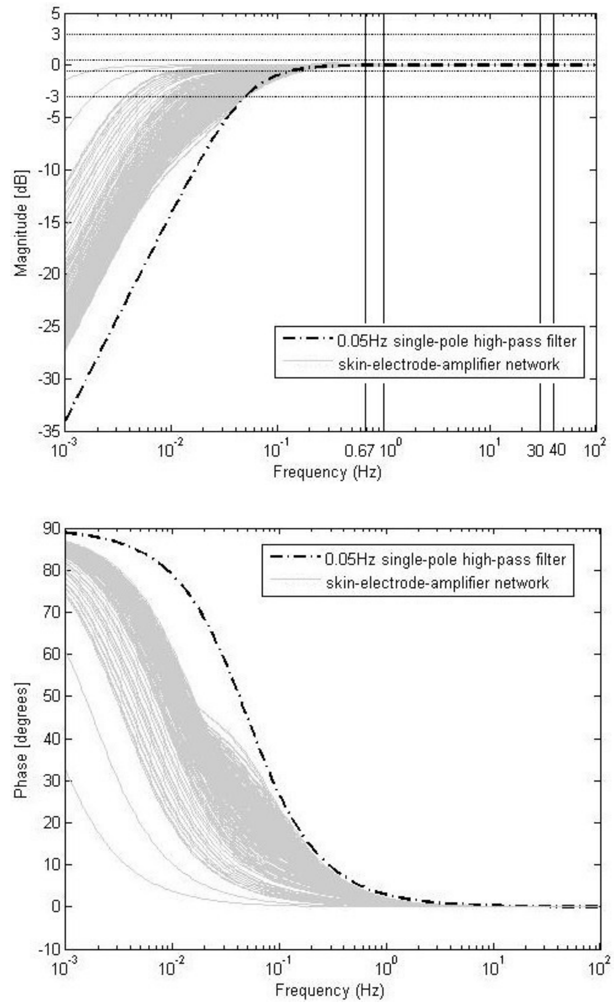

Fig. 5. Amplitude and phase as a function of frequency for 268 measurements of skin-electrode interface compared with a 0.05Hz high-pass filter. The criterion specified in eq. (13) is used for R_{in}.

B. Impulse Response requirements

Results from the analysis of the impulse response for all measurements are presented in Figs. 6 and 7. A rectangular wave of amplitude 300 mV and duration 100 ms is used as input. The response is analyzed over a 2-second period. Fig. 6 shows a plot of the maximum offset produced for a range of input impedance values between 10 kΩ and 10 GΩ. In Fig. 7, the maximum absolute values of the slopes of the responses in a 200ms region following the impulse and outside the region of the impulse are shown over the same range of input impedance values.

With C_1=0.33 µF, the required minimum input impedance varies between 3 MΩ and 1.3 GΩ. These results imply that the impulse response criteria specified by the European Committee for Electrotechnical Standardisation (ECES) require higher values of input impedance than that suggested in eq. (13).

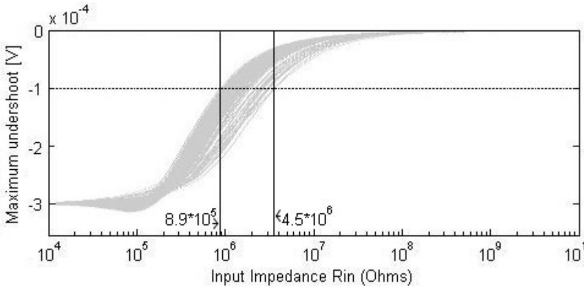

Fig. 6. Maximum undershoot as a function of input impedance for 268 measurements of skin-electrode interface [C_1=0.33μF].

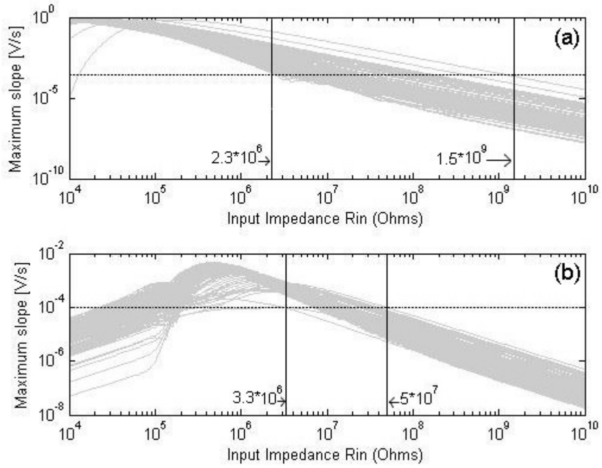

Fig. 7. Maximum slope absolute value in a 200 ms region following the impulse (a) and outside the region of the impulse (b) as a function of input impulse for 268 measurements of skin-electrode interface [C_1=0.33μF].

Tables 1 and 2 compare the values of input impedance suggested by the three criteria used: 0.05Hz single-pole high pass filter (Rin_a), impulse response as specified by the AHA (Rin_b) and impulse response as defined by the ECES (Rin_c).

TABLE I

MAXIMUM INPUT IMPEDANCE RIN AS FUNCTION OF THE CAPACITANCE OF THE DC-BLOCKING CAPACITOR C_1 FOR ALL MEASUREMENTS

C_1 (μF)	0.1	0.22	0.33	1	2.2	3.3
Rin_a (MΩ)	794	759	750	737	733	732
Rin_b (MΩ)	1072	1126	1126	1126	1126	1126
Rin_c (MΩ)	1303	1303	1363	1368	1368	1368

Maximum value Input impedance R_{in} suggested for all 268 measurements as function of the capacitance of C_1 according to three criteria: 0.05Hz single-pole high pass filter (Rin_a), impulse response as specified by the AHA (Rin_b) and impulse response as defined by the ECES (Rin_c).

TABLE II

MAXIMUM INPUT IMPEDANCE RIN AS FUNCTION OF THE CAPACITANCE OF THE DC-BLOCKING CAPACITOR C_1 FOR 99.25% OF MEASUREMENTS

C_1 (μF)	0.1	0.22	0.33	1	2.2	3.3
Rin_a (MΩ)	312	277	268	255	251	250
Rin_b (MΩ)	316	366	385	385	404	404
Rin_c (MΩ)	385	445	445	468	468	468

Maximum value of Input impedance R_{in} suggested for 99.25% of measurements as function of the capacitance of C_1 according to the three criteria used in table 1.

The values of R_{in} are given in both tables for a range of non-electrolytic capacitance values varying from 0.1 μF to 3.3 μF, available in multilayer ceramic forms. Table 1 gives the maximum values of input impedance suggested by all measurements. When two outlining measurements are extracted, the requirements suggested in 99.2% of the data are shown in table 2. Results for both tables show that the value of R_{in} levels out at around a value of C_1=1 μF. As suggested in the expression of R_{in} in eq. (13), with increasing dc-blocking capacitance value, the parameters of the skin-electrode interface become the limiting factors. Furthermore, all results confirm that the criteria specified by the European Committee for Electrotechnical Standardisation require the highest value of input impedance, which is selected as the target design value.

V. CONCLUSION

Measurements of the skin-electrode interface obtained in a previous study have been used as the basis for the design of the front-end amplifier of an ECG recording system using dry electrodes. The performance requirements recommended by the American Heart Association (AHA) and the European Committee for Electrotechnical Standardisation (ECES) for ECG recording systems have served as criteria ensuring the preservation of T-wave and ST segment of the ECG profile. The minimum requirement for the input resistance of the amplifier is determined as 1.3 MΩ over a range of electrodes, measurement conditions and the value of dc-blocking capacitors used. However, 99.25% measurements suggested values of R_{in} under 500 MΩ.

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