The skin's electrical asymmetry

N M Birlea¹, S I Birlea² and V Toşa³

¹ Technical University of Cluj-Napoca, Physics Department, 15 Constantin Daicoviciu, 400020 Cluj-Napoca, Romania

² National University of Ireland, Electrical and Electronic Engineering Department, Galway, Ireland

³ National Institute for Research and Development of Isotopic and Molecular Technologies, 65-103 Donath, 400293 Cluj-Napoca, Romania

E-mail: mbirlea@phys.utcluj.ro

Abstract. We studied the asymmetry of skin response to a constant current pulse (4mA/0.1ms) of positive or negative polarity, followed by a free decay of skin's potential. Negative polarity pulse is related with a lower skin resistance and higher electrical capacity. This behavior corresponds to 2 of the 3 relaxation times found in our skin measurements.

1. Introduction
In order to find the relevant electrical parameters describing the skin condition, we studied the relaxation times of the skin potential in response to a constant current impulse of positive or negative polarity. We believe that the relaxation times are markers of skin's structure or processes.

Bioimpedance spectroscopy has many applications [1] in skin assessment from measuring skin moisture [2], to detect skin cancer [3]. Usually, bioelectrical measurements are performed using sinusoidal currents at several frequencies and the experimental data are fitted with electrical models or empirical formulas. An alternative approach uses square-wave electrical pulses [4] to measure the skin's electrical properties. The method has the advantage of measuring electrical response in a broad range of frequencies and allows a more direct and explicit modality to measure skin characteristics [5].

2. Experimental Method
The electrical properties of human skin were measured using constant current electrical impulses. The measuring system comprises of a signal generator (made in the laboratory) with a 9 V battery as power supply, a bipolar transistor as an open collector current drive, and an oscilloscope (Picoscope 2203) connected to a laptop, which visualizes the potential difference between the electrodes and the current through the electrodes, as shown in figure 1(a). The signal generator supplies an electrical current impulse (width $T = 0.1$ ms, the "ON" period) followed by a pause (1 s, the "OFF" period) when the electrodes cannot receive or transmit current (high impedance status).

The oscilloscope (Picoscope 2203, maximum sampling rate 20 MS/s) displays the potential difference between the two electrodes on channel A, the oscilloscope's "ground" being connected to the common point of the electrode with the 100 Ohm resistance, used for measuring the current on
channel B. The signal on the channel B triggers the data acquisition and the display. Two metallic electrodes (Ag), covered by wet cotton (saline solution), deliver the electrical signal to the skin. The reference electrode has a greater surface (25 cm$^2$) than the active electrode (2 cm$^2$). To avoid influences on the results from sweat, the skin is wiped using ethanol before the measurement, and after 5 minutes the electrodes are attached on the desired place using elastic ribbons. The reference electrode was placed on the middle of the ventral side of the forearm (hairless skin), and the measuring electrode on the forearm close to the wrist. A constant current $I = 4 \text{ mA}$ is injected with the described device for a period of $T = 0.1 \text{ ms}$, then the skin’s potential is recorded. Figure 1(b) shows the oscilloscope traces for the potential difference between the electrodes (upper and middle traces, channel A) and the potential difference on the 100$\Omega$ resistor (lower trace, channel B), generated by an electrical current of 4 mA.

![Diagram](image)

**Figure 1.** (a) Experimental arrangement and (b) oscilloscope traces for the potential difference between the electrodes (upper trace for positive impulse and middle trace for negative impulse) and the potential difference on the 100$\Omega$ resistor (lower trace), generated by an electrical current of 4 mA. Potential difference between electrodes is 10 times greater than that on the scale (scope probe 1/10).
3. Model and data analysis
The electrical signal applied to the skin is an impulse of constant current with the width T, the "ON" period, followed by a pause when the skin can not receive or transmit current, the "OFF" period. The electrical model for the skin we have chosen consists of 3 parallel R<sub>i</sub>C<sub>i</sub> configurations (I = 1, 2, 3) that are all connected in series and a series resistance R<sub>s</sub> (Z = R<sub>s</sub> + ΣR<sub>i</sub>C<sub>i</sub>), as shown in figure 1(a). The solutions of the Kirchhoff equations system for t ∈ [0,T] are:

\[ I_i = I [1–exp(–t/\tau_i)] \]  \hspace{1cm} \text{(1)}

\[ U = IR_s + IR_1[1–exp(–t/\tau_1)] + IR_2[1–exp(–t/\tau_2)] + IR_3[1–exp(–t/\tau_3)] \]  \hspace{1cm} \text{(2)}

where \( \tau_i = R_iC_i \) is the time constant of the i-th loop;
\( I = \) constant current through circuit for the time period [0,T];
\( I_i = \) current trough parallel resistance R<sub>i</sub>;
\( U = \) the potential difference between the two electrodes;
\( U_i = \) the potential difference on R<sub>i</sub> (I<sub>i</sub>R<sub>i</sub>);
\( U_s = \) the potential difference on R<sub>s</sub> (I R<sub>s</sub>).

For \( t > T \), the OFF period, the skin does not receive any electrical current so the potential drop on the series resistance is equal to 0 and we are left with a simple exponential decay of the potential for each R<sub>i</sub>C<sub>i</sub> configuration. For sake of simplicity we adopted the time value \( t = 0 \) at the beginning of the decay, thus the potential difference between the electrodes will be:

\[ U = \Sigma U_i = I \cdot \Sigma R_i[1–exp(–T/\tau_i)] \cdot exp (–t/\tau_i) \]  \hspace{1cm} \text{(3)}

Dividing the potential difference by the excitatory current we obtain the skin response function (dimensionally an impedance)

\[ U/I = \Sigma R_i[1–exp(–T/\tau_i)] \cdot exp (–t/\tau_i) \]  \hspace{1cm} \text{(4)}

We extracted from the measured data only the points corresponding to the free exponential decay of the electrical potential of the skin (\( t > 0 \)). Each time series of the potential difference between the electrodes was divided by the injected current used for measurement. The resulting response function, dimensionally an impedance, presented in figure 2, was fitted with a third order exponential decay function using the Microcal OriginPro8 software package. The results of the numerical analysis are given in table 1.

![Figure 2](image-url)  \text{Figure 2. Response function (free decaying skin potential divided by pulse current 4 mA, an impedance) for positive pulse (upper curve) and negative pulse (lower curve).}

Fitting to multiple exponentials is more difficult than fitting to a single exponential. Because the fitting function is:
the parameter \( y_0 \) must be zero, as imposed by the physics of our problem (at very long time the skin potential vanishes). To avoid the numerical problem instability we begun the nonlinear fitting session by fixing only \( A_1 = 0 \) and \( t_1 \). When the program attains a stable value for fitting parameters we permit \( A_1 \) and \( t_1 \) to vary. The chi-square values were monitored all the time, in order to see if it is necessary to increase or decrease the number of time constants used.

Comparing equation (4) for the response function and the fitting function (5) we can calculate the resistance \( R_i \) and the capacitance \( C_i \) as below and the values are given in table 1:

\[
R_i = A_i / [1 - \exp(-T/t_i)] \text{ and } C_i = t_i/R_i = t_i [1 - \exp(-T/t_i)]/A_i
\] (6)

**Table 1.** Values of skin resistances and capacitances corresponding to the amplitudes and time constants resulted from the fitting procedure.

| I (mA) | \( A_1 \) (Ω) | \( t_1 \) (µs) | \( R_1 \) (Ω) | \( C_1 \) (nF) | \( A_2 \) (Ω) | \( t_2 \) (µs) | \( R_2 \) (Ω) | \( C_2 \) (nF) | \( A_3 \) (Ω) | \( t_3 \) (µs) | \( R_3 \) (Ω) | \( C_3 \) (nF) |
|--------|---------------|----------------|--------------|--------------|---------------|----------------|--------------|--------------|---------------|----------------|--------------|--------------|
| +4     | 296           | 28.0           | 304.6        | 91.9         | 800           | 177.9         | 1403         | 126.7        | 2303          | 2828          | 66287        | 42.7         |
| -4     | 238           | 26.9           | 243.9        | 110.3        | 832           | 136           | 1598         | 85.1         | 1967          | 1309          | 26744        | 73.5         |

4. Discussion and conclusion

Biological materials have unusual dielectric spectra with large values of time constants and static polarization. These complex effects result from physical processes at the solid-liquid interface of a porous system [6]. Identifying the characteristic electrical signatures of these physical mechanisms is important for the correct interpretation of experimental data. The chosen theoretical model has 3 time constants, electrical equivalent of the three RC groups connected in series. This choice was made because the electrical current flows successively across the different layers of the skin. This specific type of measurement, with constant current excitation, offers the advantage of a simple link between the measured data and the model parameters.

From table 1 we can see that the polarity of the excitatory current has a marked effect on the skin's electrical response. Because the epidermal stratum corneum is credited with the largest value of the resistance among skin layers, it is natural to consider that parameters \( t_2, R_3, C_3 \) belong to it. Here the parallel resistance \( R_3 \) for negative polarity pulse is 2.48 times smaller than that for positive polarity pulse, but capacity for negative pulse is larger than that for positive pulse.

Interestingly, the second set of parameters \( t_2, R_2, C_2 \) has an opposite behavior, the resistance increases and the capacitance decreases for negative pulse. We believe that this set of parameters belongs to a granular layer of keratinized cells (stratum granulosum, stratum lucidum) because of the large value of resistance. For the shortest relaxation time \( t_1 \), parameters \( R_1, C_1 \) have a similar behavior with those in stratum corneum, resistance decreases and capacitance increases for negative pulse, but with much lower amplitude.

Our measurements show the presence of 3 relaxation times in the free decay of skin electrical potential after a constant current pulse. The electrical discharge of skin charge is faster after a negative pulse than after a positive one.

References
[1] Grimnes S and Martinsen Ø G 2000 *Bioimpedance & Bioelectricity Basics* (London: Academic Press)
[2] Martinsen Ø G, Grimnes S and Karlsen J 1995 *Skin PharmacoL* 8 237-45
[3] Åberg P 2004 *Skin cancer as seen by electrical impedance* (PhD thesis) (Stockholm: Karolinska Institutet)
[4] van Boxtel A 1977 *Med. & Biol. Eng. & Comput.* 15 679-57
[5] Bârlea N M, Bârlea S I and Culea E 2008 *Rom. J. Biophys.* 18 87-98
[6] Chelidze T L and Gueguen Y 1999 *Geophys. J. Int.* 137 1-15.