MAXWELL-WAGNER EFFECT ON THE HUMAN SKIN

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Abstract. It is very important to assess the skin condition for medical or cosmetical reasons. Bioimpedance Spectroscopy studies the frequency dependence of the electrical impedance of the biological material; the most interesting application would be the skin cancer detection. We studied electrical characteristics of the human skin, R_S (series resistance), R_P (parallel resistance) and C (capacitance), measuring with electrical impulses. The signal consists of electrical current impulses (width $T' = 0.05 \div 10$ ms, the "ON" period) followed by a pause (width $T'' = 1 \div 100$ ms, the "OFF" period) when the electrodes cannot receive or transmit current (high impedance status). The potential difference and the current between electrodes are displayed with the oscilloscope. The method allows measuring the characteristics of the skin in a more direct and explicit fashion, and it makes possible to discriminate more phenomena occurring into the skin. The Maxwell-Wagner effect, an interfacial relaxation process, generates minimum two time constants for the skin. The longer time constant could be modulated by proper stimulation. It is important to note that the measuring current could be also the stimulating current and provides an easy way to avoid electrochemical burns, even before irritation appearance in chronic electric stimulation or iontophoresis.

Key words: skin, bioimpedance spectroscopy, pulsed iontophoresis, electrostimulation.

INTRODUCTION

The skin is the largest organ of the body and it protects the organism from the environmental factors (physical, chemical and microbial). To perform this role, epidermal keratinocytes undergo a differentiation program that results in the expression of structural proteins that function as a protective barrier. A defective barrier has its origin in a disturbed skin physiology. So, it is very important to assess the skin condition for medical or cosmetical reasons.

The measurements of the skin electrical impedance are a noninvasive and fast method for assessing the skin. The electrical impedance of the skin can be used to measure skin moisture [5], to monitor skin irritations and allergic reactions [7], to detect skin cancer [1], to investigate the transdermal drug delivery [2, 4], to

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detect skin burns induced by surface electrodes in transdermal electrical stimulation [8] and others.

The electrical properties of the skin can be represented by an electrical model that consists of an ohmic resistance R_P with a capacitor C in parallel and a series resistance R_S (Figure 1). These components show the ability of the skin to store (and release) the electrical energy (the capacitive component) and to dissipate the electrical energy (the resistive components).

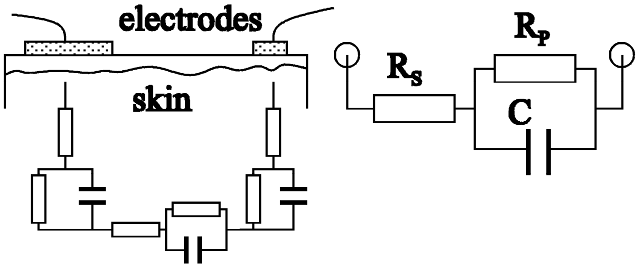


Fig. 1. A simplified equivalent circuit describing the electrodermal system.

Usually, the skin impedance is measured with a sinusoidal signal, at one or more frequencies, obtaining an impedance modulus and a phase angle for every frequency. Various electrical models can support the results of the measurement. To choose an impedance model that fits to the measured data is to some degree arbitrary, because the electrical model is an electric circuit constituting a substitute for the real system under investigation, as an equivalent circuit. The values of the electric components of the skin are important parameters, which describe the "normality" of the skin.

METHOD

We studied electrical characteristics of the human skin, measured with electrical impulses. Using a pulsed current or voltage source to measure skin impedance we can reduce from the arbitrariness of the chosen electrical model. This method is very useful for quickly determining the three global electrical parameters of the skin: R_S (series resistance), R_P (parallel resistance) and C (capacitance).

The measuring system, shown in Figure 2, has a signal generator (made in the laboratory) with batteries as power supply, and a bipolar transistor as an open collector current drive, and an oscilloscope, which visualizes the potential difference and the current between electrodes. The signal from the generator consists in electrical current impulses (width T = 0.05÷10 ms, the "ON" period) followed by a pause (width T'' = 1÷100 ms, the "OFF" period) when the electrodes cannot receive or transmit current (high impedance status).

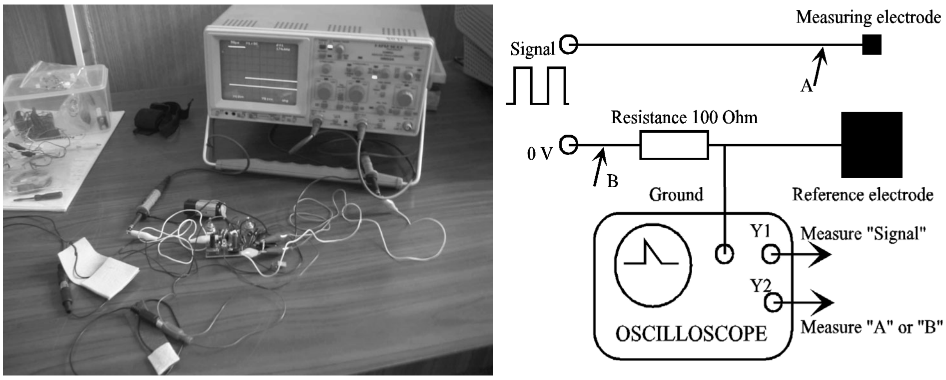


Fig. 2. The experimental arrangement.

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 (4 cm^2). To avoid influences on the results from the 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 oscilloscope (Hameg HM504, 50MHz) displays the potential difference between the two electrodes, oscilloscope's "ground" to the reference electrode, and "input" to the active electrode (channel Y2) and the channel Y1 shows the command signal from the signal generator and is used to trigger the display. The channel Y1 could measure the current injected through the skin, using a 100 Ohms resistance. This resistance could be eliminated after setting the current.

MODEL

The electrical signal applied to the skin consists in 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 (high impedance status), the "OFF" period during T'' seconds. The signal has the period $T = T' + T''$. The Kirchhoff equations for the node and for the loop formed by R_P and C of the circuit shown in Figure 3 are:

$$I = I_P + I_C \tag{1}$$

$$R_P \cdot I_P = \int \frac{I_C}{C} \mathrm{d}t \quad \text{or} \quad R_P \cdot \frac{\mathrm{d}I_P}{\mathrm{d}t} = \frac{I_C}{C} \tag{2}$$

where: I = constant current through circuit for time period $[0,T']$; I_P = current through parallel resistance R_P; I_C = current through capacitor.

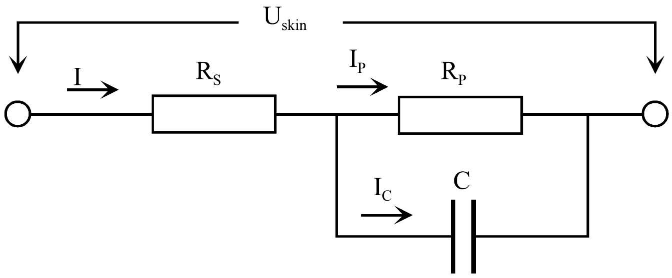


Fig. 3. The current flow in the analyzed circuit.

If we apply only a single impulse, the solutions of the equations are:

$$I_P(t) = I(1 - e^{-t/\tau}) \tag{3}$$

$$I_C(t) = Ie^{-t/\tau} \tag{4}$$

where

$$\tau = R_P C \tag{5}$$

is the time constant of the skin circuit.

For the "ON" period, the potential difference between the electrodes is:

$$U_{skin}(t) = IR_S + I_P R_P = I(R_S + R_P - R_P e^{-t/\tau}) \tag{6}$$

For the "OFF" period, the applied current "I" vanishes and the potential difference between electrodes remains that of the capacity C which is discharging on the resistance R_P:

$$U_{skin}(t) = IR_P(1 - e^{-T'/\tau})e^{-(t-T')/\tau} \text{ for } t > T' \tag{7}$$

If we apply periodically impulses of width T', with period $T' + T''$, then the equation for the loop formed by R_P and C becomes:

$$R_P I_P = U_L + \int \frac{I_C}{C} dt \tag{8}$$

where U_L is the potential difference across the capacitor C at the end of the OFF period (discharging period), created by the residual electric charge from the capacitor. With the equations (1) and (8), the solutions are:

$$I_{\mathrm{P}}(t) = I(1 - \mathrm{e}^{-t/\tau}) + \frac{U_{\mathrm{L}}}{R_{\mathrm{P}}}\mathrm{e}^{-t/\tau} \tag{9}$$

$$I_{\mathrm{C}}(t) = I - I_{\mathrm{P}} = (I - \frac{U_{\mathrm{L}}}{R_{\mathrm{P}}})\mathrm{e}^{-t/\tau} \tag{10}$$

Using equation (9), the voltage across the capacity is U_{H} at the end of the ON period (charging period):

$$U_{\mathrm{H}} = R_{\mathrm{P}} I_{\mathrm{P}}(T') = R_{\mathrm{P}} I(1 - \mathrm{e}^{-T'/\tau}) + U_{\mathrm{L}}\mathrm{e}^{-T'/\tau} \tag{11}$$

and U_{L} at the end of the OFF period (discharging period), using equation (7):

$$U_{\mathrm{L}} = U_{\mathrm{H}}\mathrm{e}^{-T''/\tau} \tag{12}$$

From relations (11) and (12) we found:

$$U_{\mathrm{L}} = \frac{R_{\mathrm{P}} I(1 - \mathrm{e}^{-T'/\tau})\mathrm{e}^{-T''/\tau}}{1 - \mathrm{e}^{-(T'+T'')/\tau}} \tag{13}$$

$$U_{\mathrm{H}} = U_{\mathrm{L}}\mathrm{e}^{T''/\tau} = \frac{R_{\mathrm{P}} I(1 - \mathrm{e}^{-T'/\tau})}{1 - \mathrm{e}^{-(T'+T'')/\tau}} \tag{14}$$

Hence, the skin potential for the ON period will be:

$$U_{\mathrm{skin}}(t) = IR_{\mathrm{S}} + I_{\mathrm{P}} R_{\mathrm{P}} = IR_{\mathrm{S}} + IR_{\mathrm{P}}(1 - \mathrm{e}^{-t/\tau}) + U_{\mathrm{L}}\mathrm{e}^{-t/\tau} \tag{15}$$

and for the OFF period the skin potential becomes:

$$U_{\mathrm{skin}}(t) = U_{\mathrm{H}}\mathrm{e}^{-(t-T')/\tau} \text{ for } T'' > t > T' \tag{16}$$

From these equations we can emphasize some practical aspects useful in the experiment. For the OFF period, time evolution of the skin potential is described by equation (16) and for any two moments $T' < t_1 < t_2 < T''$ we have between skin potentials U_1 and U_2 the relation:

$$\ln(U_1 / U_2) = \frac{t_2 - t_1}{\tau} \tag{17}$$

that permits to find the time constant τ:

$$\tau = R_{\mathrm{P}} C = \frac{t_2 - t_1}{\ln(U_1 / U_2)} \tag{18}$$

For the ON period, just in the very beginning at $t = 0$ the potential on the skin has a vertical increase from $U_{\mathrm{skin}} = U_{\mathrm{L}}$ to $U_{\mathrm{skin}} = U_{\mathrm{L}} + I\cdot R_{\mathrm{S}}$ and at the very end of the ON period, at $t = T'$, appears a vertical decrease of the skin potential from $U_{\mathrm{skin}} = U_{\mathrm{H}} + I\cdot R_{\mathrm{S}}$ to $U_{\mathrm{skin}} = U_{\mathrm{H}}$:

$$\Delta U_{\text{skin}} = IR_{\text{S}} \text{ at } t = 0 \tag{19}$$

$$\Delta U_{\text{skin}} = -IR_{\text{S}} \text{ at } t = T' \tag{20}$$

because of the appearance or of the disappearance of the injected current and because the capacitor appears like a short-circuit for the fast variations of potential. These equations give us the possibility to find the series resistance R_{S}.

If we choose a large period $T' >> \tau$ then at the end of the ON period we have from equation (15):

$$U_{\text{skin}} = I(R_{\text{S}} + R_{\text{P}}) \tag{21}$$

a useful relation for determining the parallel resistance R_{P}.

If we choose a very short period $T' << \tau$, then the evolution in time of the skin potential, equation (15), becomes:

$$U_{\text{skin}}(t) = IR_{\text{S}} + U_{\text{L}} + \left(\frac{I}{C} - \frac{U_{\text{L}}}{R_{\text{P}}C}\right)t \tag{22}$$

For the case when the OFF period is very long $T'' >> \tau$, then $I >> U_{\text{L}}/R_{\text{P}}$ because in relation (13) the term $e^{-T''/\tau}$ is very small (0.0067 for $T''/\tau = 5$) and the term $(1 - e^{-T'/\tau})$ is also small (0.18) as compared with its maximal values that are 1. Then the relation (22) becomes even simpler:

$$U_{\text{skin}}(t) = IR_{\text{S}} + U_{\text{L}} + \frac{It}{C} \tag{23}$$

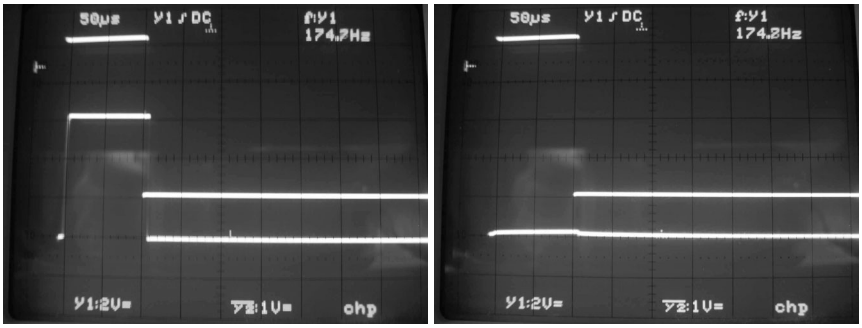
and permits direct calculation of the capacity from the linear portion of the time evolution of the skin potential:

$$C = I\frac{\text{d}t}{\text{d}U_{\text{skin}}} \tag{24}$$

EXPERIMENTAL RESULTS

A constant current $I = 3$ mA is injected for $T' = 0.1$ ms, with the described device. In Figure 4a are the oscilloscope traces for the current injected in a resistor of 1000 Ohm (lower trace, Y2 channel) and the command signal (upper trace, Y1 channel). In Figure 4b is the oscilloscope trace for the 2 wet electrodes making contact between them (short-circuit), when the same current is injected. This gives us the magnitude of the potential drop on the electrodes. The “zero” trace for the Y1 channel is with 1 division above the “zero” level of the Y2 channel, as seen in

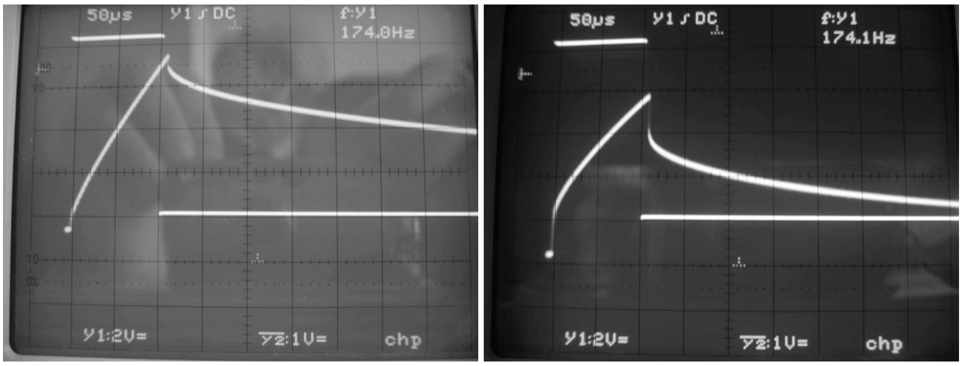
Figure 4, and remains the same throughout the experiment. The signal on Y2 channel has a small delay from the experimental device, for seeing of the U_L, residual tension on the capacitor.



a) b)

Fig. 4. Oscilloscope traces for: a) the current injected in 1000 Ohm resistor, and b) the potential difference between the two electrodes in short-circuit.

With the measuring parameters as in the previous situation, we have placed the reference electrode (25 cm^2) on the middle of the ventral side of the forearm (hairless skin), and the measuring electrode (4 cm^2) on the forearm near the wrist or on the head, between eyebrows of the human subject. The potential difference between the electrodes is presented in Figure 5.



a) b)

Fig. 5. The potential difference between the two electrodes when: a) the measuring electrode is on the forearm, and b) the measuring electrode is between eyebrows.

Using equations (19) and (24) we estimate the series resistance R_S and the capacity C:

forearm: R_S = 0.25 V / 3 mA = 83 Ohm, C = 3 mA·0.1 ms/3.5 V = 86 nF;

eyebrows: $R_S = 1$ V / 3 mA = 333 Ohm, $C = 3$ mA·0.1 ms/2.7 V = 111 nF.

For the case when the same current $I = 3$ mA is injected for the same period $T' = 0.1$ms in an electric circuit with $R_S = 100$ Ohm, $R_P = 22$ kOhm and $C = 100$ nF, Figure 6 shows the oscilloscope trace of the potential drop.

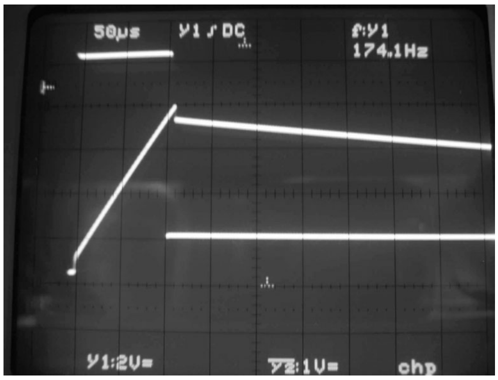


Fig. 6. Oscilloscope trace for the potential difference on the dummy circuit ($R_S = 100$ Ohm, $R_P = 22$ kOhm, $C = 100$ nF) for $I = 3$ mA, $T' = 0.1$ ms, $T' + T'' = 5.74$ ms (174.1 Hz).

MAXWELL-WAGNER MECHANISM

Comparing the traces in Figure 5, corresponding to the measurements on the skin, with the trace in Figure 6, corresponding to the measurements on the equivalent circuit, we see a more complex behavior of the skin on the OFF period (capacitor discharge) than that of the equivalent circuit. For this reason we calculate the time constant for 3 distinct time intervals: (T', T' + 0.1 ms), (T' + 0.1 ms, T' + 0.3 ms), (T' + 0.3 ms, T' + T''), from equation (18) and estimate the parallel resistance R_P in Table 1.

Table 1

Time constants for various time intervals after the current is interrupted

Time interval	$\tau_{forearm}$ (ms)	$R_{P, forearm}$ (kΩ)	$\tau_{eyebrows}$ (ms)	$R_{P, eyebrows}$ (kΩ)
T', T'+0.1ms	0.398	4.6	0.219	1.97
T'+0.1ms, T'+0.3ms	1.06	12.3	0.527	4.75
T'+0.3ms, T''	3.82	44.4	2.12	19.1

This behavior is due to the fact that the tissue is a highly inhomogeneous material and interfacial processes play an important role in the electrical properties of tissue. The Maxwell-Wagner effect is an interfacial relaxation process occurring in all systems where the electric current must pass an interface between two different dielectrics. This effect is often illustrated by means of a plate capacitor with two different homogeneous materials inserted as slabs in series between the capacitor plates. The system capacitance values converge both at low and high frequencies, the capacitance at low frequency being higher than that at high frequency. Thus with the parallel model of two slabs in series, we have a classical Debye dispersion even without any dipole relaxation in the dielectric. The dispersion is due to a conductance in parallel with a capacitance for each dielectric, so that the interface can be charged by the conductivity. For the simple case of 2 slabs, using equations (5) and (6) from appendix, we have:

$$C = \frac{\operatorname{Im} Y}{\omega} = \frac{1}{R_1 + R_2} \frac{\tau_1 + \tau_2 - \tau + \omega^2 \tau_1 \tau_2 \tau}{1 + \omega^2 \tau^2} \tag{25}$$

$$\frac{1}{R} = \operatorname{Re} Y = \frac{1}{R_1 + R_2} \frac{1 + \omega^2 [\tau(\tau_1 + \tau_2) - \tau_1 \tau_2]}{1 + \omega^2 \tau^2} \tag{26}$$

where

$$\tau = \frac{R_1 \tau_2 + R_2 \tau_1}{R_1 + R_2} = \frac{R_1 R_2 (C_1 + C_2)}{R_1 + R_2} \tag{27}$$

is the hole system time constant and if $\tau_1 < \tau_2$, then $\tau_1 < \tau < \tau_2$.

At low frequencies ($\omega \to 0$, $\omega\tau_i << 1$), corresponding to a long time interval in time domain, the capacitance and the resistance of the system are:

$$C_{\mathrm{L}} = \frac{C_1 R_1^2 + C_2 R_2^2}{(R_1 + R_2)^2} \text{ and } R_L = R_1 + R_2 \tag{28}$$

At high frequencies ($\omega \to \infty$, $\omega\tau_i >> 1$), corresponding to a short time interval in time domain near the transition of current, the capacitance and the resistance of the system are:

$$C_{\mathrm{H}} = \frac{C_1 C_2}{C_1 + C_2} \text{ and } R_{\mathrm{H}} = \frac{R_1 R_2 (C_1 + C_2)^2}{R_1 C_1^2 + R_2 C_2^2} \tag{29}$$

After some simple algebraic manipulation we find:

$$R_{\mathrm{L}} > R_{\mathrm{H}} \text{ and } C_{\mathrm{L}} > C_{\mathrm{H}} \tag{30}$$

this means that at low frequencies resistivity and permittivity are greater than resistivity and permittivity at high frequencies.

The measurements we have made allow us to say that we have minimum two time constants driving the behavior of the skin. With proper stimulation we were able to modify the longer time constant.

In a prospective experiment we stimulate with impulses of 10 mA, width 0.05 ms, 170 Hz, a dry measuring electrode (1 cm^2 silver) and a wet reference electrode (25 cm^2). After 15 minutes of stimulation, the dry electrode being negative, the discharge curve of the OFF period became steeper, the time constant is shorter, and the subject has a stinging sensation, which increases as the time constant becomes shorter. Changing the polarity of the small electrode (positive), the time constant increases in few seconds and the stinging sensation disappears. The maximum potential on the skin was 60 V and the skin color did not change during or after the stimulation.

Also, during the experiment, it seems the ON period trace did not change their aspect. This indicates that the electrical capacity of the skin is not affected, but the parallel resistance is strongly modified.

This phenomenon seems to be related with the opening of the gap junctions between epithelial cells [6]. The pH of the skin under the electrode could play a role, but it is unclear why the first modification is so slow and the recovery is so rapid.

DISCUSSION AND CONCLUSION

The measured values of the electrical components of the skin emphasize that the series resistance (~100 Ohms) is many times smaller than the parallel resistance (~kOhms). The value of the series resistance is useful to establish the output voltage for electric stimulators, taking into account that the output is usually current limited and the pulse length is between 0.1 ms and 0.5 ms. These values are associated with the tissues near the measuring electrode (4 cm^2), because the reference electrode is many times larger (25 cm^2) and its impedance is negligible.

The proposed method for the measurement of skin electrical properties allows the measurement of the characteristic resistances R_S, R_P and the capacitance C of the skin in a more direct and explicit fashion. It makes evident the existence of the skin capacitance, which has a parallel resistance across it.

Our method provides an easy way to avoid such an event like electrochemical burn, which could appear in chronic electric stimulation or iontophoresis. With a better experimental arrangement (digital high rate sampling oscilloscope) and a more sophisticated theory [3] it is possible to discriminate more phenomena occurring into the skin.

REFERENCES

1. ÅBERG, P., *Skin cancer as seen by electrical impedance* (PhD thesis), Karolinska Institutet, Stockholm, Sweden, 2004.
2. CHIZMADZHEV, Y.A., A.V. INDENBOM, P.I. KUZMIN, S.V. GALICHENKO, J.C. WEAVER, R.O. POTTS, Electrical properties of skin at moderate voltages: contribution of appendageal macropores, *Biophys. J.*, 1998, **74,** 843–856.

3. FELDMAN, YU., I. ERMOLINA, Y. HAYASHI, Time Domain Dielectric Spectroscopy Study of Biological Systems (invited paper), *IEEE Transactions on Dielectrics and EI*, 2003, **10**(5) 728–775.
4. GRIMNES, S., Skin impedance and electro-osmosis in the human epidermis, *Med. Biol. Eng. Comput.*, 1983, **21,** 739–749.
5. MARTINSEN, Ø.G., S. GRIMNES, J. KARLSEN, Electrical methods for skin moisture assessment, *Skin Pharmacol*., 1995, **8** (5), 237–245.
6. MARTINSEN, Ø.G., S. GRIMNES, H.P. SCHWAN, Interface phenomena and dielectric properties of biological tissue, in: *Encyclopedia of Surface and Colloid Science*, Marcel Dekker, Inc., 2002, pp. 2643−2652.
7. NYREN M, N. KUZMINA, L. EMTESTAM, Electrical impedance as a potential tool to distinguish between allergic and irritant contact dermatitis, *J. Am. Acad. Dermatol.*, 2003, **48** (3), 394-400.
8. PATRICIU, A., K. YOSHIDA, T.P. DEMONTE, M.L.G. JOY, Detecting skin burns induced by surface electrodes, in: *Engineering in Medicine and Biology Society, 2001. Proceedings of the 23rd Annual International Conference of the IEEE*, vol. 3, 2001, pp. 3129–3131.

APPENDIX: MAXWELL-WAGNER EQUATIONS

Each slab of tissue has a resistance R_i in parallel with a capacitance C_i. The resultant impedance of the slab is:

$$Z_i = \frac{R_i}{1 + j\omega\, C_i\, R_i} = \frac{R_i}{1+\omega^2\tau_i^2} - \frac{j\omega\tau_i R_i}{1+\omega^2\tau_i^2} \tag{1}$$

where ω is angular frequency and "$\tau_i = R_i{\cdot}C_i = \varepsilon_i{\cdot}\rho_i$" is the time constant of the slab which depends only on the electric material properties: permittivity, ε_I, and resistivity, ρ_I, of the slab, and has no dependence on geometrical dimensions. The resultant impedance of 2 or more slabs in series is:

$$Z = \sum_i Z_i = \sum_i \frac{R_i}{1+\omega^2\tau_i^2} - j\omega \sum_i \frac{\tau_i R_i}{1+\omega^2\tau_i^2} \tag{2}$$

and the corresponding admittance is:

$$Y = \frac{1}{Z} = \frac{1}{\sum_i \frac{R_i}{1+\omega^2\tau_i^2} - j\omega \sum_i \frac{\tau_i R_i}{1+\omega^2\tau_i^2}} \tag{3}$$

with the rationalized form of:

$$Y = \frac{\sum_i \frac{R_i}{1+\omega^2\tau_i^2} + j\omega \sum_i \frac{\tau_i R_i}{1+\omega^2\tau_i^2}}{\left(\sum_i \frac{R_i}{1+\omega^2\tau_i^2}\right)^2 + \omega^2 \left(\sum_i \frac{\tau_i R_i}{1+\omega^2\tau_i^2}\right)^2} \tag{4}$$

Because $Y = \mathrm{j}\omega C + 1/R$, the equivalent capacity $C = \mathrm{Im}Y/\omega$ and the equivalent conductance $1/R = \mathrm{Re}Y$ are:

$$C = \frac{\mathrm{Im}\,Y}{\omega} = \frac{\sum_i \frac{\tau_i R_i}{1+\omega^2\tau_i^2}}{\left(\sum_i \frac{R_i}{1+\omega^2\tau_i^2}\right)^2 + \omega^2\left(\sum_i \frac{\tau_i R_i}{1+\omega^2\tau_i^2}\right)^2} \tag{5}$$

$$\frac{1}{R} = \mathrm{Re}\,Y = \frac{\sum_i \frac{R_i}{1+\omega^2\tau_i^2}}{\left(\sum_i \frac{R_i}{1+\omega^2\tau_i^2}\right)^2 + \omega^2\left(\sum_i \frac{\tau_i R_i}{1+\omega^2\tau_i^2}\right)^2} \tag{6}$$