Characterization of the mechanical behavior of human skin by means of impedance spectroscopy

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Abstract. There is increased interest for the use of impedance spectroscopy to measure skin dielectric properties in vivo. The aim of such measurements can be either to evaluate the hydration state of the skin, to detect diseased states such as skin cancer, to follow the progress of transdermal drug delivery, or simply to gather data on skin tissue impedance to be used in theoretical studies. However, obtaining reliable data can be difficult. Namely, skin is a highly nonhomogeneous multi-layered structure whose composition and dimensions differ depending on the location on the body and interindividual variations. Also, impedance measurements on skin are accompanied by a number of artefacts. We performed a series of impedance measurements using an Agilent/HP 4284A precision LCR meter with parallel plate electrodes pressed on the skin, at different locations on the body. We observed substantial impedance changes over the course of the measurement. These changes can be mainly attributed to skin deformation caused by the electrodes pressing against skin. The analysis showed that skin mechanical properties and layer thicknesses can be inferred from these temporal changes. Such data on mechanical properties of skin tissue give valuable extra information, crucial for successful estimation of the impedance of different skin layers.

1. Introduction
There is increased interest for the study of different physico-chemical properties of human skin in vivo. These properties, as well as their changes, reflect the skin structure and functions, which can be used in dermatology, cosmetology, pharmaceutical sciences and oncology. We can evaluate the hydration state of the skin, its response to a specific treatment, detect diseased states such as skin cancer, follow the progress of transdermal drug delivery, and assess modifications caused by aging or external assault [1], [2]. The bulk properties of biological materials can also be used in theoretical studies, studying the effects of electromagnetic fields on cells and tissues by means of numerical modeling [3], [4]. These properties dictate the current densities and pathways that result from an applied stimulus and are thus very important in the analysis of a wide range of biomedical applications. To analyze the response of a tissue to electric current, we need data on the conductivities (when studying steady-state response) and relative permittivities (when alternating current is used or when studying transients of the modeled system) of the tissues or organs.
2. Theory
Obtaining reliable data on the electrical properties of skin can be difficult. Namely, skin is a highly nonhomogeneous multi-layered structure whose composition and dimensions differ depending on the location on the body and interindividual variations. Generally, skin consists of three main layers: the epidermis, dermis, and subcutaneous tissue. The epidermis is composed of more sub-layers, but the one that defines its electrical properties the most is the outermost layer, the stratum corneum, composed of dead, flat skin cells that shed about every two weeks. Although very thin (typically around 20 μm), it contributes significantly to the electrical properties of the skin. Its high resistivity makes skin one of the most resistive tissues in the human body. Deeper layers, including the rest of the epidermis (important in the immune response), the dermis (which gives firmness and elasticity) and the subcutaneous tissue (fat, connective tissue, larger blood vessels and nerves), all have much lower resistivities. The impedance of skin is thus dominated by the stratum corneum even though this layer is very thin [5].

For any theoretical study on skin, this layered structure has to be taken into account. However, little data exists on the electrical properties of the separate skin layers. The contributions of different skin layers towards skin impedance can only be estimated. Especially in the low frequency range (under 10 kHz), the impedance of skin is dominated by the stratum corneum. Studies show that for frequencies under 10 kHz the share of stratum corneum in the total impedance of skin is around 50%, but at 100 kHz drops to around 10% [6].

On the other hand, the mechanical properties of skin show a similar layer-dependence. The outermost stratum corneum is very firm (its hardness is comparable to glass), underneath is the less rigid viable epidermis, while the major mechanical component is the dermis - the elastic part of the skin. When skin is submitted to sustained stress, its mechanical response can be divided into three phases: i) the immediate, purely elastic phase, ii) the visco-elastic phase of variable creep, and iii) the entirely viscous phase of constant creep (see Figure 1) [7].

![Figure 1. Skin deformation versus time for constant applied stress. Phase I: immediate, elastic deformation, phase II: visco-elastic deformation, phase III: viscous deformation](image)

3. Materials and methods
Impedance measurements on skin were performed by means of precision LCR meter HP4284A in the 20 Hz to 1 MHz measurement frequency range. Special parallel plate electrodes were designed that allowed for easy changing of the distance between the electrodes. The plates were 1 mm thick and 1 cm wide and were made of stainless steel. They were pressed perpendicularly against the skin for the duration of the measurement. Also, as the pressure on electrodes influences the measurement, a special
housing with spring-loaded electrodes was designed to keep constant pressure during the measurements. We analyzed the acquired impedance data in terms of an equivalent parallel resistance-capacitance impedance model. The measurements were done on 10 volunteers, both male and female, aged 23-67, on five different locations on the body.

4. Results
The focus of our measurements was the connection between the mechanical properties of tissue and its impedance. Namely, in all instances, parallel capacitance was rising with time for the course of the measurement, faster at the beginning, slowing down over time, showing a transient phenomenon. Figure 2 shows capacitance over time, measured at 1 kHz on volar forearm for 450 seconds, for two subjects, males, aged 67 and 26.

If we compare the theoretical mechanical response (Figure 1) with the changes in capacitance over time due to mechanical deformation under plate electrodes (Figure 2), we observe a similar time dependent curve. Unfortunately, with our measuring system we didn’t record the impedance in the first few seconds after the fixation of the electrodes, where the fast elastic phase of the skin mechanical deformation takes place. Biologically speaking, this elastic phase is dictated by the straightening of the naturally furrowed stratum corneum, and by the dermal elastic network. In the visco-elastic phase, the elastic fibers are stretched and collagen network elongated, however, this is dampened by the viscosity of interstitial ground substance (proteoglycans), difficult flow of liquids in the tissue, friction between large molecules. Skin viscosity is decreased after the age of 60, which means that the time constant of the visco-elastic creep will be lower as well.

Looking at capacitance over time during the visco-elastic and viscous phase (Figure 2), we observe distinct differences between subjects. For skin of younger subjects, the ratio between the starting and the final value of the conductance seems to be consistently lower than in older subjects (due to limited space, not all data are shown, but the results are consistent for all body locations), and the time constant seems to be higher. Also, the skin of young smokers behaves closer to aged skin. These results indicate that this measured capacitance over time may reflect mechanical properties of skin. Namely, in a mechanical creep test, higher time constant also means younger skin (time constant of the visco-elastic phase is a direct measure of viscosity), and lower ratio between the starting and the final value of the visco-elastic deformation means higher electrode penetration depth, which is also a feature of younger skin. The absolute value of the capacitance is higher in older subjects, which is probably due to the lower hydration and thinner skin [7].

Figure 2. The change in capacitance with time, at 250 Hz, 1 kHz and 1 MHz on volar forearm. Data for two different subjects are shown here: Person 1: male, age 67, Person 2: male, age 26.
In the paper by Yamamoto and Yamamoto [5], the tape stripping of the stratum corneum had almost no effect on the parallel capacitance of the skin. The stratum corneum plays only minor role in the total skin capacitance, which is dominated by deeper tissues, at any frequency. Thus the impedance measurements may have potential in measuring the skin’s mechanical properties. Changes of capacitance over time may not be due only to the moistening of the stratum corneum because of sweat accumulation, but due to mechanical deformation of deeper, softer layers.

5. Conclusion

We measured skin impedance in the frequency range from 20 Hz to 1 MHz, with parallel plate electrodes, pressed against the skin. The acquired impedance data were analyzed in terms of an equivalent parallel resistance-capacitance impedance model. We noticed similarity between the theoretical mechanical temporal response of skin subjected to constant pressure and the measured capacitance over time caused by mechanical deformation of skin during the measurement. Differences in mechanical behavior of skin of different subjects, inferred from impedance measurements were in good agreement with their biological background (in terms of age and lifestyle).

These were only preliminary measurements, and several limitations of the measurement system were discovered. First, the measurement should start at the onset of force, i.e. immediately after the fixation of the electrodes, in order to record the elastic phase of the mechanical deformation. Also, temporal spacing between consecutive measurements should be decreased, especially for the duration of the elastic phase. Also, it would be beneficial to be able to change and measure the pressure under the electrodes, as well as the indentation.

Our next step will be combining our impedance measurement with purely mechanical, suction device testing of the skin of different subjects. Our aim is to check for consistency in the agreement between the impedance and the mechanical method for measuring the mechanical response of skin. Such measurements can be useful for the estimation of skin mechanical properties, to evaluate the state of the skin (aging, chemical assault, diseased state) or its response to a specific treatment. Also, combined with numerical modeling of mechanical changes and impedance response, the thicknesses of separate skin layers can be assessed. Such data, together with the variation of electrode separation, frequency and different locations on the body give valuable extra information, crucial for successful estimation of the impedance of different skin layers. In the future, this will be achieved by constructing a series of numerical models representing the measurement circumstances and employing inverse numerical modeling.

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