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Dielectric properties of some keratinised tissues. Part 2: Human hair

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Abstract--Some electrical properties of human hair have been investigated in order to determine whether a significant DC electrical conductance is present in keratinised tissues. The DC conductance was found to be substantial and highly dependent on the moisture level in the hair fibres. At high moisture levels, the conductance was found to be almost frequency independent below 1 kHz. Absorption and desorption profiles were also monitored, revealing different stages of sorption mechanisms in the fibres. Although absorption was found to be a slow process with "time constants" in the range of hours, desorption was much faster, in the range of a few minutes.

Keywords-- Bioimpedance, Electrical admittance, Hair

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1. Introduksjon

TO PROVIDE an electrical model of the human skin that is, by nature, explanatory, there is a need to relate the components in the model to the different structures of the skin. Fig. 1 shows a frequently used electrical model for skin that can be made to fit most measured data (YAMAMOTO et al., 1978; SALTER, 1979). Y_{pol} in this model must be ascribed a constant phase behaviour, at least within a particular frequency range. The focus in this study is whether G_{DC} is solely due to ohmic conduction in the sweat ducts or if the *stratum corneum* itself contributes significantly to this component.

In Part 1 of this paper (MARTINSEN *et al.*, 1997), *stratum corneum* and nail *in situ* were presented. They clearly showed that the conductance has a stable value from 1 mHz to about 10 Hz. This indicates a significant G_{DC} in keratinised tissue. In the present paper some admittance measurements on human hair are presented which confirm the existence of a stable low-frequency conductance level. This level is found to be highly dependent on relative humidity as it exhibits an increase in excess of 10^4 when relative humidity is changed from 31% to 85%. This increase is very slow and complex with a "time constant" in the range of a few hours when a positive step in RH is introduced. The decrease after a negative step is more rapid, corresponding to a "time constant" of a few minutes, which indicates that different mechanisms are involved during absorption and desorption.

Stratum corneum and hair are similar in that they are keratinised tissues composed of dead cells which are cemented together by a group of proteins called keratins. The major differences are, for example, that lipids represent about 10% of the mass of the *stratum corneum*, but only 2% of the mass of hair. Furthermore, hairs have a cortex covered by a "cuticle", which is a pile of flat cells that protect and maintain the cortex (LEVEQUE, 1994). This may account for the different sorption behaviour of these tissues. The electrical conduction mechanisms are most probably similar in these materials and hair is therefore to some extent a proper model of pure *stratum corneum.*

2. Materials and methods

A measuring cell was constructed to enable longitudinal measurements on human hair. All components were mounted under the lid of an aluminium box as in Fig. 2. Using an aluminium box serves two purposes: it works as a closed compartment where the relative humidity can be controlled, and it shields the extremely high-impedance hair circuit from

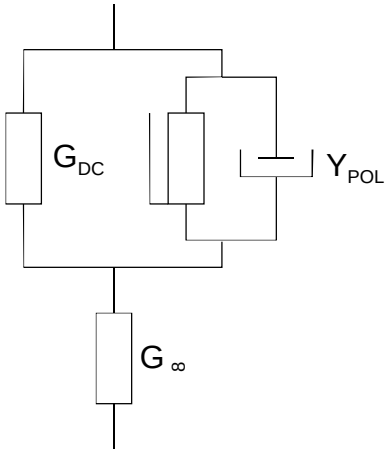

Fig. 1 *Electrical model of human skin*

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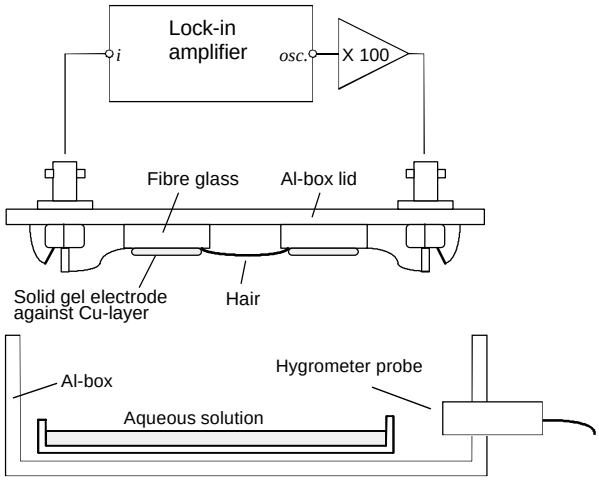

Fig. 2 *Measuring assembly under the lid of an aluminium box*

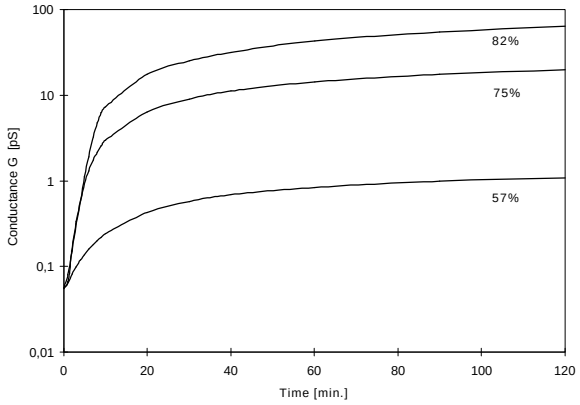

Fig. 3 *Electrical conductance of 100 hair fibres in parallel after a sudden step in RH from 30% to57%, 75% and 82%*

external noise. A hygrometer probe was inserted in the cell through a tight hole in the box wall. The measurements were carried out using a digital lock-in amplifier* which has an input impedance of 1kΩ to virtual ground in current mode. The oscillator output was connected to the measuring cell via an 100× amplifier so that the hair fibres were excited by 100 V rms. This was done to improve the signal/noise ratio. The 100 V measurements were confirmed to be within the linear range by accompanying measurements at 1 V. Measurements were also carried out on the measuring cell without hair in order to control any stray capacitance or conductance in the cell. All subsequent measurements with hair were calibrated according to these results.

All hair fibres used in these experiments were human scalp hair that had not been bleached or treated in any way that could change the structure of the fibres. The hair fibres were cleaned first in alcohol and then tap water, and afterwards kept in room humidity until the measurements were carried out. The fibres used were found to have a diameter of 54 ± 5 μm. Different saturated aqueous solutions were used to achieve constant RH in the cell. The salt in these solutions shifts the balance between vapor and fluid water towards the fluid phase to a degree which is dependent on the type of salt used (LIDE, 1993). The RH was supervised with the hygrometer.

2.1 *Time-course of absorption and desorption*

The time-course of moisture absorption was monitored by measuring 100 hair fibres in parallel. A high number of hairs was needed to reduce the extremely high impedance and hence further improve the signal/noise ratio. This measurement was done to find the necessary time needed for the fibres to equilibrate at a specific humidity. Ambient RH was 30% and temperature was 23°C. The fibres were allowed to equilibrate with the 30% RH for several hours before and between the experiments. Each experiment was carried out by introducing a sudden change in RH from 30% to 57%, 75% and 82%, respectively. The practical way of doing this was to mount the lid with the measuring assembly on the Al-box in which the appropriate aqueous solution had been placed. The conductance of the fibres at 1 Hz was then measured continuously for 120 min. Desorption from 75% RH to 30% was also measured by moving the lid to another Al-box in balance with the ambient temperature.

2.2 *Influence of relative humidity on electrical admittance*

The fibres were furthermore allowed to equilibrate in 62%, 75% and 86% RH for 24 hours in three different experiments, and the conductance and susceptance were then measured from 1 Hz to 1 kHz in each case.

To further investigate the influence of RH on the 1 Hz conductance of the fibres, the RH was increased in 11 steps from 31% to 85% and the corresponding conductance was measured for each level after 3 hours. This experiment was done with only 50 fibres in parallel.

3. Results

3.1 *Time-course of absorption and desorption*

The absorption curves are presented graphically in Fig.3 as conductance at 1Hz versus time, and the initial part of the 75% RH curve is presented separately in Fig.4. The increase in conductance after a sudden step in RH can apparently be divided in three different sections. The first section is characterized by a rather slow response to the excitation and is followed by a fast increase and then eventually a converging time-course. The conductance does not reach a stable value during the two hours plotted in the figure, but actually continues to increase for several days.

The desorption from 75% to 30% RH is plotted in Fig.5. The initial response is very fast followed by a slower phase. One hour after the reduction in RH, the conductance had still

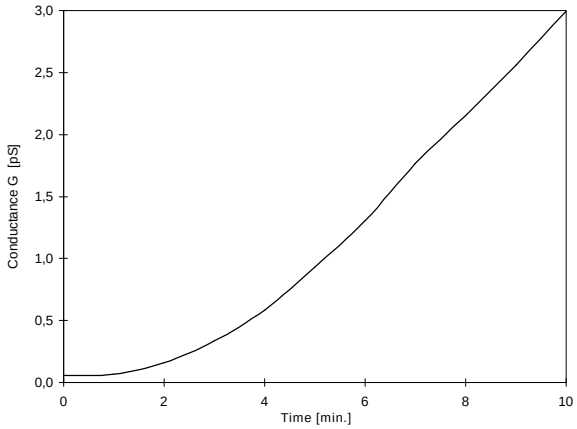

Fig. 4 *Electrical conductance of 100 hair fibres in parallel after a sudden step in RH from 30% to 75% (First 10 min of Fig. 3)*

* Stanford Research 850

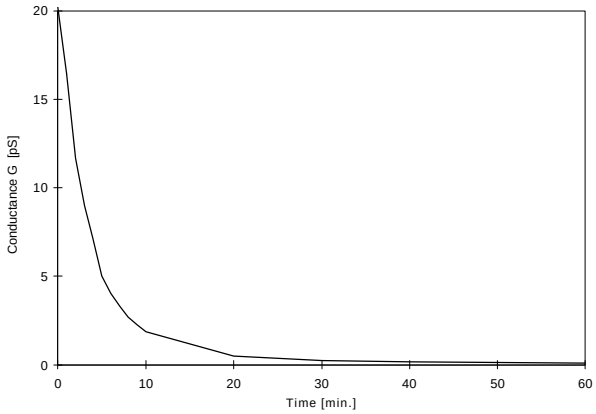

Fig. 5 *Electrical conductance og 100 hair fibres in parallel after a sudden drop in RH from 75% to 30%*

not reached a stable value, i.e. the initial value before absorption.

3.2 Influence of relative humidity on electrical admittance

The conductance and susceptance of the hair fibres are presented in Fig.6 as a function of frequency. The errors in these measurements are not significant: The error in the recorded values is roughly 1% of full scale on the lock-in amplifier, which causes a rather large error in the imaginary part at low phase angles. However, the relative phase error in this lock-in amplifier is only 0.001° so the procedure of correcting the results according to measurements made without hair fibres reduces the errors significantly. The total error in the data is difficult to calculate exactly, but is most probably restricted to a few percent of the measured values and mainly due to full scale error and an inevitable minor temperature drift.

At 86% RH the conductance is almost frequency independent, and at 75% and 62% only a small increase at the highest frequencies can be detected. The susceptance is increasing linearly at the highest frequencies, but levels off at the lowest frequencies. The frequency at which this flattening starts increases with RH.

The 1 Hz conductance measurements at different RH from 31% to 85% are presented as circles in Fig.7. The measurements show that there is a logarithmic relation between conductance and RH in the fibres. A straight line given by:

$$G(RH) = G_0 e^{k \cdot RH}$$

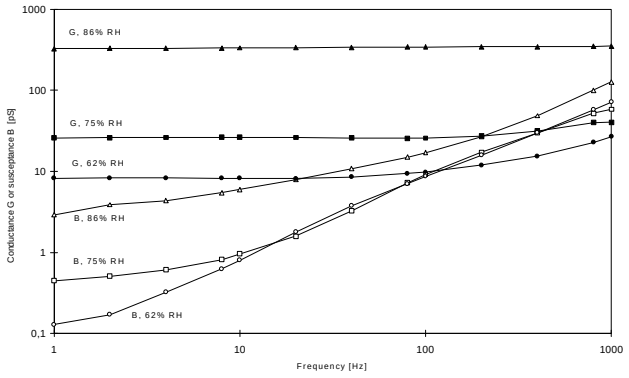

Fig. 6 *Electrical conductance (G) and susceptance (B) of 100 hair fibres in parallel as a function of frequency*

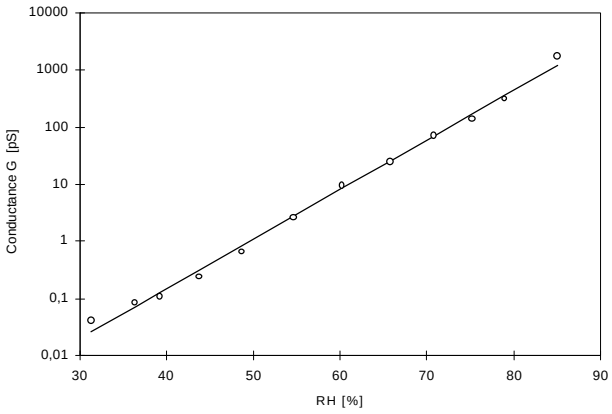

Fig. 7 *Electrical conductance of 50 hair fibres as a function of RH at 1Hz. Circles are measured values and line is logarithmic regression*

is plotted in the same figure where k is 0.2 and G_0 is 50 aS (atto-siemens).

4. Discussion

The results show that the absorption of water into hair fibres is a slow process. The first seconds after introducing a step in RH the increase in measured conductance is almost zero, implying either that no water is absorbed in the first part of the course or that the absorbed water does not contribute to an essential degree to the conductance. WATT (1980) asserts that the water in the first stage of absorption will be involved in cross-links that strengthens the molecular structure of the keratins. These water molecules do probably not contribute to the electrical conductance of the material. In the second stage of absorption, these cross-links will be broken and the molecular mobility will increase. The fibres are then allowed to swell and more water can be absorbed. Water absorbed in this stage is e.g. hydrogen-bonded to polar side chains and will contribute to the electrical conductance.

The conductance was found to increase for several days. ROBBINS (1979) reported that after a period of 18 - 24 hours the hydration of the fibres should be equilibrated with the ambient RH. This means that the conductance continues to increase after steady state hydration of the fibres is achieved. The increase in conductance over several days was found to be independent of whether the excitation voltage was applied continuously or only during the admittance readings. A possible explanation of this phenomenon could be that the absorbed water molecules regroup in a way that increases their contribution to the conductance.

The measured desorption process is initially rapid because the loosely bound water molecules that have the largest influence on the conductance, will also easily diffuse out of the fibres. The more strongly bound molecules will provide a slow desorption tail lasting for at least several hours.

Measured conductance and susceptance as a function of frequency support the findings on *stratum corneum* and nail in part 1 of this paper (MARTINSEN *et al.*1997). The conductance is dominated by G_{DC} at low frequencies (Fig.1). This component is highly dependent on RH as can be seen from Fig.6, and this dependence can be expressed by a simple logarithmic relation as shown in Fig.7. The susceptance at the upper part of the frequency range is only weakly dependent of RH. At lower frequencies this dependence increases due to what can be interpreted as a steeper dispersion region. Since the point of transition to this dispersion shifts with RH on the frequency scale, the susceptance will consequently show a

larger RH dependence at low frequencies than at high frequencies in the frequency range measured.

5. Conclusion

The keratinized tissues investigated in the two parts of this paper, i.e. stratum corneum, nail and hairs, all display a significant DC conductance. The frequency below which this component totally dominates the electrical conductance of the material, varies significantly with the hydration of the tissue. Lower humidity yields lower DC conductance and hence reduces the corner frequency where the conductance becomes frequency dependent (i.e. where Y_{POL} starts to influence in Fig.1). For the in situ measurements this frequency was found to be from 1 Hz to over 1 kHz, and for the in vitro measurements on stratum corneum about 0.1 Hz. The polarization admittance in all tissues investigated was also found to deviate from a pure constant phase behaviour at low frequencies and this was interpreted as a transition to another dispersion region.

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