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Dielectric properties of some keratinised tissues. Part 1: *Stratum corneum* and nail *in situ*

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Abstract--Blister-skin and warts have been studied as possible sources of “pure” stratum corneum without sweat ducts. The purpose of the study was to assess whether the DC electrical conductance measured on human skin is totally dominated by the sweat ducts, or is also significantly contributed to by the stratum corneum itself. By means of galvanic skin response (GSR) measurements, these tissues were found to be unreliable as sources of "pure" stratum corneum. This is because they displayed significant GSR waves, and hence should have some form of active pores. However, measurements on blister-skin and nail in situ revealed a substantial frequency independent electrical conductance at frequencies typically below 10Hz.

Keywords--Bioimpedance, Electrical admittance, Stratum corneum, Nail, Skin

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1 Introduction

A FREQUENTLY used electrical model of the human skin is shown in Fig.1 (YAMAMOTO *et al.*, 1978; SALTER, 1979). The polarization admittance Y_{POL} in this model, is commonly regarded as having a constant phase angle, whereas G_{DC} and G_∞ affect the admittance at low and high frequencies. The components comprising Y_{POL} are frequency dependent and are therefore represented by symbols that are different from ordinary resistors and capacitors. The model will produce a circular arc with the center depressed below the real axis in the complex admittance plane, or above the real axis in the complex impedance plane (COLE, 1932). The model is descriptive by nature, as, by proper choice of component values, it is able to simulate the dielectric behaviour of the skin, at least within a certain range of frequencies and current densities. The model is not explanatory, however, because it contains no inherent information about the electrical properties of the different substructures of the skin.

The interpretation of skin admittance values is restricted to pure empiricism as long as adequate skin models are only descriptive, i.e. electrical equivalents based on measurements. An important task is therefore to differentiate the model, and to connect the different properties of the model to the substructures of the skin.

In a previously reported ongoing study (MARTINSEN *et al.*, 1992*a*), the possible existence of lateral capacitance in the sweat ducts is considered. The present paper, however, presents some low-frequency electrical properties of keratinised tissue, with emphasis on whether G_{DC} in Fig.1 is solely due to the sweat ducts, or also contains significant contribution from the *stratum corneum* itself. Measurements on *stratum corneum* and nail *in situ* from 1 mHz to 1 kHz are presented. Furthermore, blister-skin and warts were investigated as possible sources of *stratum corneum* without sweat pores. This was done by means of GSR measurements, which showed that blister-skin to some degree still may have active pores, and that palmar warts exhibit sweat activity comparable to normal skin. These areas were thus found to be unreliable as sources of "pure" stratum corneum. The results furthermore indicate that keratinised tissues yield a low frequency conductance plateau, and hence a measurable G_{DC} (Fig.1).

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2 Materials and methods

Measurements of GSR were performed on palmar skin, using two independent 88 Hz electrical admittance meters (MARTINSEN *et al.*, 1992*b*). The conductance and susceptance

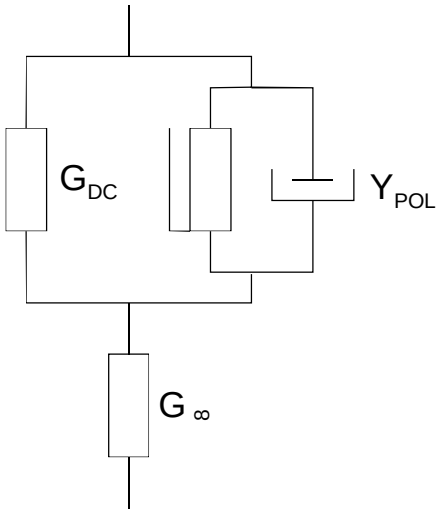

Fig. 1 *Electrical model of human skin*

outputs from the meters were connected to a multichannel, differential input, 12 bit A/D-converter system, and monitored using a general purpose data acquisition and instrumentation software package*. The Ag/AgCl hydrogel electrodes† were cut to fit the area of the measured objects. The measured palmar skin sites were located as shown in Fig.2.

The counter-electrode of the three-electrode system was placed at the wrist on the ventral side of the forearm, and the reference-electrode was placed on the thenar region. Four different GSR measurements were performed, and in each measurement the conductance and susceptance of a defined palmar skin area were recorded simultaneously in both hands. The skin sites were normal skin, blister on right thumb (6 days old), blister on left hand (1 day old) and wart on right hand. The blisters were friction-induced. The wart extended about 1.5 mm from the skin surface. A data sampling frequency of 10 Hz was chosen, as the Fourier spectra of measured GSR waves have been found not to have significant frequency components over 2 Hz (MARTINSEN---unpublished data). The GSR waves were produced by taking a deep breath after a period of relaxation. In all measurements, the electrodes had been applied for approximately 10 min before recording started. Relative humidity was 40% and temperature was 22°C.

The electrical admittance of the blister-skin in the left hand was measured *in situ* from 1 mHz to 1 kHz, using a digital lock-in amplifier‡, and a three electrode system (GRIMNES, 1983). The lock-in amplifier was DC-coupled which ensures reliable measurements at low frequencies. The errors in the measured values are specified to 1% of full scale, and the relative phase errors are 0.001º. Errorbars are plotted in all Figures where the errors are significant. An applied voltage of 20 mV RMS was used and the electrodes, as well as RH and temperature, were the same as in the previous experiment. The electrodes were applied about 30 min. before the measurements. After the experiment, the skin was removed and the thickness was measured to be 218 μm.

The same lock-in amplifier and electrodes were used with a two electrode system to measure the low frequency electrical admittance of the nail on the left thumb *in situ*. A voltage of 100 mV RMS was used and the counter-electrode was placed on the adjacent skin. These measurements were considered to be quasi-monopolar, because the counter-electrode was approximayely eight times larger than the measuring electrode and was also placed on the better conducting skin. Different measurements were done at 22°C, with RH ranging from 38% to 50%.To further increase the moisture level of the nail, the entire thumb was placed in warm water for 30 min. The thumb was then wiped dry with a paper towel, the electrode was quickly applied and the thumb was wrapped in occlusive plastic foil. This arrangement was allowed to stabilize for 90 min before the measurements were carried out (i.e. before the first value, 1 mHz, was recorded). The thickness of the nail was 450 μm.

The influence from electrode polarisation impedance on the results was eliminated by means of the following procedure: Impedance measurements were done on two electrodes connected together face to face. The series data from these measurements were subtracted from the series representation of the results obtained on nail and skin, taking into account the specific area of the electrodes used and whether the measurements were monopolar or bipolar. The corrected values were then converted to parallel data, i.e. admittance values. The GSR measurements have not been corrected in this manner.

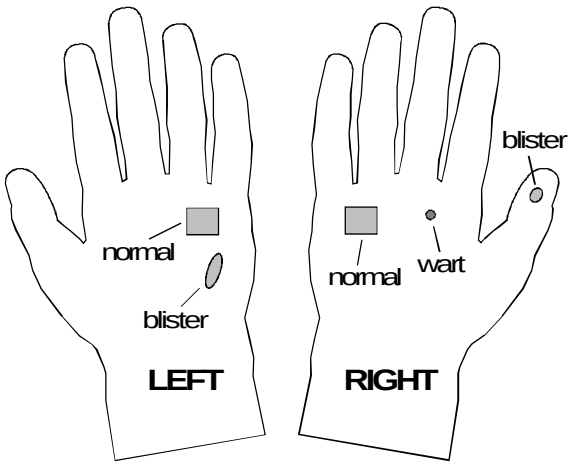

Fig. 2 *Skin sites subject to 88Hz GSR measurements*

* LabVIEW® ver. 3.0
† Medtronic FASTRACE® 4
‡ Stanford Research

3 Results

The results from the GSR measurements on normal palmar skin (Fig.2) are presented graphically in Fig.3. Figure 3 shows that the admittance level is slightly larger in the right hand and that the conductance wave in the right hand is somewhat more distinct at the onset compared to the left hand. Both hands show clear conductance waves, but no substantial susceptance waves. No time delay can be seen between the onset of the conductance waves in the two hands, but the almost undetectable susceptance waves appear a few seconds after the changes in conductance.

The measurements on the blister on the right thumb and the reference on the left thumb are presented in Fig. 4. These results show a significantly higher phase angle (i.e. atan (B/G)) on the blister-skin than on the reference area, and a reduced but still substantial conductance wave on the blister. There is also a small initial increase in conductance at the onset of the GSR on the left hand that is not present on the blister. It should also be noted that the admittance level measured on the left thumb is 3-4 times higher than on the palmar site in Fig. 3.

Figure 5 shows the admittance measured on the blister on the left hand and on the reference in the right hand. In this measurement, the phase angle of the blister-skin is not larger

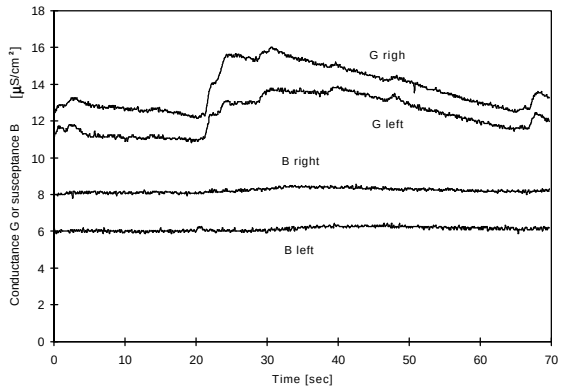

Fig. 3 *Conductance (G) and suseptance (B) from 88 Hz GSR measurements on normal skin in both hands*

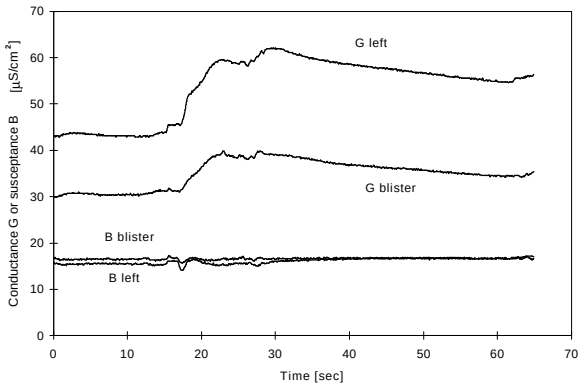

Fig. 4 *Conductance (G) and susceptance (B) from 88 Hz GSR measurements on blister on right thumb and reference on left thumb*

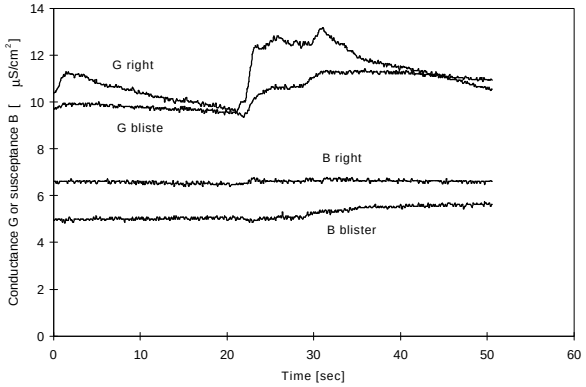

Fig. 5 *Conductance (G) and susceptance (B) from 88 Hz GSR measurements on blister on left hand and reference in right hand*

than on the reference. The conductance of the blister increases significantly after the GSR, but the timing is slower than on the reference. The descending part of the wave is not present in the blister measurement and only a slight decrease can be observed during the recorded period. A few seconds after the GSR-wave, the susceptance of the blister increases to an approximately 10% higher level.

The results from the measurements on the wart on the right hand are presented in Fig. 6. Separate axes are used for the admittance values of right and left hand because of the much larger admittance values of the wart. Because of low bit-resolution in the measurements in the left hand, those two original curves have been replaced by smoothed curves that were produced using a three periods moving average method. From visual comparison, no information was lost in this operation.

Fig. 6 shows a surprisingly high admittance level on the wart compared to the reference. The phase angle was furthermore, lower than the reference and the wart exhibits a significant GSR wave.

The three-electrode measurements on the blister on the left hand are presented in Fig. 7. The uncertainty in measured values related to full scale on the lock-in amplifier, is significant in the low-frequency part of the susceptance measurements, as indicated by the error bars. The conductance in this frequency range is totally dominated by G_{DC} (Fig. 1), but starts to increase at about 10 Hz. The susceptance displays an almost stable level below 0.1 Hz.

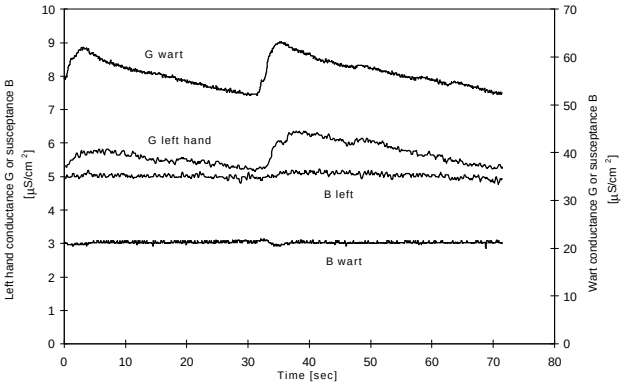

Fig. 6 *Conductance (G) and susceptance (B) form 88Hz GSR measurements on wart on right hand and refereednce in left hand*

Measurements were also done on nail *in situ* and the results for RH=38%, RH=50%, and nail immersed in warm water are presented in Fig. 8. Because of long time constant for the 1 mHz measurements, the electrodes were applied approximately one hour before the admittance values could be recorded (90 min for the case of nail immersed in warm water, as previously explained). The values for the different frequencies were then recorded within a period of 30 min. The influence from ambient relative humidity is consequently small, as can be seen from the curves. The low-frequency

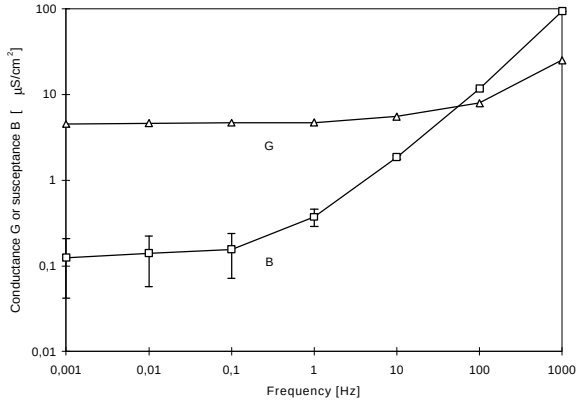

Fig. 7 *In situ conductance (G) and susceptance (B) of blister on left hand*

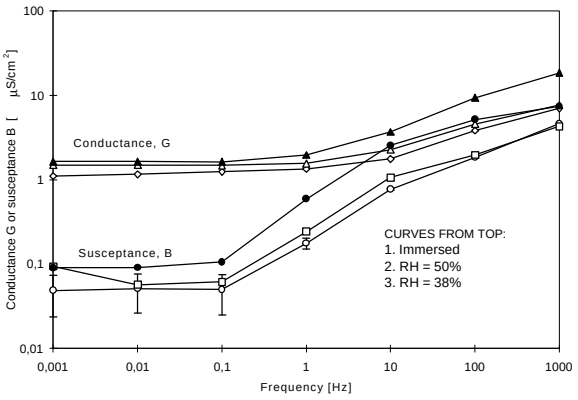

Fig. 8 *In situ conductance (G) and susceptance (B) of nail on left thumb*

conductance plateau extends to somewhere between 1 Hz and 10 Hz, and the susceptance also exhibits a stable level below 0.1 Hz. A significant break occurs in the susceptance curves at 10 Hz. Immersing the nail in water causes increased conductance and susceptance. The relative increase in conductance values is largest at the highest frequencies, whereas the relative susceptance increase is largest around 1 Hz.

4 Discussion

Both blister-skin and warts show GSR activity comparable to that of normal skin and are thus unsuitable as measuring objects in the investigation of electrical properties of genuine *stratum corneum*, i.e. without appendices.

The minor increase in susceptance a few seconds after the leading flanks of the conductance part of some of the GSR waves, indicates that these changes have different causes. The quick conductance change is presumably a sweat duct effect and the slower change in susceptance is most probably due to a resultant increased hydration of the *stratum corneum* itself. There are no susceptance waves that could indicate any significant capacitance in the sweat ducts.

The increased phase-angle measured on the blister on the right thumb can be explained by a swelling of the *stratum corneum* due to the liquid inside the blister. This may reduce the total pore area and hence reduce the conductance. Despite the separation of the part of the sweat duct that is located in the *stratum corneum*, and the remainder of the sweat duct, these measurements clearly indicate that these pores are still influenced by GSR activity, probably through the blister liquid. The stable susceptance channel eliminates the possibility that the conductance change is located in the remains of the sweat ducts underneath the blister, since a change in series resistance would influence both channels.

The increased admittance level on the left thumb compared to the palm, could be due to thinner *stratum corneum* on the thumb. The difference in conductance is also larger than the difference in susceptance, which could be explained by a larger number of sweat glands on the fingertips than in the palm. ROBERTS *et al*. (1970) reported an average of 359 sweat glands per square centimetre on the fingertips of Caingang Indians (Brazil) compared to an average of 258 in the palms.

The time-course of the conductance of the blister on the left hand was found to be less abrupt than the reference. The sweat pores are probably therefore even more closed on this area and the GSR wave, hence, more determined by hydration of the *stratum corneum*. This could also explain the lack of increased phase-angle, since preceding GSR activity has a more accumulating effect on this blister-skin than on the reference skin. The step in susceptance value also supports this assumption.

A clear indication that warts may display extensive sweat activity is provided by the curves of Fig. 6. Sharp leading flanks in the conductance channel and small accumulation effect verifies that this is mainly sweat duct activity and not hydration of the stratum corneum.

The measurements on blister and nail *in situ* (Figs. 7, 8) show that the conductance is very much dominated by G_{DC} in the frequency range considered in this study. The results for skin and nail are very similar when taking the measured thickness into account. The curves in Fig. 7 can be modelled by the electrical equivalent in Fig. 1, by using the following values per square centimetre: G_{DC} = 4.4 μS, Y_{POL} = 100 nS || 50 nF and R_∞ < 1kΩ (Fig. 9). Y_{POL} is provided a constant phase feature by giving the component values the following frequency dependence:

$$C = C_0 \cdot f^{m-1}$$

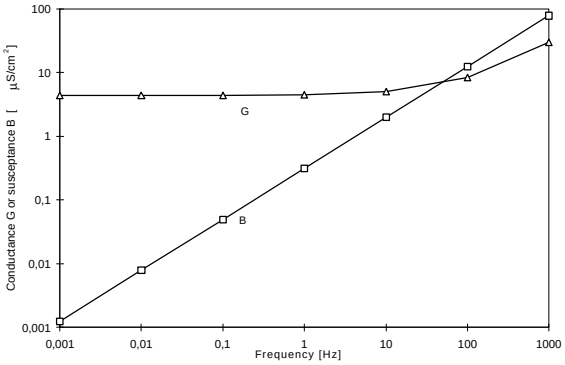

Fig. 9 *Conductance (G) and susceptance (B) of the model in fig.1, for values given in the text*

and

$$G = G_0 \cdot f^m$$

The values listed for Y_{POL} are thus C_0 and G_0. The constant phase angle is therefore approximately 72° and m=0.8 in Fig. 9.

Figure 9 is similar to Fig. 7 apart from the susceptance below 1 Hz. This low-frequency plateau cannot be simulated by the electrical model of Fig. 1 or any electrical equivalent to it if the polarization admittance is given a pure constant phase characteristic. That is, given the electrical model in Fig. 1 and the frequency dependence described above for C and G, it can be shown that the inequality:

$$\frac{\partial^2 B}{\partial \omega^2} < 0$$

is always true. This behaviour can be explained, however, by considering the relaxation type of dispersion mechanisms that is extensively treated in the literature (SCHWAN, 1957; SCHWAN and TAKASHIMA, 1993). A system involving a distribution of relaxation times could give a constant phase like behaviour over a broad frequency range, but still exhibit large deviations outside this range. This will not be discussed any further in this paper.

The frequency limit of the conductance and susceptance plateaus is often found to be shifted down when the tissue gets dryer. An example is shown in Fig. 10 where the blister-skin from the right thumb has been measured *in vitro*, 24 hours after removal. The admittance measurements were carried out

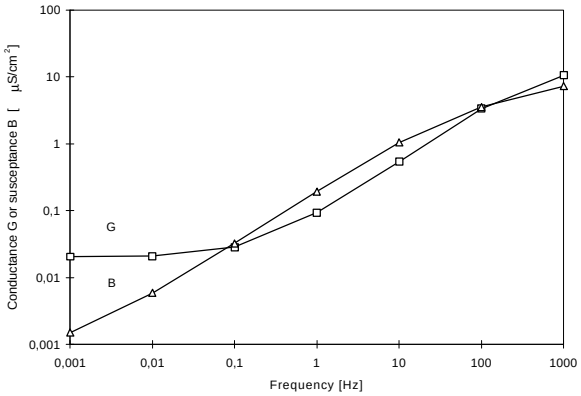

Fig. 10 *In vitro conductance (G) and susceptance (B) of blister-skin from right thumb*

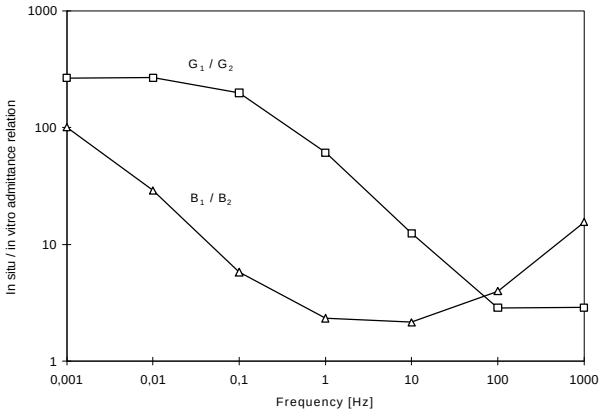

Fig. 11 *Relative difference in admittance-values for blister skin in vitro and in situ*

using the lock-in amplifier with a two electrode system, 20 mV RMS and the same solid gel electrodes as previously described. RH was 50% and temperature was 21°C. The thickness of the skin segment was 180 μm. The uncertainty was insignificant in this measurement and no error-bars are therefore indicated. The conductance is dominated by G_{DC} at the lowest frequencies, but starts to increase at about 0.1 Hz. The susceptance is linear in this plot, but starts to diverge at 1 kHz because of the influence from the series conductance G_∞. The low-frequency conductance plateau is approximately two decades lower than in the *in situ* measurements made on the blister skin in the left hand and the increase starts at a frequency approximately three decades lower.

Figure 11 shows the relative difference in admittance values between blister-skin *in situ* and *in vitro*. The values have been adjusted to account for differences in thickness of the two specimens. The relation is about 2-3 for the conductance and susceptance channels at the upper frequencies, although an increase in the relation between susceptance values can be seen in this range. This increase in probably due to differences in influence by the series resistance R_∞ in the two samples. However, a frequency shift in the dispersion of relative permittivity, as mentioned above, may also be responsible for this effect.

The large differences in conductance at low frequencies are most probably caused by the sweat pores that were found to be present in the *in situ* blister skin. These pores yield a significant increase in G_{DC} compared to *in vitro* skin, and consequently a considerable change in conductance at low frequencies. The low- frequency susceptance plateau that was found in the *in situ* measurements, is absent in the *in vitro* measurements. Drier *stratum corneum* could give a permittivity dispersion shift downwards in frequency, because reduced molecular mobility may increase the relaxation times. The plateau could therefore be located below 1 mHz, and, hence, the difference between the two samples could be large at low frequencies because of this.

In conclusion, a frequency independent and substantial conductance value is found at low frequencies in the studied tissues. This value is comparable to that found on skin *in vivo*. The electrical conductance of keratinised skin is therefore found to contribute significantly to the overall skin conductance. The electrical properties of nail and *stratum corneum in situ* were furthermore, found to be very similar, and nail is, thus, found to be a proper model for studying the electrical properties of the *stratum corneum*.

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