Manuscript published in
Skin Research and Technology
14, 142-146, 2008

Water sorption and electrical properties of a human nail

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Background/purpose: Water absorption is important for the overall function of keratinized tissues like the stratum corneum and nail. Hence, measurement of water sorption dynamics and water content of these tissues is of great interest.

Methods: We have studied water sorption and electrical properties of a human nail in a measuring cell where the temperature and relative hydration could be controlled.

Results: We found the amount of absorbed water to be linearly dependent on ambient relative humidity up to about 70%, followed by a stronger dependency. Furthermore, we found that electrical conductance and capacitance are exponentially dependent on the water content.

Conclusion: Both electrical conductance and susceptance are good indicators of water content in the nail. The results also possibly indicate that the capacitance is dependent on the mobility of the keratin chains, while the conductance is probably more dependent on water molecule mobility.

Key words: nail – water – sorption – keratin – electrical admittance

Accepted for publication 26 May 2007

THE HYDRATION state and water-holding capacity of keratinised tissue, such as skin (stratum corneum) and nail, are important for the overall function of these tissues (1, 2). There is now increased awareness of the influence of water content on the function of the human nail and recently a study was published where NIR spectrometry was used to assess the hydration level in nail (3). The aim of this work was to study the absorption isotherm of the human nail and to establish the relationship between the absolute water content of the nail and the electrical admittance. A number of studies have been carried out on the electrical measurement of stratum corneum hydration (4–10), but water sorption in the skin and nail is somewhat different and data from skin measurements cannot directly be applied on a nail (11, 12). The water-binding capacity of a nail is comparable to that of the stratum corneum at low values of relative humidity (RH), but at values over 90%, the stratum corneum is able to take up considerably more water than a nail. Studies where pieces of stratum corneum and nail were submerged in water showed that while the stratum corneum absorbed 200% water by weight, the nail absorbed $<30\%$ (13, 14).

In the study presented in this paper, both electrical conductance and capacitance were found to be dependent on absolute water content according to a simple exponential relationship. Our results also indicate that macromolecules play a significant role in the low-frequency capacitance of keratinised tissue.

Materials and Methods

Electrical measurements

In all electrical measurements, a piece of toenail was fixed between two cylindrical stainless-steel electrodes (2 mm diameter) inside a measuring chamber, where the RH could be controlled using saturated aqueous solutions. The construction actually included two separate chambers so that the electrode assembly could be transferred quickly from one RH to another. The electrodes were spring-loaded with a spring constant of about 1.1 N/cm, and they were connected to a Stanford Research 850 lock-in amplifier (Stanford Research Systems Inc., Sunnyvale, CA, USA) in a two-electrode, constant voltage set-up. The measurements were calibrated to remove influence from stray capacitance and electrode polarisation. The contribution from electrode polarisation was

removed by means of a method that we have described earlier (15). This involves plotting the measured frequency response in the complex admittance plane and then extrapolating the largest (highest frequency) dispersion region.

Sorption time constant and anisotropy

A first experiment was designed to estimate the time constant for the sorption processes in the nail. A piece of toenail was cut to the following size: 2.10 mm in the direction of growth, 2.05 mm across and 0.45 mm thick. It was mounted between the electrodes with the growth direction spanning the gap, so that the area exposed to the surroundings was six times the area covered by the electrodes. This was done to ensure rapid equilibration with the surrounding air.

The RH in the measuring cell was adjusted to 54%, and this set-up was allowed to stabilise for several hours at room temperature (22 °C). Conductance and capacitance were then measured continuously at 200 Hz using a constant applied voltage of 100 mV rms. A step in RH from 54% to 68% was introduced after a few minutes, and this RH was maintained for about 5 h before it was reduced back to 54% again.

Measurements were also carried out from 1 Hz to 1 kHz on a similar piece of toenail, both along and across the growth direction at 25 °C and 55% RH. There were no significant differences in the frequency response in the two directions, although the admittance across the growth direction was somewhat higher. One possible reason for this could be that the keratin chains are mainly oriented across the growth direction (13).

Absorption isotherm and electrical admittance

A combination of gravimetric and electrical measurements was utilised in order to determine the relation between absolute water content and the electrical properties of nails. Weight measurements were carried out using a Mettler H10 balance (Mettler-Toledo Inc., Columbus, OH, USA). The balance was placed in a closed compartment and saturated aqueous solutions were inserted for stable RH. Pieces of both finger and toenails from healthy, young, male students were used in this study. In each case, the nail was first allowed to stabilise on the balance for 48 h in 20% RH before the weight was recorded. The RH was then increased successively up to 82%, always waiting for 48 h before the weight was recorded. Ultimately, an RH of 0% was achieved using a so-called 'blue gel'. The nail was stabilised in this environment for 120 h before the dry weight was registered.

Electrical admittance was then measured at 80, 200 and 1,000 Hz at the same RHs from 0% to 82%. An applied voltage of 100 mV was used, and the temperature was 22 °C. To reduce contribution from stray capacitance and electrode polarisation, three pieces were cut from a fingernail, formed as cylinders with the same radius as the electrodes and with a thickness of 0.34 mm. The pieces were honed and polished and placed in series between the electrodes to form a nail cylinder of 1.02 mm. (Note that any remaining contribution from stray capacitance and electrode polarisation was still subsequently removed as described above.) Measurements on the individual pieces of nail were also conducted to verify that the combined effects of these were consistent with the results from all three pieces together. In the electrical measurements, the nails were allowed to stabilise in a new RH for 24 h before the electrical admittance was recorded. Before recording values for 0% RH (using 'blue gel'), the nails were stabilised for 120 h.

Reproducibility of the electrical measurements

Repeated measurements on the same piece of nail remounted several times at 68% RH and 80 Hz, with intermediate restabilisation at room environment, gave a coefficient of variance for the measurements of 11% (conductance), 9% (susceptance) and 2% (phase angle). Owing to the small variance in phase angle, this was interpreted as being due to variations in contact area between the electrodes and nail.

Results

Sorption time constant

The results from the RH step response measurements are shown in Fig. 1. Both conductance and capacitance increase rapidly during the initial phase of adsorption, followed by a slower course. They both reach a maximum value and then decline slightly. The phase angle decreases rapidly in the initial phase, but then increases somewhat again at the stage where the conductance and capacitance have reached 74% and 70% of their maximum values, respectively. The time

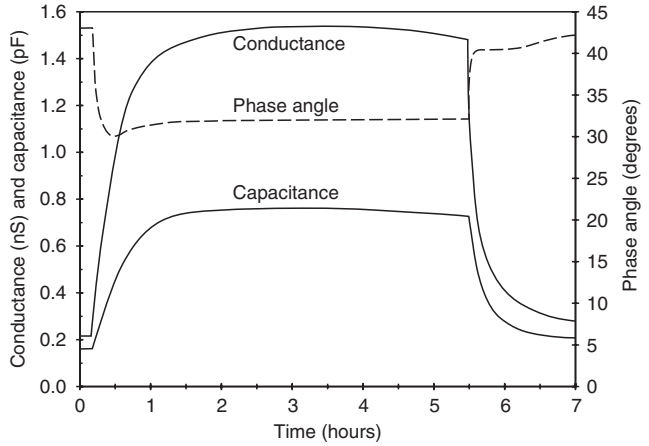

Fig. 1. Conductance and capacitance for a piece of toenail after introducing a step in relative humidity from 54% to 68% and back to 54% again. Measured with 100 mV at 200 Hz.

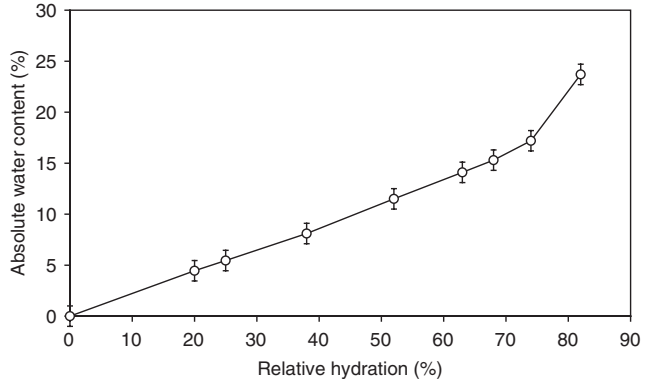

Fig. 2. Absolute water content of finger nail as a function of ambient relative humidity.

course is slightly different in the desorption phase. The phase angle increases rapidly due to a very quick response in the conductance, and then levels off and subsequently increases again.

Absorption isotherm and electrical admittance

The results from gravimetric measurements on one fingernail are shown in Fig. 2 as per cent increase in weight from dry nail. The uncertainty in the measurements is typically 1% as indicated by the error bars. Other pieces of nails from toes or fingers differed only insignificantly from this curve. The water content increases linearly up to about 75% RH, where a much higher dependency suddenly occurs. This is in good agreement with the data reported by other investigators (13).

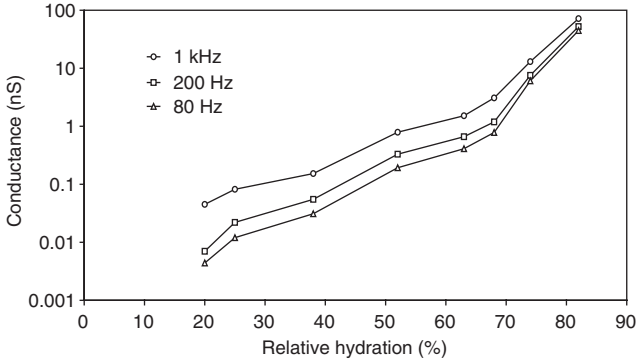

Fig. 3. Conductance of three pieces of nail in series as a function of frequency and relative humidity.

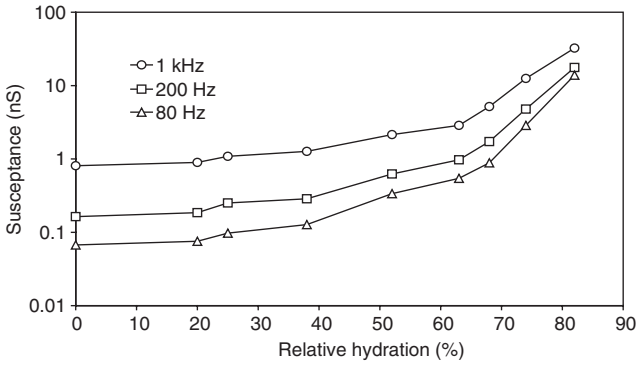

Fig. 4. Susceptance of three pieces of nail in series as a function of frequency and relative humidity.

Figure 3 shows the conductance and Fig. 4 the susceptance of the RH dependency of the three cylindrical pieces of nail in series, measured at three different frequencies. We were not able to measure the extremely low conductance at 0% RH.

Combining the results from Figs 3 and 4, we can now deduce the relation between absolute water content and the admittance parameters. The result of this is shown in Fig. 5 where the error bars stem from the uncertainty in the gravimetric measurements. The water content could be interpreted as follows:

$$W = \frac{weight\,H_2O}{dry\,weight} \times 100\%$$

The results of the logarithmic regression are also presented in Table 1.

Discussion

Figure 4 shows that there is a marked increase in electrical susceptance and hence capacitance above 70% RH. This is interesting when

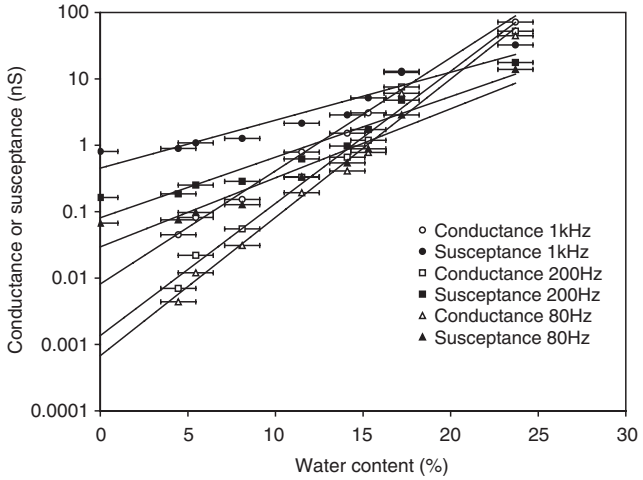

Fig. 5. Conductance and susceptance of nail as a function of frequency and absolute water content. Points represent measured values and lines represent logarithmic regression.

TABLE 1. Results of logarithmic regression of data presented in Fig. 5

Parameter	Frequency	Exponential trend	R^2
Conductance	1 kHz	$G(pS) = 8.1e^{0.39W}$	0.99
	200 Hz	$G(pS) = 1.4e^{0.46W}$	0.98
	80 Hz	$G(pS) = 0.7e^{0.48W}$	0.98
Susceptance	1 kHz	$B(pS) = 453e^{0.17W}$	0.91
	200 Hz	$B(pS) = 81e^{0.21W}$	0.93
	80 Hz	$B(pS) = 29e^{0.24W}$	0.93

compared with Baden (13), who reported a marked increase in the mechanical flexibility of a nail above approximately 70% RH. This could indicate that the change in capacitance is linked to structural changes caused by increased water content. The water dependency is also somewhat higher at low frequencies and our interpretation is that this implies that macromolecules like e.g. keratin may play a significant role in the α-dispersion of keratinised tissue (see e.g. (16)).

One cannot totally exclude the possibility that the increase in electrical admittance is partly due to increased effective contact area between an electrode and nail. However, our results correspond well with earlier studies on keratinised materials (17, 18), which strengthen the credibility of the data. We also believe that the process described for removing the contribution from electrode polarisation impedance will also remove any series capacitance due to impurities in the polished nail surface, and hence eliminate influence from reduced contact area at low RH.

The capacitance in Fig. 1 reaches its maximum value before the conductance. We interpret this as being due to different mechanisms behind the water dependence for the capacitance and conductance, the capacitance being more dependent on the mobility of the keratin chains, and the conductance dependent on water molecule mobility. By desorption, the decrease in conductance is quicker than for the capacitance, indicating that free water diffuses rapidly out of the nail, whereas water bound to polar groups in the keratin is released more slowly. It should be noted that this only applies to the dc part of the conductance, because ac conductance is caused by dielectric loss and hence connected to the same mechanisms as the capacitance.

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