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A quantitative approach to the dielectric properties of the skin

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Abstract. The results of measurements using an open-ended coaxial probe of the audio/radiofrequency dielectric properties of human skin *in vivo*, either dry or moistened with physiological saline, are reported. Permittivity and conductivity dispersion curves were parametrized by using a newly reported dispersion function (Raicu V 1999 Dielectric properties of biological matter: model combining Debye-type and 'universal' responses *Phys. Rev.* E **60** 4677), and the results obtained are discussed in the light of the recent advances in this field. It is suggested that the coaxial probe reports on the properties of the superficial layer, the stratum corneum, when the skin surface is dry, whilst the signal from deeper skin layers becomes dominant after wetting the skin with conductive physiological saline.

In vivo measurements of audio/radiofrequency dielectric properties of the skin have decisively benefited from the use of non-invasive coaxial probes (Raicu 1995, Gabriel *et al* 1996, Naito *et al* 1997). From an electrical point of view, the skin can be regarded as a two-layered structure, namely the poorly conducting stratum corneum and the more conductive epidermis (without the stratum corneum)/dermis layers taken together. How faithfully a coaxial probe can report the electrical properties of these layers depends primarily on two factors: the probe size (Lahtinen *et al* 1997, Alanen *et al* 1998), as defined by radii a and b in figure 1, and the degree of hydration of the stratum corneum (Gabriel 1997), both of which affect the degree of electric field penetration into the tissue.

Alanen *et al* (1999) have recently shown that another factor may well have an impact upon the outcome of the measurements, namely the marked frequency dependence of the contributions of the two skin layers. Its importance was demonstrated by sound theoretical rationale and by measurements on an artificial dielectric system consisting of a thin plastic film and several saline solutions. Unfortunately, however, Alanen *et al* (1999) did not provide equally convincing results for the skin itself, a fact that hampered a quantitative account. The present communication intends to remove this inconvenience by putting forward experimental dispersion curves obtained from measurements on dry and wet skin over a wide frequency range. To settle the discussion on a quantitative rather than a qualitative basis, the dispersion curves are parametrized with the aid of a pertinent dispersion function (Raicu 1999).

The experimental set-up, based on a 4.5 mm ($= 2b$, figure 1) coaxial probe connected to a computer-controlled impedance analyser, is essentially the same as described by Raicu (1995) and Raicu *et al* (1998). However, a new type of impedance analyser (HP 4294A) was used in this work, which provided highly accurate data over a relatively wide frequency range (100 Hz–100 MHz). A coaxial probe is characterized by the 'effective penetration depth' of its field lines into the sample, d_{eff} (figure 1), which can be defined as that thickness of a *homogenous* sample for which the measured permittivity and conductivity deviate by 1% from

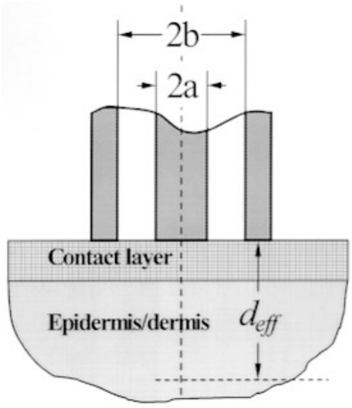

Figure 1. Longitudinal section of a coaxial probe in contact with a layered sample (skin). The contact layer is a combination of the rough-surfaced stratum corneum and air (or saline). Electrode dimensions: $2a = 3.5$ mm, $2b = 4.5$ mm.

their true values, namely those that could be obtained from measurements on an ideally *infinite* sample (Raicu *et al* 1998). For the present probe, d_{eff} was $\sim$2.5 mm.

Figure 2 shows typical results obtained from measurements *in vivo* (human, young male) on dry skin and on skin moistened with physiological saline (i.e. 0.9% NaCl). For a quantitative analysis, a newly reported dispersion function (Raicu 1999) has been used to fit the data, as it seems to be a most suitable representation of dielectric properties of biological tissues. The function reads

$$\varepsilon^* \equiv \varepsilon - \mathrm{j}\kappa/(2\pi f\varepsilon_0) = \varepsilon_h + \frac{\Delta}{[(\mathrm{j}f/f_c)^\alpha + (\mathrm{j}f/f_c)^{1-\beta}]^\gamma} + \frac{\kappa_l}{\mathrm{j}2\pi f\varepsilon_0} \tag{1}$$

where the permittivity ε is relative to the value for free space ($\varepsilon_0 = 8.854 \times 10^{-12}$ F m^{-1}), l and h refer to the low and high frequencies respectively, α, β and γ are real constants taken over the interval $[0, 1]$, $\mathrm{j} = \sqrt{-1}$, f_c is the characteristic frequency and Δ is a dimensional constant, which in some cases ($\alpha = 0$, for instance) is called the dielectric increment ($= \varepsilon_l - \varepsilon_h$). With proper choices for α, β and γ, equation (1) gives all of the Debye-type (i.e. Debye, Cole–Cole and Davidson–Cole) and the constant-phase-angle (CPA) functions as its particular cases.

As seen from figure 2, the simulations by equation (1) excellently reproduced the experimental permittivity and conductivity curves, both for dry and wet skin; this is unlike the simulations based on the Cole–Cole function (i.e. equation (1) with $\alpha = 0$) that are also shown in figure 2. Apparently, the characteristic frequency obtained from the simulations by equation (1) was higher for dry than for wet skin, while the conductivity was higher for the wet condition. These findings are in line with the predictions by Alanen *et al* (1999) and with our previous simulations for the properties of a bilayered dielectric system (see figure 6 in Raicu *et al* (1998)). As with Alanen *et al*, under dry skin conditions the dielectric properties of the first layer (figure 1) having low permittivity and conductivity values are dominant, as the field lines concentrate almost exclusively into that layer; the situation is reversed when the skin surface is moistened with the conductive physiological saline. In other words, the 'effective penetration depth' of the field increases as the contact region (including the stratum corneum) becomes more conductive. This is also supported by the increase in the dispersion magnitude Δ from 2200 to $\sim$11 000 elicited following addition of physiological saline, which means that the deeper skin layers become better represented by the results.

Another important aspect revealed by the present analysis is the decrease of β from 0.152 to 0.076 after hydrating the skin with aqueous NaCl solution. If the non-zero values of β were to

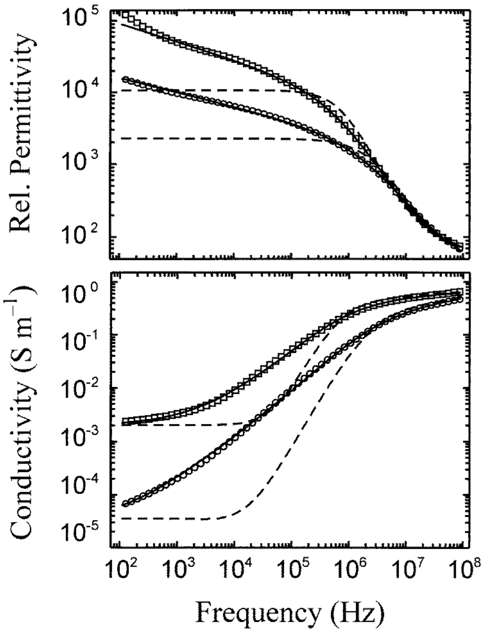

Figure 2. Typical dispersion spectra of relative permittivity and conductivity of human skin *in vivo* (nape of neck, young male). ○, dry and □, moistened with physiological saline. Full curves: simulations by equation (1) with $\Delta = 2200$, $f_c = 2.51$ MHz, $\alpha = 0.21$, $\beta = 0.152$, $\gamma = 1$, $\kappa_l = 32\ \mu$S m^{-1}, $\varepsilon_h = 35$ for dry skin, and $\Delta = 10\,600$, $f_c = 0.76$ MHz, $\alpha = 0.25$, $\beta = 0.076$, $\gamma = 1$, $\kappa_l = 2$ mS m^{-1}, $\varepsilon_h = 61$ for wet skin. For wet skin, the slight mismatch between experimental and theoretical permittivity curves at very low frequencies might reflect electrode polarization artefacts. Broken curves: predicted from the Cole–Cole function with the same parameter values except for α (= 0).

be ascribed to a superposition of several sub-dispersions occurring at high frequencies, then the recorded decrease in β should reflect the disappearance of at least one of such sub-dispersions. Conceivably, this sub-dispersion corresponds to a Maxwell–Wagner-type relaxation of the dielectric system made of the two skin layers (Alanen *et al* 1999), and may therefore vanish (or diminish, at least) when the stratum corneum is made conductive by addition of the highly conductive saline solution.

In conclusion, the interposition of a more or less conductive contact layer between the tip of the probe and the deeper layers of the skin may modulate the results of the measurements. Special attention should therefore be paid to this aspect in future dielectric studies of the skin. However, to assert that the presence of the stratum corneum impairs the measurements of the dielectric properties of deep skin layers appears to be too drastic a conclusion. Although this holds true for the dry skin, it can be avoided by suitably treating the probe/skin interface, as for example with physiological saline. A deeper insight into this as well as other challenges posed by the dielectric measurements of skin will be dealt with in a forthcoming paper from this laboratory.

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