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Human Skin as Arrays of Helical Antennas in the Millimeter and Submillimeter Wave Range

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Recent studies of the minute morphology of the skin by optical coherence tomography showed that the sweat ducts in human skin are helically shaped tubes, filled with a conductive aqueous solution. A computer simulation study of these structures in millimeter and submillimeter wave bands show that the human skin functions as an array of low-Q helical antennas. Experimental evidence is presented that the spectral response in the sub-Terahertz region is governed by the level of activity of the perspiration system. It is also correlated to physiological stress as manifested by the pulse rate and the systolic blood pressure.

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Experimental evidence indicating that the electromagnetic properties of the human skin in the sub-Terahertz frequencies are governed by its morphology is henceforth presented.

The human skin is the largest organ of the body, designed as the primary interface, utilizing numerous of functions and interactions between us and our environment. The complexity of the multilayered skin morphology provides an extremely broad range of features of sensors that utilize a number of physical phenomena. One of these skin features is the perspiration system that traditionally is mainly considered for body thermoregulation [1]. Its main components are sweat glands embedded into the dermis and connecting through the epidermis with the pores on the surface of the stratum corneum by ducts, filled with a conductive aqueous solution. The general illustration of sweat glands presents a convoluted arrangement for the sweat gland and a more or less straight tube for the duct [1,2]. In recent investigations of the subcutaneous morphology of the human skin by optical coherent tomography [3,4], it was found that the sweat duct is in fact a remarkably arranged helical conductive tube (Fig. 1). This, together with the fact that the dielectric permittivity of the dermis is higher than that of the epidermis, brings forward the supposition that as electromagnetic entities, the sweat ducts could be regarded as low-Q helical antennas. Inherent to this supposition is the requirement that the duct possesses an electrical conductance mechanism that is effective at the extremely high frequency (EHF) range. Even though the ducts are filled with conducting electrolytes, the ions mobility rates associated with sweat are slow compared to the characteristic frequencies under consideration. A mechanism that qualifies for such a requirement is fast proton hopping through distributed H-bond networks along the duct surface. It is well established that these networks exist in biological structures [5] and it was found that the characteristic time for such proton transport is about 10^{-13} sec [6].

When the potential drop caused by the difference in pH values between the skin surface and the dermis is taken into consideration [2], such hopping can account for the ac conductivity that is necessary for the sweat ducts to yield an electromagnetic response in the EHF range. Moreover, it is known that the human skin contains approximately 2 to 5×10^6 eccrine sweat glands distributed over most of the body, with higher density in several areas such as on the palms of the hand, the forehead, and on the soles of the feet [7,8]. As each gland is connected to the skin surface by a helical sweat duct, the skin organ in its entirety can be regarded as an array of helical antennas that operate in the EHF range. It has been ascertained that the level of sweating has a dominant effect on the conductance parameters of the various components of the skin tissue. As pointed out above, these parameters strongly affect the spectral response of the skin organ. Hence, it is predicted that the physiological and psychological parameters that are known to be expressed in the activity of the perspiration system [9]

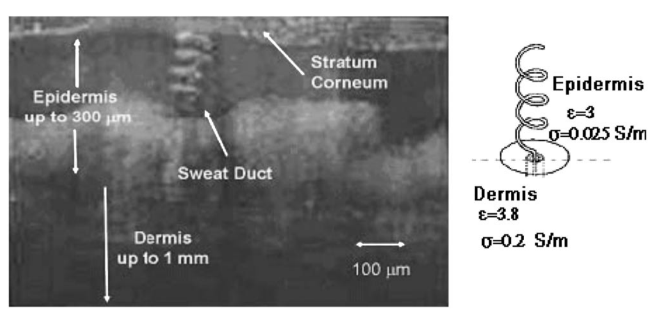

FIG. 1. 3D optical coherence tomography image (reproduced with permission from ISIS GmbH) of a single human eccrine sweat gland embedded in the human skin and a schematic presentation of the duct as a helical antenna [20] embedded in the skin, where the dermis-epidermis interface acts as a dielectric reflector. The respective permittivities of the skin layers are marked. They were estimated for the specific frequency range based on the water content of the layers [10].

will also be manifested in the spectral response of the skin in the EHF frequencies.

To test the validity of this prediction we conducted a series of *in vivo* measurements of the skin reflection coeffcient of the hand palm in several subjects. The first set of measurements was done using a vector network analyzer (VNA) in the spectral range of 75 GHz to 110 GHz (*W* band). In order to avoid parasitic reflections and diffraction effects the first set of measurements was done in a system that was configured for near field measurements. The initial real system measurement was done when the subject was fully rested. The subsequent measurement was done immediately after a period of 20 min of intense jogging, and was followed by a series of measurements every 1 min as the subject relaxed. A typical series of measurements for one subject is presented in Fig. 2(a). As can be seen there is a pronounced difference between the reflectance spectra that were measured in the calm state and immediately after a period of physical activity. In the subsequent measurements, as the subject relaxed back to the calm state, the spectral response of the coefficient also relaxed back towards its initial curve. These results were compared to a computational study of the propagation of an electromagnetic beam in an idealized section of the skin containing eight helical sweat ducts. The sweat ducts were modeled as conducting coils of 2 to 4 turns with diameters 60 to 80 μm and heights 300 to 350 μm (see Figs. 3 and 4). The skin layer was modeled as three strata representing the stratum corneum, the epidermis, and the dermis. The water concentration was set to be 10%–15% in the stratum corneum, 45%–55% in the epidermis, and 70%–80% in the dermis [10]. The stability of the hydrogen network inside the coil and hence the resultant level of proton conductivity is expected to exhibit a direct dependence on the sweat rate. Hence, the conductivity of the coil can be used as the parameter that quantifies the level of relaxation following intense physical activity [11,12], i.e., it is expected that the conductivity of the coil will follow the same time dependence as the decaying sweat flow in the ducts. The computed spectra of the reflectance coefficient for different levels of duct conductivity are shown in Fig. 2(b). It can be seen that the spectral response of the reflectance coefficient is very similar to the experimental results.

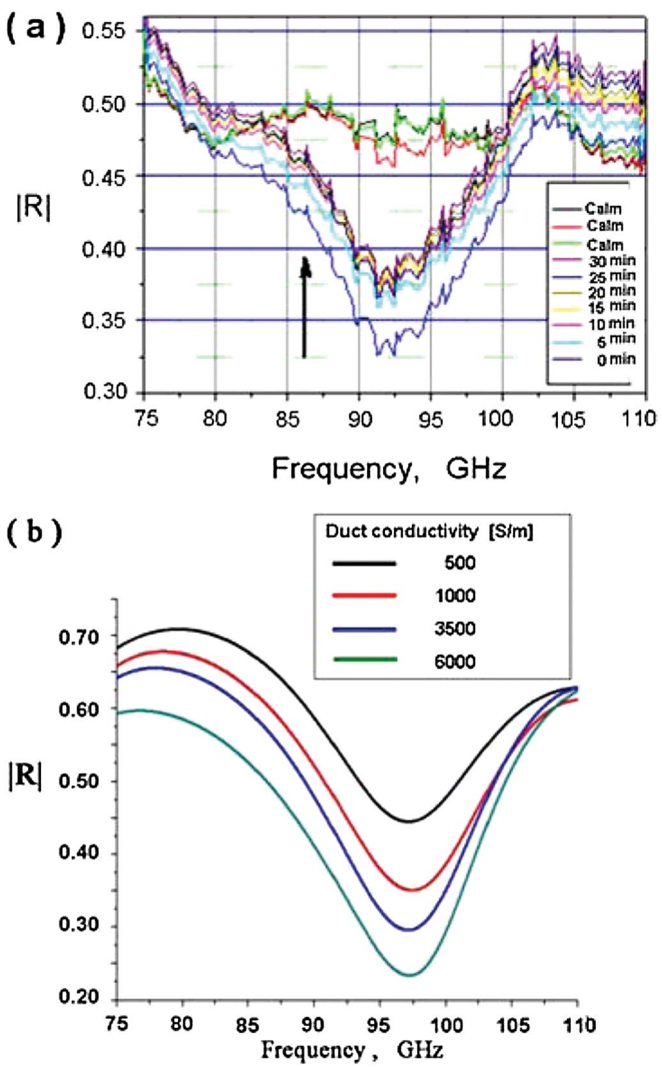

FIG. 2 (color). (a) Measurements of the modulus of the reflection coefficient R of the human palm in the frequency region 75 to 110 GHz. The subject was measured using VNA HP 8510C in the near field in a calm state and then during 30 min relaxation after intense physical activity. The arrow on the graph indicates the direction of the time line and shows how the signal returns to the calm state with relaxation; (b) The simulation of the reflection coefficient from 8 coils embedded in an idealized skin.

The second set of measurements was done in a system that was configured for distance measurements. The palm was held steady by a stand that was placed 22 cm from the horn antenna at the input of the VNA, and a dielectric lens was used to collate the beam. Sets of identical measurements were taken of an ensemble of 13 subjects differing in gender, age and ethnic origin. Each set included a measurement of the skin reflectance, and concurrent recordings of the pulse rate, the systolic blood pressure, and the skin temperature.

The subjects performed 20 min of jogging after which a sequence of 30 sets of measurements were taken at 1 min intervals.

A typical sequence of sets of measurements is presented in Fig. 5(a). The skin reflectance is presented in terms of its

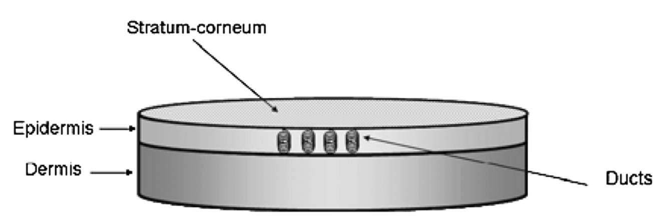

FIG. 3. The model used for 3D Electromagnetic simulations. The disk represents a portion of skin consisting of 3 separate layers and an array of 8 sweat ducts being subjected to a signal from the wave guide.

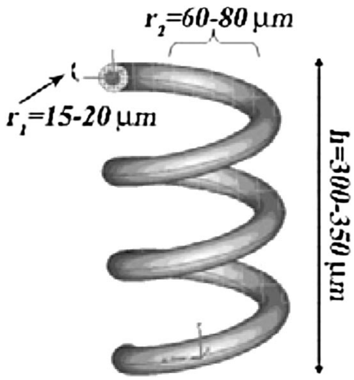

FIG. 4. The idealized sweat duct used in the simulation software "CST microwave studio" with the relevant dimensions. The sweat duct coil was modeled as a helical pipe filled with electrolyte. It is permanently full of sweat and so there exists a hydrogen bond network along the surface. Fast Proton hopping in H-bond network has been measured at 10^{-13} [6]. The difference in pH between the skin surface and the dermis results in a concentration gradient $\Delta[H^+] = 3 \times 10^{-6}$ mole/l and subsequent potential drop. This is the possible cause of fast currents in the coil. Proton conductivity in bulk water in biological structures has been measured at 100–1000 S/m [21]. Therefore in the simulation duct conductivity was set accordingly high, $\sigma = 500$–$20\,000$ S/m [see Fig. 2(b)].

frequency averaged relative signal intensity given by

$$\langle W_{\rm rel} \rangle = \frac{1}{f_2 - f_1} \int_{f_1}^{f_2} \frac{|U_{\rm subject}|^2}{|U_{\rm reference}|^2} df, \qquad (1)$$

where $U_{\rm subject}(f)$ is the reflected signal from the subject after physical activity, $U_{\rm reference}(f)$ is the reflected signal measured from the subject while sitting calmly before physical activity, $f_1 = 75$ GHz, and $f_2 = 110$ GHz. It can be seen that after the physical activity an exponential-like relaxation is observed, which is correlated to physiological stress as evidenced by parallel relaxations in pulse rate and systolic blood pressure. The results are summarized in Fig. 5(b) in which the normalized ensemble average of $W_{\rm rel}$, denoted as $\langle W_{\rm rel} \rangle$, for the 30 measurement points are presented vs the respective ensemble average of the systolic blood pressure. A strong correlation, defined by the coefficient r is clearly manifested with $r = 0.984$

$$r = \frac{\sum_{i=1}^{N}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{N}(x_i - \bar{x})^2 \sum_{i=1}^{N}(y_i - \bar{y})^2}}. \qquad (2)$$

To rule out the possibility that the observed phenomena could be due to the water content in the skin and underlying tissues, an additional set of measurements using a pressure cuff were performed. This allowed control of the blood flow during the measurement without activating the sweat gland system. As the cuff pressure is increased (0–100 mm Hg), it reduces the capillary blood flow [13] resulting in an increase of the total amount of blood in the skin and underlying tissue [14].

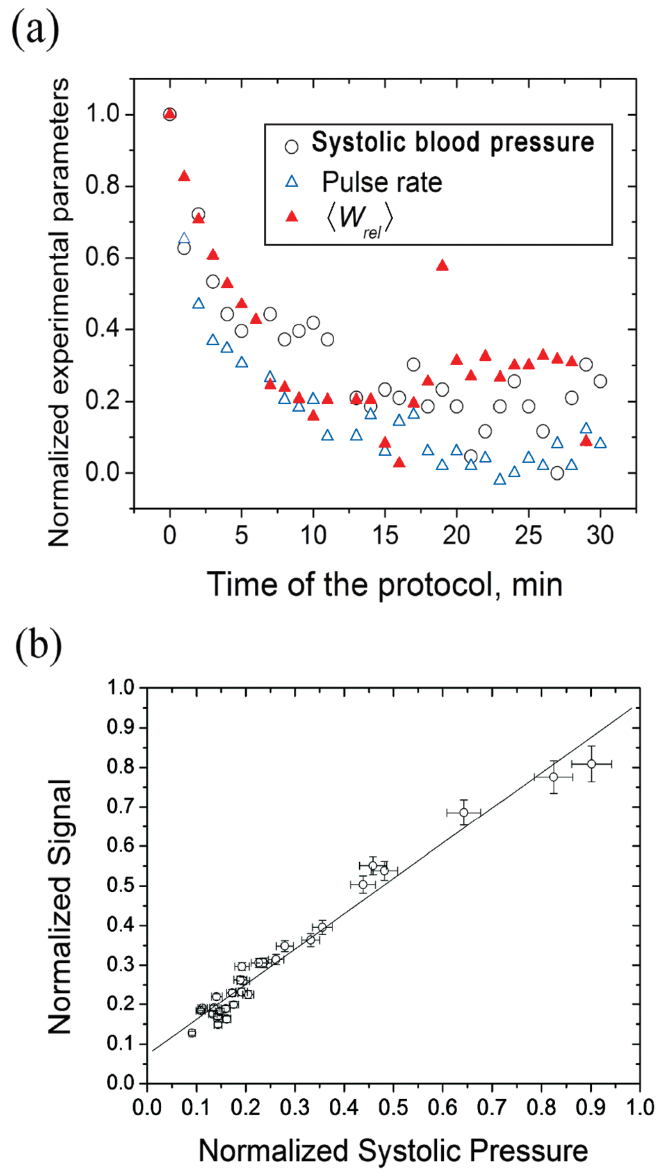

FIG. 5 (color). (a) The frequency averaged relative signal intensity $\langle W_{\rm rel} \rangle$ recorded from reflection coefficient measurements in the frequency band 75–110 GHz of the palm of a subject at rest following 20 min of intense physical activity. To avoid reflection from surface water the hand was kept dry; (b) the correlation graph between systolic blood pressure and $\langle W_{\rm rel} \rangle$, obtained from the average of 13 subjects measured as they relaxed for a period of 30 min after intensive physical activity. The intensities and blood pressures were normalized over their amplitudes to allow averaging and the correlation coefficient was calculated from linear regression. The value $r = 0.984$, close to unity, demonstrates a strong correlation between them. Essentially they exhibit similar temporal behavior. The correlation of $\langle W_{\rm rel} \rangle$ with the pulse rate is $r = 0.85$.

Measurements of the normalized average reflectance show no noticeable dependence on the capillary blood flow or change in volume fraction in this tissue compartment.

In order to test the effect of active or inactivate sweat glands on the reflection coefficient a creme containing a

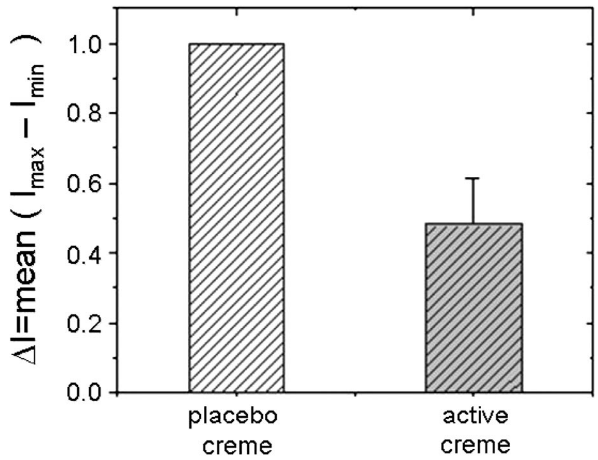

FIG. 6. The effect of temporally deactivated sweat glands on the relative signal intensity is illustrated by the lowered amplitude, using the synthetic tripeptide, applied to the skin surface 120 min before measurement. The amplitudes are averaged over 8 subjects and shown relative to the amplitude recorded when using a placebo creme.

snake venomlike synthetic tripeptide acting as an antagonist of the postsynaptic muscular nicotinic acetylcholine membrane's receptor (mnAChR), was applied to the test area [15]. The measurements of the reflection coefficient were repeated again after exercise. The same subjects were then treated with a placebo creme, based on the same matrix but not containing the synthetic tripeptide [16]. This was done in order to account for any hydrating effects of the creme itself. The results demonstrated a significantly lowered signal intensity when the active component was used, indicating the importance of neurally active/regulated sweat glands in the received signal. The results are illustrated in Fig. 6.

In summary it is claimed that individual sweat ducts are low-Q helical antennas and that their presence in the skin means that the skin can be regarded as a 2D antenna array in the sub-terahertz region. The spectral response is sensitive to the activity of the sweat system. These claims were substantiated experimentally where it was shown that the spectral response of the EM reflectance of the skin is indeed correlated with the activity level of the perspiration system and follows the same temporal behavior as other physiological parameters, such as the pulse rate and the systolic blood pressure. This phenomenon can be used as the basis for a generic remote sensing technique for providing a spatial map of the sweat gland activity of the examined subjects. As the mental state and sweat gland activity are correlated [17–19] it has the potential to become a method for providing by remote sensing information regarding some physiological parameters and the mental state of the patients.

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