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Invited Paper

Human sweat ducts as helical antennas in the sub-THz frequency range-an overview

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Abstract: Detailed anatomical studies of the human skin using optical coherence tomography (OCT) have revealed that the morphological structure of our eccrine sweat ducts is remarkably helical. These findings have raised the hypothesis that human sweat ducts can be the biological equivalent of helical antennas and hence resemble their electromagnetic (EM) behavior by receiving signals in the sub-THz frequency range. Here we show how this hypothesis evolved and was experimentally tested over the recent years, driven by the prospect of developing remote sensors for obtaining information about our physiological and mental state, as well as better understanding the consequences of using this frequency band for communications in the very near future.

Keywords: sub-THz frequency, Helical antennas, Sweat ducts

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1. Introduction and background

For more than 50 years there have been a number reports of non-thermal effects of extremely high frequency microwaves (MMW) on biological systems [1, 2]. Intriguingly, the reported frequencies are virtually absent in natural biological surroundings, making these effects all the more unusual [3, 4]. The interpretation of these phenomena has proven to be elusive. Theoretical ideas discussed in earlier papers in connection with experimental observations, have proved to be largely inconclusive, with poor reproducibility and several confounding results [5, 6]. To compound this conundrum, there is ample experimental evidence of beneficiary effects of low power (less than 20 mW/cm^2) MMW electromagnetic radiation in a number of therapeutic avenues such as coronary artery disease, various cancers, pain relief, wound regeneration and hyper tension [1, 6-8]. Many of these reports include an interaction with a subject via the skin. Few consider the reported effect theoretically on the level of a deterministic mechanism. In short, while there has been extensive documentation and some serious theoretical consideration, the true cause of these phenomena remains a mystery. At the reported power levels, almost all-electromagnetic energy at the frequencies of interest would be absorbed in the skin layer. It is worth considering for a moment what exactly the skin is.

The skin is the largest organ of our body, intended as the primary interface between the body and the environment. Its complexity and multi-layered morphology provide an extremely broad range of sensors and features, among them the perspiration system, mainly considered for body thermoregulation. Its main component is an ensemble of eccrine sweat glands, embedded at the bottom of the dermis layer and distributed with varying degrees of density. The sweat glands are controlled by the Central Nervous System (CNS) and when activated they secrete sweat into the sweat ducts, small tubular structures, distributed throughout the outer layer of the skin, which in their turn deliver the sweat up to the skin surface, where it evaporates.

Common illustrations of the skin present a convoluted arrangement for the sweat glands and a more or less straight tube for the sweat ducts and in the interaction of microwave radiation and human beings, the skin is traditionally considered as just an absorbing sponge stratum filled with water. However, detailed anatomical studies of the human skin, using optical coherence tomography (OCT), have revealed that the morphological structure of our sweat ducts is remarkably helical (see Figure 1) [9]. This observation, together with the fact that the dielectric permittivity of the dermis is higher than that of the epidermis [10], brought forward the hypothesis that human sweat ducts could exhibit electromagnetic (EM) behavior similar to that of classical helical antennas.

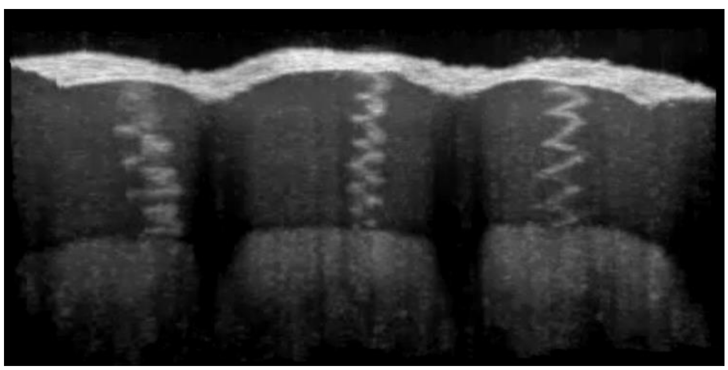


Fig. 1 OCT imaging of human sweat ducts in the upper epidermis of the fingertip in vivo (Image by P. Camilla, 2009, See [47])

In 2008, based on this idea, we published the first study confirming that the sweat duct could indeed behave as passive, low -Q antenna at sub-THz frequencies [11]. By applying basic antenna theory [12] to the typical duct dimensions, the characteristic frequencies of both end fire and normal modes were found to be in the sub-THz frequency range (see Figure 2).

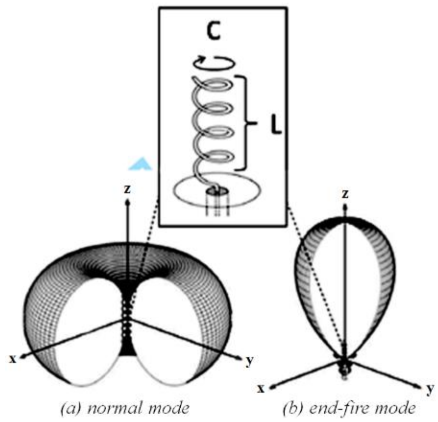


Fig. 2 Three-dimensional power patterns for helical antenna (a) normal mode and (b) axial (also called end-fire) mode [4]; the characteristic frequency of the modes depends on the dimensions C and L respectively. f~1/C≈400 *GHz* and f~1/L≈ 100 *GHz*. (Reproduced with permission of John Wiley & Sons Ltd, See Balanis [13]).

Since electric conductivity is necessary for any response, it was proposed [11] that the *ac* electric current "activated" in the "duct antenna" would be due to the diffusion of protons via hopping through distributed H-bond networks, known to exist in biological structures [14, 15]. The estimated hopping rates are in the range of 10^{13}-10^{14} s^{-1} (see Figure 3), sufficient to supply an oscillation in the sub-THz range.

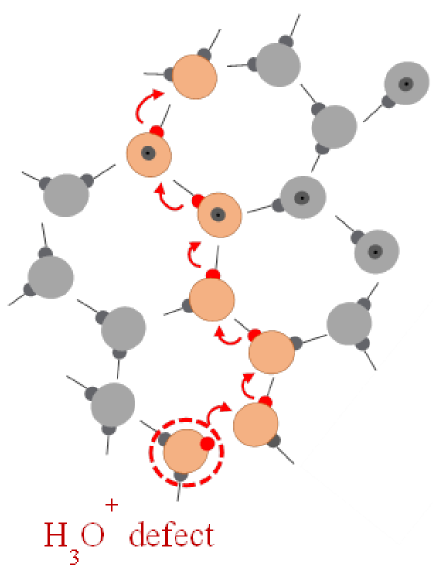


Fig. 3 Schematic representation of proton hopping through a distributed H-bond network (Reproduced with permission of N. Betzalel et al., 2018, See [48, 16, 17])

Furthermore, the diffusion of the proton though the network can be considered as "forced" along the direction of the duct. This is due to the drop in the electric potential caused by the pH difference between the skin surface (pH~5.5) and the dermis (pH~7) [15]. Thus, the sweat ducts possess all required features to reveal antenna-like behavior in the extremely high frequency band (EHF band or the millimeter/sub-millimeter band). There remains a question as to whether forced proton diffusion could supply a current strong enough for a noticeable effect? In bulk water, at 100 *GHz*, *ac* conductivity was measured and found to be ~100 *S/m* [18]. However, there is evidence that in the vicinity of a lipid/water interface, such as that along the inner surface of the sweat duct, water is well structured [19]. In such near-surface layers an increase in the proton diffusion rate by a factor of 100 [20], in comparison to that in bulk water, was found by fluorescence spectroscopy. Accordingly, the effective proton conductivity should be significantly higher than that in bulk water.

The skin contains between 2 to 5 million sweat ducts [21] spread over the body, with differing distribution densities depending on body zone. Furthermore sweat ducts constitute an active system, working according to a number of different stimuli (physiological, mental, emotional, or gustatory), not only due to thermoregulation [15]. Consequently, one would expect that the sub-THz spectra of the reflection coefficient (R) are also functions of skin morphology, the distribution of perspiration activity over the skin surface and the stimuli causing the sweating. The supposition pertaining to morphology and activity was substantiated by a series of the computer simulations that showed that the spectral response of the ducts indeed coincides with the prediction of antenna theory [22].

2. Physiological stress

The results obtained from the simulation work were verified in series of in vivo experiments conducted on a number of subjects in the W-band (75-110 *GHz*). It was shown that the reflection coefficient of their skin strongly depends on the physiological stress of the subject [11, 23]. In the experiments, the palm was held steady by a stand that was placed at a fixed distance from a horn antenna connected to the port of the Vector Network Analyzer (VNA). The measurements were carried out using subjects with different gender, age and ethnic origin [11, 23]. Every experimental run included both the measurement of skin reflectance and simultaneous recordings of the pulse rate, the systolic blood pressure, and the skin temperature. The subjects jogged for 20 minutes, and afterward a series of 30 measurements were conducted at 1 min intervals. These signals were compared to those of the same person measured when seated calm before the exercise. The results of the typical experimental run are presented in Figure 4. The skin reflectance is presented in terms of the relative signal intensity averaged over frequency interval, namely as

$$\langle W(t)\rangle_f = \frac{1}{(f_2 - f_1)}\int_{f_1}^{f_2} \left|\frac{U_{subject}(f,t)}{U_{reference}(f,t)}\right|^2 df$$

where $U_{subject}(f,t)$ is the signal reflected from the subject after his/her physical activity, $U_{reference}(f,t)$ is the signal taken from the same subject before engaging in physical activity. The frequency range was between f_1=75 *GHz* and f_2=110 *GHz* in this particular set of the experiments as shown in Figure 4. After physical activity an exponential-like decay can be observed in signal intensity, and it correlates well with the relaxation rate of the subject's systolic blood pressure [11, 23].

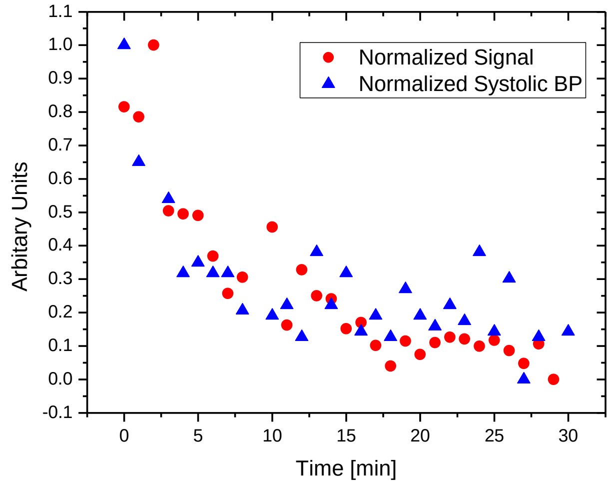


Fig. 4 The relative signal intensity (75–110 *GHz*) of the subject's palm, following 20 *min* of the intense physical activity [1] and the normalized systolic blood pressure, measured for the same subject during the same experiment (See [11,23], Reproduced with permission of Y. Feldman et al., 2009)

In order to substantiate that the observed phenomena are indeed governed by sweat duct activity, other sources that might also affect the measurement must be ruled out. Fortunately, in biological systems the potential background signal within the mentioned frequency range can only originate due to absorption of the impinging signal by water. The main absorption peak of water is located near 25 *GHz* (at 37 ℃), i.e., far from the frequencies under consideration [16-18]. However, it is possible that its high frequency tail affects the detected signals in the sub-THz region as well. Thus, it is a priori feasible that the observed activity can reflect, at least partially, changes that occur in the water content of the skin organ and in the underlying tissues (e.g., due to the capillary blood flow-perfusion processes, which strongly depend upon the physical activity). In order to eliminate this water effect, additional measurements using a pressure cuff (a rubber cuff wrapped around the upper arm and inflates to constrict the arteries) were performed [11, 23]. This enabled us to control blood perfusion during the measurement, without activating the sweat gland system. As the cuff pressure was increased (0–100 *mm Hg*), capillary blood flow was reduced resulting in an increase of the total amount of blood in the skin and the underlying tissue, effectively changing the average water content of the skin [24]. The relative skin intensity showed that changing the capillary blood flow in this tissue compartment had no effect on the reflection coefficient of the skin [23]. In order to test the effect of active or inactivate sweat glands on the reflection coefficient a cream containing snake venom-like synthetic tripeptide acting as an antagonist of the postsynaptic muscular nicotinic acetylcholine membrane's receptor (mnAChR) was applied to the test area [25]. Measurements of the reflection coefficient were then repeated after the same physical exercise as described above. After 24 hours, the same subjects were then treated with a placebo cream, based on the same matrix but not containing the synthetic tripeptide [26]. This was done in order to account for any hydrating effects of the cream itself. The obtained results exhibited significantly lowered signal intensity when the active cream was used [11, 23].

3. Mental stress

Sweat glands are directly controlled by the Sympathetic Nerve System (SNS) [27]. Consequently, stress, emotion, fear, pain, anxiety and disease can induce sweating [28, 29]. This provokes the question whether very gentle stimulation of the SNS, e.g., mental activity rather than intense physical activity, can elicit a detectable electromagnetic response of the skin. In order to answer this one must correlate the EM response to recognized triggers of mental stress [30]. There are several common ways to evoke mental stress, such as the Stroop effect [31], speaking in front of an audience and performing mental arithmetic [32]. We chose to exploit the Stroop effect during which a person is subjected to competing semantic and visual inputs. For example, the subject is requested to name the color of the fonts used to write the name of a different color, e.g., the word "blue" is written in red. Such an experiment is also called a color word test (CWT). This test was chosen since its duration is longer than most other mental tests (about 15 minutes), even though it induces only mild stress.

Stress can be monitored in a number of ways, including tracing the pulse rate, blood pressure, electrocardiogram, and other physiological parameters [33]. However, the most popular stress-detection method is based on the Galvanic Skin Response (GSR). Measuring the GSR is a standard approach for tracking changes in the SNS of a human subjected to psychological stress [34, 35]. The results of our recent study [30] clearly indicate that the reflection coefficient of the human hand in both W (75-110 *GHz*) and D (110-170 *GHz*) bands is correlated to universally accepted indicators of mental stress. The signals averaged over both frequency bands had correlations ranging from 0.74 to 0.93 for common indicators of stress, i.e. blood pressure and pulse rate. Particularly, the correlation between the GSR signal and $\langle W \rangle_f$ in the D band reaches 0.82 [30].

4. Circular dichroism

Despite this correlation with physiological and mental stresses [11, 23, 30], the link between the electromagnetic reflection properties of the skin and the helical structure of the sweat duct remained questionable. The key to identifying such a necessary link can be found in an important property of the sweat ducts' helical structure-homochirality. It was established in 1958 that 90% of human

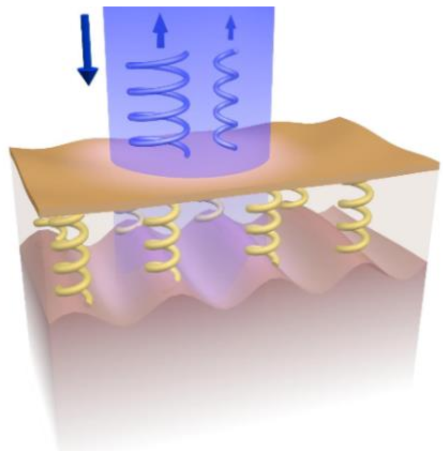
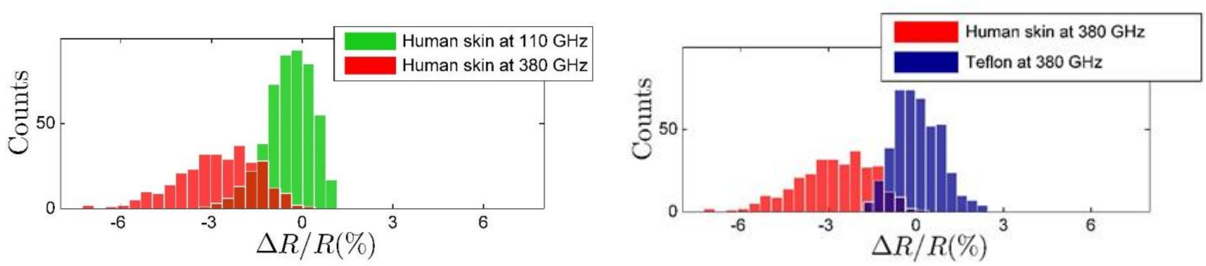


Fig. 5 In the schematic above the blue arrows represent the impinging linear wave and reflected circular components (right and left handed) of the reflected wave respectively. As the majority of the sweat ducts are right-handed, the reflected wave exhibits predominantly right handed circular polarization (Reproduced by permission of Y. Feldman et al., 2014, See [37])]

sweat duct have a right-handed turn [36]. This homogeneity will mean that an electromagnetic wave reflected from them will exhibit predominantly right-handed circular polarization (see Figure 5). The predominance of right-handed over left-handed polarization is known as Circular Dichroism and this was confirmed in the reflection coefficient of the palm of the hand [37].

Experimental verification of circular dichroism was provided at two frequency points: 380 *GHz*, which is estimated as the approximate axial mode of the helical structures, and 110 *GHz* for comparison (only negligible CD is expected at 110 *GHz* [22]). A typical histogram showing the pronounced CD effect for one subject is presented in Figure 6. CD was demonstrated at 380 *GHz* (red histogram) but not at 110 *GHz* (green histogram see Figure 6a). To eliminate any artifact of the measurement system, CD was also sought for Teflon at 380 *GHz*, and was not detected. (see Figure 6b). These results show that the residual CD is not due to the measurement setup.



(a) (b)

Fig. 6 (a) Histograms of the CD measured in the reflection from the skin of one typical human subject at 380 *GHz* (left histogram) and from the same subject at 110 *GHz* (right histogram); (b) Histograms of the CD reflection measurements from the skin of one typical subject (left histogram) and from a Teflon plate (right histogram). Significant nonzero CD is detected in the reflection from the human skin. (Reproduced by permission of Y. Feldman et al., 2014, See [37])])

Summarizing our main accomplishments thus far, the novel effect of absorption of sub-THz radiation by human sweat ducts, which operate as low-quality-factor helical antennas was predicted, discovered, and initially studied. Our findings also indicate that electromagnetic reflectance of skin correlates with the mental and physical human state. Recent experiments conducted by groups of American, Japanese British and Swiss scientists confirm our conclusions in many respects [38-41].

5. Emotional stress

Physical and mental stress are examples of tonic stress, in that the excitation of the SNS is long lasting and steady [42]. Some emotional stress, on the other hand, can be an example of a phasic stress. In this case, the excitation is momentary and strong. An example would be fright at the sight of a snake. It is a question as to whether such an episode would also lead to a measured response in the reflection from the sweat duct. In order to investigate the electromagnetic response to stimuli such as quick and emotional stress, a Picture/Guilty experiment was carried out on six healthy male subjects who were chosen at random with an average age of approximately thirty and with different skin colors. The pictures were chosen from the International Affective Picture System (IAPS), developed at the University of Florida [43]. The measurements were taken with the ABmm VNA system in the dual frequency mode, with the frequency set to 404 *GHz* and its dual frequency set to 303 *GHz*, with the sample rate set to 0.1 seconds. Concurrently the heart rate was monitored and Heart Rate Variability (HRV) was calculated as a stress indicator. The relationship between HRV and emotional stress is well documented [42, 44]. In general, lower HRV level indicated increased levels of emotional stress.

An example of the traces recorded is given in Figure 8. The reflection coefficient at 404 *GHz* is recorded as a function of time, while the subject is shown a series of images as described above, in the top pane. HRV was calculated by $HRV(t_n) = \sqrt{\left(NN(t_n) - NN(t_{n-1})\right)^2 + \left(NN(t_{n+1}) - NN(t_n)\right)^2}$, where $NN(t_n)$ is the time interval between successive heart beats (R peak to R peak) at time point t_n and the HRV is averaged over a 16 second window. Typically, after particularly distressing pictures (murder scenes or violence) the HRV is depressed and a drop in the signal strength of the reflection coefficient is noted. This can be observed in Figure 8 after the picture at 255 seconds, which was a gruesome murder scene. Between each image, the subject is exposed to a white screen.

Part of the reflection coefficient trace is repeated in Figure 9. In this figure, a periodic oscillation is noticed on the signal that can be traced to the effect of the heartbeat on the signal [45]. This has been related to the periodic expansion and contraction of the skin induced by capillary blood flow.

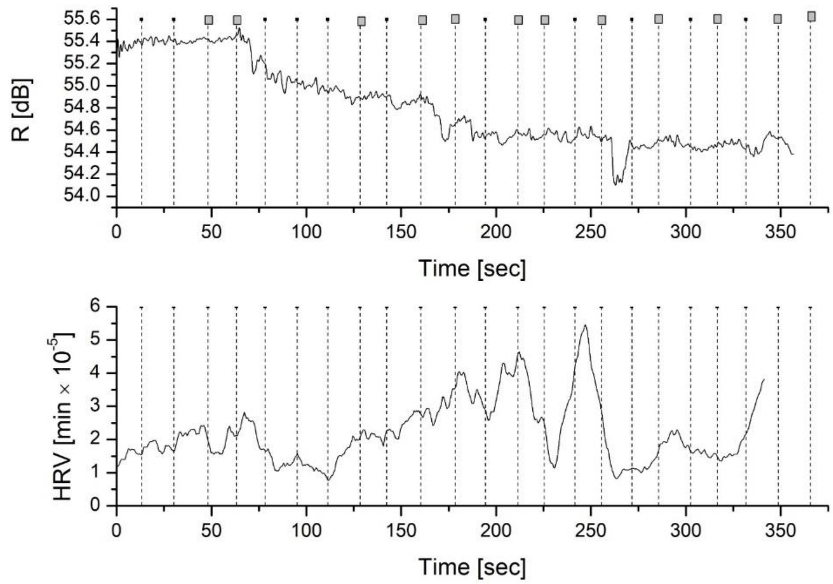


Fig. 7 Picture test results for a single subject. The dashed lines represent the points in time where an image appeared. The specifically difficult images, representing fear or disgust, are explicitly marked. The top pane is the reflection coefficient in dB and the bottom pane is the HRV trace of the subject, measured concurrently. Sharp drops in the signal are noted, specifically after disturbing images.

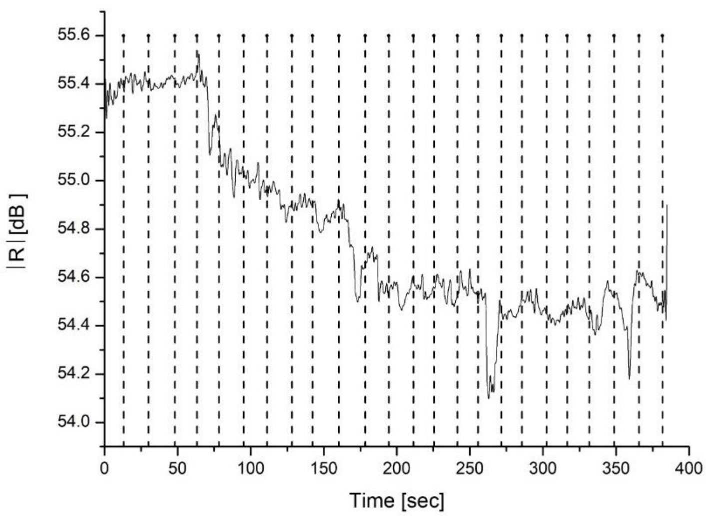


Fig. 8 Zoomed in view of the electromagnetic response as measured by the ABmm amplitude signal at 404 *GHz* during the Picture Arousal Test.

6. SAR

Many of previously described works were accompanied by simulations, starting from a very basic skin model, through refining the roughness of the layers when shifting to higher frequencies to improve the model to a multilayered unit cell model with helically shaped sweat duct embedded in it (see left hand side of Figure 10). This improved model enabled to simulated the specific absorption rate (SAR) [46] of human skin in the frequency range of 50 *GHz* to 700 *GHz*, using different conductivity levels of the duct (2000 *S/m*, 5000 *S/m*, 10,000 *S/m* and no duct). The results showed a clear difference between the model simulated with sweat duct and the one without. On the right-hand side of Figure 11 a demonstration of the maximal SAR value as function of the frequency [46].

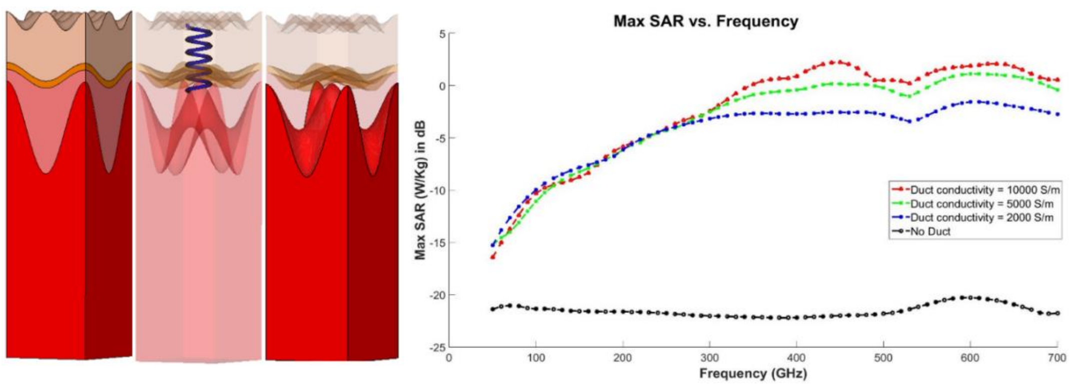


Fig. 9 On the left: CST human skin model, with and without sweat duct. On the right: maximal SAR values as function of the frequency. It is clearly seen that the maximal SAR in a model, which contains helical duct is higher than that of a model with no duct. (Reproduced with permission of N. Betzalel et al., 2018, See [48])

The results show a clear evidence of the fact that, even low levels of duct conductivities, i.e. 2000 *S/m*, consequent in high levels of SAR. The skin model exhibits strong peaks at 410 *GHz* and 500 *GHz*. These conclusions are further accentuated when one visualizes the electric field distributions inside the model (Figure 11). It can be seen that the EM field is absorbed effectively in the duct and concentrated there.

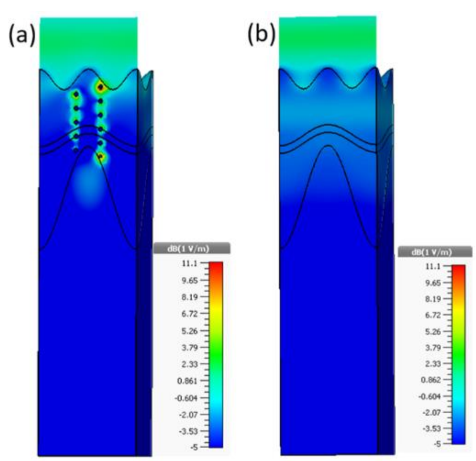


Fig. 10 Cross-section of the E-field of a thick skin in frequency of 450 *GHz*. (a) Model with duct. (b) Model without duct. (Reproduced with permission of N. Betzalel et al., 2018, See [48])

The results of this study emphasize the reaction of human skin to the EM radiation in the sub-THz range, due to helically shaped sweat ducts spaded all over our body, which possess EM properties in this range. While the influence of the sub-THz radiation on our body is not yet understood, we definitely witness an explicit response of our skin to that range of frequencies, and encourage further study of this field before giving a green light to exploiting this frequency range in the industry [47].

7. Conclusions

The hypothesis that human sweat ducts can be the biological equivalent of helical antennas and hence resemble their electromagnetic (EM) behavior by receiving signals in the sub-THz frequency range has evolved and was experimentally tested in several different ways in recent years. Although the entire mechanism is not yet fully understood, these works have showed that our body is sensitive to radiation on this frequency range. Hence, while the signals originating from the sweat ducts hold promising prospects for developing remote sensors for mental stress and physiological parameters, it also poses danger due to the absorption levels obtained in simulations. Current safety recommendations date back to 2009 and related principally to thermal damage. As the information industry gallops towards the 5G standards, with correspondingly higher frequency windows, this body of work suggests that there is a real need to re-assess how safety levels are established.

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