Frequency of the resonance of the human sweat duct in a normal mode of operation

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Abstract: The applications of terahertz (THz) waves have been increasing rapidly in different fields such as information and communication technology, homeland security and biomedical engineering. However, study on the possible health implications due to various biological effects induced by THz waves is relatively scarce. Previously, it has been reported that the human sweat ducts play a significant role in the interaction of the THz wave with human skin due to its coiled structure. This structure imposes on them the electromagnetic character of a helical antenna. To further understand these phenomena, we investigated the morphological features of human sweat ducts and the dielectric properties of their surrounding medium. Based upon these parameters, we estimated the frequency of the resonance of the human sweat duct in a normal mode of operation and our estimation showed that there is a broad resonance around 228 GHz. This result indicates that careful consideration should be given while designing electronic and photonic devices operating in the sub-terahertz frequency region in order to avoid various effects on human health due to these waves.

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possess a spectral fingerprint in THz frequency region rendering them detectable, based on testing and evaluation. Moreover, wide variety of materials such as narcotics and explosives can penetrate through wide variety of materials such as plastics, papers and cloths making them gigahertz (GHz) to few terahertz (THz) known as terahertz waves. These waves can penetrate through skin and other materials and are known to be useful in various applications such as security screening and non-destructive testing and evaluation. Furthermore, terahertz waves possess a spectral fingerprint in THz frequency region rendering them detectable, based on THz spectral imaging. Along with these applications, terahertz waves are being exploited in a wide range of fields such as medicine, biology, and materials science.
in wireless communication owing to their ability to satisfy the increasing demand for high speed data transfer. All these characteristics make the THz wave an attractive option in diverse fields from biomedical sciences and homeland security to information and communication technologies [1–5]. With the rapid development of THz applications in such fields, the THz frequency is now becoming ubiquitous. Despite these developments, a thorough study of the interaction of the terahertz wave with human skin has yet to be undertaken. More worryingly, evidence of non-thermal biological effects of electromagnetic energy in the GHz range is beginning to emerge [6–9], and one must ask what are the implications for exploiting the sub-THz band for cellular communications. Therefore, it is crucial to understand the possible biological effects induced by THz waves on human beings.

There have been a number of studies on various biological effects caused by THz waves. The majority of such studies deal with thermal and non-thermal effects due to THz irradiation [10,11]. For example, the influence of a high peak electric field of the THz wave has been investigated and effects such as DNA damage have been reported [12]. Besides these studies, Feldman et al. have reported that the human sweat ducts in skin play a significant role in the interaction of THz wave with human skin [13,14]. In these works, it has been experimentally demonstrated that the sweat duct can act as a low-Q-factor helical antenna when the helical structured sweat ducts are filled with sweat consisting of conducting electrolyte. The conductivity mechanism in this case is assigned to proton hopping though ordered aqueous H-bond networks, rather than ionic conductivity. These results have also been assessed by Yang et al. [15]. Based upon the numerical modeling and experimental data, it was suggested that the sweat duct play a role in characterizing the phenomena of resonance behavior. Moreover, circular dichroism in this frequency band - the signature of the helix, has also been reported in the measurements of human skin in the sub-THz range [16,17]. Similarly, Shaferstein et al. reported that the sweat ducts play a significant role in millimeter wave absorption, indicating possible thermal effects induced by such waves [18]. Recently, Betzalel et al. thoroughly investigated the absorbance of sub-THz radiation by human skin and demonstrated that the absorption of THz wave is governed by the topology for the skin and the sweat duct [19]. All these studies have demonstrated that the presence of helically structured sweat ducts in skin plays a significant role in the interaction of THz wave with human skin and this knowledge will impact on the future directions of THz wave research. Besides this, study on THz wave interaction with human skin is stressed by various works on THz channel characterization in human skin for body-centric nano-communication [20–22], for development of extremely high-power gyrotron operating in sub-terahertz frequency region [23–25] and high data-rate terahertz communication links [26–27].

When the wavelength of electromagnetic waves is comparable to the dimension of biological structures, it is important to know the electromagnetic wave interaction with these structures and to consider possible resonating behavior. In our previous study, we found that the dimensions of the helical portion of sweat duct are comparable to the wavelength of terahertz wave and we reported the frequency of resonance in the axial mode of operation [28].

In order to further investigate the influence of human sweat duct on the interaction of the THz wave with skin, it is essential to understand the various modes of operation of such a helical structure. According to antenna theory, the helical structure operates mainly in two modes: the axial mode (also known as the end-fire mode) and the normal mode (also known as the broadside mode) [29]. In the axial mode, the circumference of helix is proportional to the wavelength and the amplitude pattern is along the axis of the helix as shown in Fig. 1(a). On the other hand, in the normal mode, the dimensions of the helix are small in comparison to the wavelength. The amplitude pattern has its maximum in a plane normal to the axis when the wavelength is proportional to the length and is nearly null along the axis as shown in Fig. 1(b). The basic geometry of the helix is described in terms of its diameter (D), the number of turns (N) and the length (L) as shown in Fig. 1(c). Based on this, the circumference of the
The helix (C) is calculated as $C = \pi D$, the spacing between the turns (S) is calculated as $S = L/N$ and the pitch angle ($\alpha$), which is the angle formed by a line tangent to the helix wire and a plane perpendicular to the helix axis, was calculated as $\alpha = \tan^{-1}(S/\pi D)$. Finally, the total length of the helix ($L_t$) was calculated as $L_t = NL_0 = (L^2 + C^2N^2)^{1/2}$, where $L_0 = (S^2 + C^2)^{1/2}$ is the length of the helix between each turn.

Fig. 1. Modes of operation of a helix: (a) axial mode and (b) normal mode. The structural parameters (c) of the helix, which is characterized by its length (L), its diameter (D) and the spacing between the turns (S).

Recently we have investigated the frequency of resonance of human sweat duct in the axial mode of operation where we found that the central frequency of resonance is approximately 442 GHz with a standard deviation of 76 GHz [28]. In this work, we have extended our study to the normal mode of operation. In order to compute the frequency of resonance, we first obtained the structural parameters of sweat duct such as their length, number of turns and the diameter of the helical portion of human sweat duct. We also investigated the dielectric properties of stratum corneum based upon a mixture formula [19]. Finally, we estimated the frequency of resonance of human sweat duct in the normal mode of operation based upon the principles of antenna theory.

2. The morphology of sweat ducts

Human sweat glands are distributed throughout the skin and the number of glands in the skin varies from 2 - 4 millions [30]. These glands consist of three major parts: a coiled secretory portion in the dermis, a straight duct that passes through the dermis to epidermis and a helical portion extending from epidermis to the stratum corneum [31]. In this study, the helical portion of the sweat duct is of prime concern as it is responsible for the interaction with terahertz waves, since its diameter is comparable to the wavelength of the THz wave. We performed an in-vivo systematic study of the morphological features of the human sweat duct using optical coherence tomography (OCT) and determined their structural parameters such as their diameter, the number of turns and their length. We recruited 28 subjects (adult = 18, child = 10) and performed OCT measurements in vivo on different regions of the palm (R1 = the base of the little finger; R2 = between thumb and wrist; R3 = the right index finger tip) and foot (R4 = the inner arch; R5 = mound of the big toe; R6 = the right second toe on the foot.) as shown in Fig. 2(a).

In our study, we used a commercially available OCT system (Santec Inc. IVS-300), which consists of a fiber laser with a wavelength of 1310 nm. The scanning rate of the system is 30 kHz. We took 2D images at a rate of 25 frames/sec, which were displayed as a vertical slice in a plane perpendicular to the surface of skin. In our experiment, a 3D data set consisting of $(x = 255, y = 255, z = 849)$ pixels covering a volume $2.5 \text{ mm} \times 2.5 \text{ mm} \times 8.49 \text{ mm}$ was recorded for each measurement. The lateral pixel resolution was 9.8 $\mu\text{m}$ and the depth resolution was 4.2 $\mu\text{m}$. We took 125 images in x-z plane and we extracted en-face images in the x-y plane. Figure 2(b) is the typical OCT image showing the stratum corneum, the helical
structured sweat duct in stratum corneum and dermis. These morphological features of skin are consistent with previously published results [32,33].

![Image](image1.png)

Fig. 2. (a) The measurement regions on the palm and the foot (b) A typical OCT image showing the stratum corneum and the helical sweat duct.

Figure 3(a) shows the diameter of the helical portion of the sweat duct in all the measurement regions. We observe that the diameter of the duct, regardless of the subject, is almost equal for all measurement regions. This was confirmed by employing the Welch t-test on the data sets [34]. P values of more than 0.6 were observed, confirming the null hypothesis. The average duct diameter was 95 μm. The relative standard deviation (RSD = standard deviation / mean × 100) was maximum in region R4 whereas it was minimum in region R6. Figure 3(b) shows the number of turns of the helix in different measurement regions and the average number of turns was 5. The length of the sweat duct in helical region is shown in Fig. 3(c), where the average length calculated from all regions was 306 μm. The longest ducts in average lie in region R5 and shortest duct is in region R2. However, the maximum and minimum RSDs are in regions R1 and R2 respectively. The total length of duct in helical region is shown in Fig. 3(d). Overall comparison shows that the RSD in duct diameter is significantly small in comparison to other duct parameters such as number of turns and duct length.

We also investigated the Pearson’s correlation coefficient between different sweat duct parameters as shown in Table 1. We observed that the correlation coefficient between the length and total length of helical region of sweat duct is 0.98. Moreover, the number of turns is also strongly correlated with length and total length of the sweat duct. This indicates that the pitch angle (α) is almost constant irrespective to the site of the measurement.

| Table 1. Pearson’s correlation coefficient between different sweat duct parameters |
|---------------------------------|-----------------|-----------------|-----------------|
| Length (L)                      | Total Length (Lₜ) | No. of turns (N) | Diameter (D)    |
| Length (L)                      | 1                |                 |                 |
| Total length (Lₜ)               | 0.98*            | 1               |                 |
| No. of turns (N)                | 0.98*            | 0.99*           | 1               |
| Diameter (D)                    | -0.28            | -0.25           | -0.32           | 1               |

* Significant linear correlation at p < 0.01

We have summarized these parameters along with duct density at each of the measurement sites in Data File 1 in order to provide further information. We calculated the average values, the standard deviation, the interquartile ranges and the medium values for each site. The values are given for the sub-sets (men, women and children) as well as for the total set.
Fig. 3. Box plots showing median (central line of box), 1st and 3rd quartile ranges around the median (bottom and top of box respectively) and maximum and minimum (represented by whiskers) of (a) sweat duct diameter (b) number of turns in sweat duct (c) length of the duct and (d) total length of the duct in different measurement regions. ‘×’ indicates the mean of data.

3. Frequency of Resonance

When the helix is irradiated by an electromagnetic wave, the frequency of resonance is predominantly determined by the diameter of the helix (D), length of the helix (L) and number of turns in the helix (N). Now, the spacing between the turns (S) is computed as L/N and the pitch angle (α) is computed as tan⁻¹(S/C), where C (= πD) is the circumference of the helix. In normal mode of radiation, the dimension of helix is small compared to the wavelength and the polarization of the helix is elliptical, where the axial ratio (AR) can be approximated as [29]

$$AR = \frac{2\lambda_0 S}{\pi D^2}$$  \hspace{1cm} (1)

Here, by varying the diameter (D) and the spacing (S), the axial ratio attains the value of $0 \leq AR \leq \infty$. In a special case, when AR becomes one (AR = 1), the field of radiation is circularly polarized. This condition is satisfied when the relationship between circumference, spacing and wavelength.
\( C = \pi D = \sqrt{2S\lambda_0} \) \hspace{1cm} (2)

holds true. For which, pitch angle \( \alpha \) can be written as follows:

\[ \tan \alpha = \frac{S}{\pi D} = \frac{\pi D}{2\lambda_0} \] \hspace{1cm} (3)

In this case, the polarization of this mode is same in all directions except along the axis of the helix. Figure (4) shows the axial ratio when \( D = 95 \, \mu m \), \( S = 61 \, \mu m \) and the refractive index of the skin \( n = 1.8 \) [16,19]. Based upon these equations, the frequency of resonance with the consideration of refractive index of stratum corneum is written as [29]

\[ f = \frac{c}{n} \frac{2s}{\pi D^2} \] \hspace{1cm} (4)

Here, \( c \) is the velocity of light and \( n \) is the refractive index of the skin. From this expression, the frequency of resonance of sweat duct in normal mode of operation is estimated as 228 GHz. However, it is important to note that the refractive index of stratum corneum depends upon the water content [35,36]. The profile of the water content has been measured [19] and varies for 10% at the skin surface, 30% approximately in the stratum corneum and rising to 80% at the junction with the dermis. Consequently, the index of refraction in Eq. (4) should be used as an averaged effective value for the skin. Along with this, the variation in sweat duct diameter causes a slight variation in the frequency of resonance. It is intriguing to note that simulation studies of the reflection coefficient of the sweat duct by Hayut et al. [16] reveal a broad minimum centered around 230 GHz. This is most likely the predicted normal mode. However, it is important to note that the axis of sweat duct is normal to surface of the skin therefore, the axial mode of operation is likely to be dominant.

Fig. 4. Axial ratio of the helix with diameter \( D = 95 \, \mu m \), spacing between the turn \( S = 61 \, \mu m \) and refractive index \( n = 1.8 \).

4. Conclusion

The study on interaction of THz wave with human skin with the consideration of helical structured sweat duct as an antenna is relatively new. Previously, we investigated the frequency of resonance of sweat duct in axial mode of radiation. Since, the helix has two modes of operation, in this paper we extended our previous research and studied the frequency of resonance of human sweat duct in normal mode of operation by investigating the various morphological features of sweat duct such as their diameter, length and number of turns. We estimated that the sweat duct in normal mode of operation resonates at 228 GHz.
and we believe that this finding will help to further investigate the various effects caused by high frequency electromagnetic wave in the sub-terahertz frequency band. Moreover, this result shows the important criteria to select high frequency electromagnetic wave for the development of biomedical devices and high-speed wireless communication system since the recent progress shows that the next generation communication systems such as THz wireless communication and body-centric nano-communications are expected to operate in a few hundreds of GHz. For example, research on high-speed THz communication systems is progressing rapidly utilizing the various frequency windows such as 140 GHz and 240 GHz due to the low atmospheric propagation loss. Besides this, extremely high-power sources of gyrotron operating in few hundreds of GHz are being studied for fusion experiments, where small stray radiation of such high power might become an important health issue for the workers in such environment.

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**Informed consent**
Informed consent was obtained from all individual participants included in the study.

**Disclosures**
The authors declare that there are no conflicts of interest related to this article.