Computational simulations of the penetration of 0.30 THz radiation into the human ear

ZOLTAN VILAGOSH,1,2,* ALIREZA LAJEVARDIPOUR,1,2 AND ANDREW WOOD1,2

1Swinburne University of Technology Melbourne, Australia
2Australian Centre for Electromagnetic Bioeffects Research, Australia
*zvilagosh@swin.edu.au

Abstract: There is an increasing interest in industrial and security applications and the establishment of wireless communication operating at frequencies of up to 0.30 THz. Soft tissue has a high coefficient of absorption at 0.30 THz and this limits effective penetration of the energy to a depth of 0.2 to 0.4 mm. The capacity of 0.30 THz radiation to access the deeper parts of the ear by diffusing through the ear canal and exposing the tympanic membrane (ear drum) to the radiation has not been studied. Simulations show that, with excitation parallel to the ear canal, the average power flux density within the central tympanic membrane region is 97% of the incident excitation. The structures of the outer ear are highly protective; less than 0.4% of the power flux density is directed at 45° from the parallel reached the same region. Given the sensitivity of the tympanic membrane to mechanical change, in-vivo assessment of the penetration of 0.3 THz into the ear canal is warranted to assess the suitability of the present radiation safety limits and to inform 0.3 THz emitting device design.

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1. Introduction

Terahertz (THz) frequency region of the electromagnetic spectrum lies between the infrared and microwave bands. It is defined as radiation of 0.1 to 10.0 x10¹² Hz, (wavelengths of 3 mm - 0.03 mm). The THz region has been poorly explored in the past due to the technical difficulties in creating and detecting the radiation [1]. Novel THz production and spectroscopy methods have allowed THz radiation to be used for non-destructive quality control in manufacturing [2], airport security screening and quantitative analysis of chemical mixtures [3]. The higher frequency promises greater data carrying capacity, thus there are proposals for telecommunication systems using frequencies up to 0.30 THz [4]. This has the potential to expand data capacity by two orders of magnitude over the present 1.0 GHz networks, but it also increases individual photon energy by a factor of 300. Water has high absorption coefficient in the THz frequency and thus a closely spaced transmission network for any telecommunication links would be needed to overcome the signal loss. This creates the potential for head height transmitters, whether mobile or fixed, to become commonplace.

There are no data on long term exposure of humans to THz radiation [5]. The current safety standards for exposure for 6-300 GHz (0.006-0.3 THz) by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [6,7] recommend that incident power flux density (PD) rather than specific absorption rate (SAR) is the appropriate measure for the setting of standards for this frequency range. Incident PD is directly related to the incident electric (E) field strength by the formula PD = E² / Z, where Z is the impedance of the medium. Z₀ = 377 Ω, the impedance of free space, whilst Z for other media can be calculated using the formula E/H, where H is the magnetic field strength. The recommendation for the use PD of rests on the high absorption coefficient of human tissues over the 6-300 GHz range. The absorption increases with frequency, to be in the order of 80 cm⁻¹ for dermis or connective tissue at 0.3THz. This results in the absorption of 55% of the
incident radiation in the first 0.10 mm at 0.3 THz leading to a 75% drop in the PD after passage through 0.1 mm of tissue. SAR is derived by the formula \( \text{SAR} = \sigma E^2 / \text{Md} \), where \( \sigma \) is the conductivity and \( \text{Md} \) is the mass density of the tissue. Given the rapid falloff of \( E \) in the tissue at 0.3 THz, any derivation of SAR is valid for only a small layer of tissue in the order of 0.02-0.03 mm thickness. The ICNIRP standard for 6-300 GHz for the maximum time averaged PD for the general public is 10 Wm\(^{-2}\), with an averaging time of six minutes, translating to an incident electric field of 61.4 Vm\(^{-1}\) in air (\( Z \approx 377 \Omega \)).

The outer surface of the eye and the skin take up the bulk of any radiation from THz sources outside the body. The penetration of radiation into the human ear canal and the tympanic membrane (ear drum) from THz devices has not been studied. Given the expanding uses and the associated increasing exposure, there is a need to develop an understanding of how THz radiation penetrates into the ear. This will allow informed exposure recommendations and for safe THz emitting device design.

The human ear dimensions have a large individual variability [8]. In adult humans, the ear canal is angled in the superior (upwards) and anterior (forward) direction from the horizontal and has an average 9 mm height and 7 mm width. The canal is wider near the tympanic membrane (ear drum) [9]. There is a thick layer (0.1 mm) of stratum corneum (SC) lining the inner canal as the area is not abraded mechanically. Deeper to the SC lies a thin layer (0.01-0.02 mm) of epidermis directly over connective tissue as there is no dermis layer. The tympanic membrane is approximately 25 mm from the canal entrance, angled at 25-30% from the vertical, with the lowermost region being deeper in the canal. The thickness of a typical tympanic membrane is between 0.06 and 0.25mm. The membrane is thicker in children and becomes thinner throughout life [10]. Given these dimensions, the tympanic membrane is capable of absorbing a significant portion of the 0.30 THz radiation presented to it. The tympanic membrane is richly innervated [8,11] and is highly sensitive to inflammation and mechanical insult. Small changes in the local environment of the tympanic membrane may elicit noticeable symptoms and chronic damage may lead to hearing loss. At a 3.5 mm radius (the narrower dimension of the ear canal), the expected cut-off frequency below which a cylinder cannot act as a wave guide is approximately 25 GHz. Above this frequency, and therefore at 0.30 THz, the absorption and reflection properties of the tissues of the outer ear, the ear canal and the tympanic membrane become important in the propagation of EM radiation.

The exploration of 0.3 THz frequency radiation exposure of the ear drum is hampered by a lack of a suitable animal model for in-vivo studies. The usual laboratory animals, such as guinea-pigs, rabbits and pigs, have disproportionate tortuosity of their ear canal, their tympanic membranes are too small to manipulate or are too obliquely angled [12]. Under these circumstances, the use of computer-based phantoms becomes an attractive option to perform the preliminary studies.

### 2. Methods

A finite difference time domain (FDTD) solver, XFdtd (Remcom Inc., State College, PA, USA), was used for the design and execution of the simulation. The simulation was undertaken at three angles, the first parallel to the ear canal (angled 10° superior and 5° anterior from the true horizontal), the second at 30° anterior to the parallel direction and the third at 45° above the parallel direction (Figs. 1(a)-1(c)). A further simulation was undertaken with the features of the outer ear removed, using the parallel excitation signal. This simulation further explored the protective aspects of the outer ear and also emulated a transmitting device beaming directly into the ear canal. The model size was 708 x 788 x 1418 cells, giving a total of 7.9 x 10^8 mesh cells. The “staircase” effect was minimised by the use of the “exact mesh” feature of the solver, which smoothed the edges of the tympanic membrane model. Each simulation was run for a 40,000 time steps of 7.04 x 10^-2 picoseconds (ps), giving a total simulation time of 2816 ps.
The model had representation of the outer tragus and inner parts of the antitragus and antihelix (Figs. 1(d) and 1(e)). The simulation was performed using a variable geometry, with a minimum 15 Yee cells per wavelength, and a maximum of 250 Yee cells per wavelength in crucial areas such as the tympanic membrane. The model included an angled ear canal with dimensions 9.0 x 7.0 mm at the entrance and becoming more capacious near the tympanic membrane. Given that the major interest lies in the absorption in the outer layers, of a simplified tympanic membrane was represented with a 0.03 mm SC, 0.10 mm fibrous layer and a 0.05 mm mucous membrane on the inner aspect of the tympanic membrane. The dielectric parameters for the absorption and reflection of the radiation within the ear were expressed as the real ($\varepsilon'$) and imaginary ($\varepsilon''$) parts of the permittivity (Fig. 2(a)). The values were derived from Maxwell-Wagner mixing equation [13] and data from [14–16].

Three planar electric (E) field sensors were used. The sensor output was a false colour, decibel (dB) scale image of the absolute value of the E-field. The sampling interval was every 100 timesteps (7.04 ps). One planar sensor was positioned to bisect the ear canal longitudinally, one placed vertically at 20 mm inside the canal (Fig. 1(g)) and a third 0.01 mm inside the tympanic membrane surface (Fig. 1(h)). Point E-field and H-field sensors were used to sample the absolute value of the fields at every timestep. These were placed in 2 arrays. A 6-sensor array (3 horizontal x 2 vertical) was placed within the central region of the tympanic membrane, 0.01 mm, inside the tympanic membrane surface. The placing was chosen to exclude any reflected radiation at the outer tympanic membrane surface and to exclude anomalies caused by the staircase effect. A second, matching, 6 point array was placed 0.02 mm beyond the tympanic membrane in the middle ear to gauge the radiation entering the middle ear. The individual point sensors in the arrays were separated from each other by 0.5 mm.

A modified Gaussian excitation with a peak amplitude of 1.0 V, at 0.3 THz and a duration of 50 ps. was used (Fig. 2(b)), giving a total excitation pulse length of 15 mm. The use of a 15 mm pulse allowed for the differentiation of the direct effect of the pulse from any reflections or interference from the back of the model. The excitations were directed as per Figs. 1(a)-1(c).

<table>
<thead>
<tr>
<th>Tissue Type</th>
<th>$\varepsilon'$</th>
<th>$\varepsilon''$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connective tissue and Dermal</td>
<td>3.5</td>
<td>2.6</td>
</tr>
<tr>
<td>Stratum Spinosum</td>
<td>5.1</td>
<td>5.2</td>
</tr>
<tr>
<td>Stratum Corneum</td>
<td>3.2</td>
<td>1.3</td>
</tr>
<tr>
<td>Mucous Membrane</td>
<td>6.5</td>
<td>7.2</td>
</tr>
</tbody>
</table>

Fig. 2. (a) The list of the values for the real ($\varepsilon'$) and imaginary ($\varepsilon''$) parts of the permittivity of the tissues for the model. (b) The characteristics of the excitation used in the simulations.
The results are quoted in terms of the E-field intensity (V m\(^{-1}\)), H-field (A m\(^{-1}\)), PD (W m\(^2\)), SAR (W kg\(^{-1}\)) and the maximum temperature rise per second (°C s\(^{-1}\)). The values for the tissue mass density (Md) of 1150 kg m\(^{-3}\) and heat capacity (c) of 3000 Joule °C\(^{-1}\) kg\(^{-1}\) are from Collins [17]. The temperature rise formula used is \(\Delta T = \sigma \text{SAR}/c\) which sets aside any contribution from blood flow and radiative loss and is the maximum amount of the heating that could be expected from the excitation.

3. Results

Images of the E-field propagation of the parallel pulse is shown in Figs. 3(a) and 3(b). The planar sensor output with the 30° anterior, and the 45° above the horizontal pulse is shown in Figs. 3(c) and 3(d). The parallel pulse propagates preferentially near the middle of the ear canal, producing a central high intensity region. The planar E-field patterns at a plane 20 mm from the entrance of the canal and within the tympanic membrane are depicted in Fig. 3(e) and 3(f) respectively. There is a similar pattern in the simulation with the outer ear features removed, albeit at a higher E-field intensity (Figs. 3(g) and 3(h)). The preferential central propagation is evident at the planar sensor output displayed in Figs. 3(f) and 3(h), indicating that the central region of the tympanic membrane is most exposed to the incident radiation.

The mean of the maximum values of the E-field point sensor array placed 0.01 mm within the tympanic membrane are displayed in Table 1A. The mean of 0.74 V m\(^{-1}\) for the 6 point sensor array was noted, with a standard deviation of 0.22 V m\(^{-1}\). The results adjusted to the upper ICNIRP general public safety limit of 61.4 V m\(^{-1}\) (PD of 10 W m\(^{-2}\) in air) are presented in Table 1B. The values for the H field and the resultant estimation of \(Z_{\text{tissue}}\) is shown in Tables 1(C) and 1(D). The derived PD values are displayed in Table 1E. The SAR for the region layer of tissue that surrounds the E-field point sensors is given in Table 1(F). The calculated maximum temperature rise after 1 second during a 10 W m\(^{-2}\) exposure is given in Table 1G.

If the excitation is equivalent to the general public safety limit (10 W m\(^{-2}\)), the average PD reaching the tympanic membrane is 9.71 W m\(^{-2}\) when using the parallel excitation. The structures of the ear and the canal reduce the average PD to 0.088 W m\(^{-2}\) and 0.035 W m\(^{-2}\) for the excitations directed from 30° anterior and 45° superior to the ear canal respectively. The removal of the outer ear increases the average PD to 16.47 W m\(^{-2}\) for the parallel excitation. The SAR, which, as noted, is only valid for the immediate environs within 0.02 mm of the sensors suggest an average “micro SAR” of 84.2 W kg\(^{-1}\) when the excitation is parallel to the
ear canal. The equivalent SAR values for the 30° anterior and 45° superior excitations were 0.77 Wkg$^{-1}$ and 0.31 Wkg$^{-1}$ respectively. The ICNIRP general public safety recommendation for whole body average SAR for the 100 kHz to 6 GHz range is 0.08 Wkg$^{-1}$. The estimated initial temperature rise, (ignoring the effects of blood flow, diffusion or radiative loss), is estimated to be 0.028 °C per second of exposure. The removal of the outer ear produced mean E-fields within the tympanic membrane of 0.91 Vm$^{-1}$, with a larger central high intensity region. This translates to higher PD and SAR values as shown in Table 1. The mean PD exiting the tympanic membrane at the sensors within the middle ear (and therefore in air, ($Z = 377) was 1.19 Wm$^{-2}$.

Table 1. Simulation results. (A) The maximum absolute values of the point sensor E-field, mean value and the standard deviation (SD) for the 6-point array 0.01 mm within the tympanic membrane is shown. The “0°” denotes parallel excitation, as per Fig. 1(a), “30° forward” the excitation as per Fig. 1(b), “45° up”, as per Fig. 1(c), the excitation for “no outer ear” is as per Fig. 1(a), but with the outer ear features removed. (B) The E-field values adjusted for the ICNIRP safety limit, the radiation in air, ($Z=377). (C) The maximum magnetic field, from the parallel simulation. (D) Calculated tissue impedance for power density calculations. (E) The resultant PD adjusted for the ICNIRP safety limit of 10 Wm$^{-2}$ incident PD excitation outside the ear. (F) Calculated “micro SAR” (G) The estimated initial temperature rise at the point sensors 0.01 mm within the tympanic membrane.

<table>
<thead>
<tr>
<th>A</th>
<th>Maximum Electric Field (E, Vm$^{-1}$) for exposure of 1.0 Vm$^{-1}$</th>
<th>E</th>
<th>Power Flux Density (PD, Wm$^{-2}$) for exposure of 10 Wm$^{-2}$ in tissue, $Z=230$ Ω</th>
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</thead>
<tbody>
<tr>
<td>0°</td>
<td>forward</td>
<td>up</td>
<td>no</td>
</tr>
<tr>
<td>mean</td>
<td>0.74</td>
<td>0.069</td>
<td>0.044</td>
</tr>
<tr>
<td>SD</td>
<td>0.22</td>
<td>0.026</td>
<td>0.015</td>
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<td>B</td>
<td>Maximum Electric Field adjusted for exposure of 61.4 Vm$^{-1}$ (10 Wm$^{-2}$)</td>
<td>F</td>
<td>SAR for exposure of 10 Wm$^{-2}$ outside ear</td>
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<tr>
<td>0°</td>
<td>forward</td>
<td>up</td>
<td>no</td>
</tr>
<tr>
<td>mean</td>
<td>45.2</td>
<td>4.22</td>
<td>2.70</td>
</tr>
<tr>
<td>SD</td>
<td>13.7</td>
<td>1.60</td>
<td>0.89</td>
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<td>C</td>
<td>Maximum Magnetic Field (H, Am$^{-1}$) for exposure of 1.0 Vm$^{-1}$</td>
<td>G</td>
<td>Initial Temperature Rise (°C s$^{-1}$) for exposure of 10 Wm$^{-2}$ outside ear</td>
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<tr>
<td>mean</td>
<td>0.0032</td>
<td>(parallel stimulation)</td>
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<tr>
<td>SD</td>
<td>0.00074</td>
<td></td>
<td>mean</td>
</tr>
<tr>
<td>mean</td>
<td>230</td>
<td>(parallel stimulation)</td>
<td>0.015</td>
</tr>
</tbody>
</table>

4. Discussion

Computational simulations suggest that the tympanic membrane has the potential to receive a significant proportion of 0.3 THz radiation presented to the front of the ear canal and that the planar sensor images and point sensor variability evident in the large standard deviations in the results indicate a variability in the intensity of the radiation reaching the tympanic membrane. The simulations also suggest that the anatomy of the canal and the outer ear is highly protective when the radiation is at 30° and 45° angle from the parallel. This protective effect is reinforced by the finding that the removal of the outer ear in the simulation produces an average 24% greater electric field intensity at the tympanic membrane.

The resultant power flux density estimations underline the fact that the ear canal is capable efficiently conducting the 0.3 THz radiation to the tympanic membrane. Although SAR is not the recommended radiation safety measure in the 6-300 GHz (0.006 –0.3 THz)
It should be noted that the “micro SAR” in the immediate environs of the sensors placed 0.01 mm within the tympanic membrane is estimated by the simulations to be in the order of 84 Wkg\(^{-1}\) when the maximum recommended “general public” PD of 10 Wm\(^{-2}\) is used as the parallel excitation outside the ear. As with PD, excitation directed from 30° anterior and 45° superior to the ear canal, the “micro SAR” at 0.01 mm within the tympanic membrane is reduced markedly. Even the reduced “micro SAR” with the 45° superior excitation, the value of 0.31 Wkg\(^{-1}\) is significantly above the ICNIRP “whole body” SAR limit of 0.08 Wkg\(^{-1}\) for the 100 kHz to 6 GHz range. Given that the tympanic membrane is a delicate, highly innervated organ, the reliance on conservative “whole body” SAR or PD recommendations pertinent to normal skin is not sufficient, and further exploration of the magnitude and effects of 0.3 THz radiation on the tympanic membrane needs to be undertaken. It remains to be seen if the projected “micro SAR” and temperature rise is significant in-vivo, or if the 0.3 GHz radiation produces any long-term effects. Although the tympanic membrane is a highly specialised organ, its function is determined by its structure rather than any peculiar tissue or cellular components, thus any non-thermal effects are likely to be in line with other similar tissues such as connective tissue.

The capacity of the tympanic membrane to dissipate the radiative energy by direct radiation and the role of local blood flow in reducing the effect of the incident energy deposition in-vivo need to be understood before any definitive conclusions can be reached, however, for the time being, the possibility of significant tympanic membrane exposure must be considered in the design and placement of devices emitting radiation at 0.30 THz. It is worth noting that (with the parallel excitation), significant incident radiation penetrates into the middle ear. Given that a simplified model was used for the tympanic membrane, the precise amount of transmitted radiation into the middle ear and any impact of the resultant thermal currents or preferential heating of small regions need to be explored in more detail in the future.

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Disclosures

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References