The Thermal Impact of Wireless Sub-Terahertz Radios on the Human Eye in Next-Generation Extended Reality Headsets

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***Abstract*—The emergence of 6G wireless networks has the potential to completely redefine the wearable devices market by pushing the limits of connectivity and user experience. Many of these wireless wearable devices often cover the eyes, increasing the exposure to electromagnetic fields on the cornea. In this article, the heat generated on the corneal tissue by the electromagnetic radiation from wireless wearable devices operating on the sub-terahertz (THz) frequency band (100 GHz - 300 GHz) is modeled on COMSOL Multiphysics®. We observed that devices operating on the sub-THz frequency band will have a high thermal impact on the human eye. Nonetheless, by controlling the device transmission power and the allowed usage time, the temperature rise in the eye corneal tissue can be limited. Additionally, results indicate that the eyelid will not be a sufficient barrier against sub-terahertz electromagnetic radiation. These outcomes provide essential insights into electromagnetic exposure safety requirements in next-generation extended reality headsets.**

***Index Terms*—6G, wearable devices, human eye, sub-terahertz communications, thermal effects**

I. INTRODUCTION

A revolutionary age of technological innovation has begun with the introduction of 5G and the anticipated future advances of 6G wireless networks. Industries are using 5G's unmatched speed, capacity, and low latency to allow various groundbreaking applications in various fields. From autonomous vehicles and smart homes to remote surgeries and remote learning, 5G is reforming real-time connections because of its extremely low latency. 6G is expected to provide higher capacity and lower latency to be able to handle more seamlessly connected devices. Future technologies will enable and deploy a broad range of frequency spectra, including, but not limited to, the sub-terahertz (THz) frequency band (100 GHz - 300 GHz) [1]. Hence, emerging technologies like holographic communication, extended reality, and a genuinely interconnected Internet of Things connecting and integrating smart devices will seamlessly become part of every aspect of our lives.

Future networks will bring significant advancements, particularly to the world of wearable headsets, enhancing their potential and enabling new possibilities for their functionality and user experiences [2]. These wirelessly connected wearable devices will often cover the human eyes, with transmission and reception from other connected devices occurring near the eyes/cornea [3]. The eye's absorption of electromagnetic (EM) radiation may cause thermal effects in addition to the heat generated by the device [4]. The eye's cornea will gradually become warmer due to this. Since it is a fragile and sensitive tissue, concerns about comfort and eye health must be resolved for these devices to meet health and safety requirements.

In recent years, the thermal impact of THz exposure has started being numerically and experimentally investigated. Some research focused on studying the temperature rise of human skin [5], cells [6], [7], and proteins [8] while being exposed to THz radiation. Other research groups explored the non-thermal effects of radiation on cells [9], [10], and proteins [11]. However, few research groups studied the exposure of the eye cornea to sub-THz/THz radiation. Human eye cells showed no non-thermal effects after being exposed to low-power THz electromagnetic radiation for different durations [12]–[14]. Nevertheless, a radiation power of 300 mW (24.7 dBm) was capable of increasing the corneal tissue temperature to 12.95 $^{\circ}C$ [15]. The thermal impact of THz radiation from wearable wireless devices on the eye cornea is still not well-studied. This is essential in setting the maximum safe power and usage time limits to prevent heating up the corneal tissue, eye dryness, or other eye diseases.

The main goal of this work is to study the thermal impact of sub-THz electromagnetic radiation from wireless headsets on the cornea of the eye. The paper is organized as follows. First, we present the envisioned future of wearable devices utilizing the sub-THz band in Sec. II. Then, we describe the consequences of heating up the eye cornea in Sec. III. In Sec. IV, we introduce our multi-physics numerical model of the eye. Then, we present the numerical results and discussion in Sec. V. Finally, we draw up some conclusions and identify future extensions of this work in Sec.VI.

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II. WIRELESS WEARABLE HEADSETS

Wearables, in general, are anticipated to be greatly impacted by the adoption of 6G technology, which will remarkably improve their capabilities and enable new applications/uses. This section introduces some of the existing and newly enabled wireless headsets.

Extended Reality (XR) is a generic term for headsets used to encompass Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), and any other technology that alters reality. Also known as Metaverse, these technologies enable various degrees of interaction and immersion in both virtual and physical environments. With VR, the actual world is completely supplanted by an entirely digital experience, while in AR, digital content is superimposed on the real world. On the other hand, MR seamlessly integrates digital objects into the user's real world, creating the illusion where they both share the same space [16], [17].

Smart glasses are lightweight headsets designed to be worn like regular eyeglasses in daily life. They could offer an AR experience and other capabilities like notifications, navigation, and real-time information display.

A Brain-Computer Interface (BCI) headset, commonly referred to as an Electroencephalography (EEG), brainwave headset, or neuroheadset, enables direct brain-to-computer or other external device connection. BCIs use sensors to track, analyze, and convert brain impulses into digital information that can be used to operate hardware, software, or other devices [18].

There are numerous potential applications for XR headsets, smart glasses, BCIs, and other headsets in multiple industries and sectors. They enable communication and navigation for disabled individuals and tourists, realistic training scenarios, immersive gaming experiences, and interactive learning, among many other advantages. 5G is an enabler of these technologies, however, the evolution of 6G networks could offer various extra benefits to enhance headset user's experiences in the form of ultra-low latency, extremely high data rates, precise localization, seamless connectivity, etc [19].

Since wearable devices contain hardware components like batteries and processors, they may dissipate some heat. However, producing a significant amount of heat would violate safety standards as it could result in eye discomfort, dryness, or other adverse effects. Although these devices are made by manufacturers to effectively dissipate heat and prevent overheating even during prolonged usage, any device used for an extended period of time close to the eyes may cause slight variations in temperature. In addition to this, wireless wearable headsets enabled by 5G and 6G future networks include transmission and reception antennas for untethered communication at a rate of multiple Gbps [20]–[22]. These headsets along with other wireless devices we use in our daily lives may increase the electromagnetic radiation the human eyes, corneas in particular, are exposed to, hence increasing the likelihood of their temperature rise. As illustrated in Fig. 1, most of the time, the back lobe of the headset antenna will be directed towards the eye. However, with beam steering techniques, which will be employed in 6G technology, the main beam might be partially impacting the eye, increasing the EM field exposure.

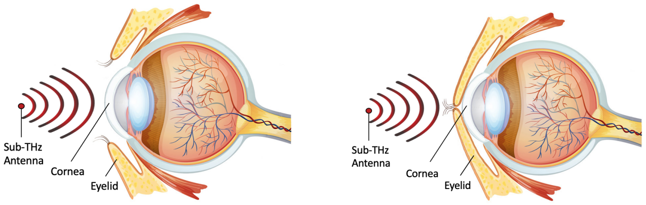
Fig. 1: Electromagntic radiation emitted from a wireless XR headset with a back lobe hitting the eye cornea.

III. HEATING THE EYE CORNEAL TISSUE

The cornea is the outermost transparent layer of the eye, and it is extremely susceptible to external insults/changes. It plays an essential role in focusing light onto the retina for precise vision. The lack of blood flow in the cornea and the lens prevents temperature regulation. Also, the absence of heat sensors, beyond the blinking reflex, allows for potentially hazardous effects from temperature rise. Excessive heat exposure to the cornea can result in several unfavorable effects on vision and eye health such as vision reduction, corneal infections, dry eye syndrome, or photophobia.

For instance, thermokeratoplasty (TKP) uses the thermal energy generated from radio frequency electrodes to heat the corneal tissue, reaching around $65\ ^{\circ}C$. This temperature rise leads to collagen shrinkage, which changes the cornea's curvature. This technique is an alternative to Laser-Assisted in Situ Keratomileusis (LASIK) which involves cutting/removing part of the cornea for reshaping and correcting farsightedness, nearsightedness, and astigmatism. Heating the cornea using RF electrodes is being studied, and has already been proven that low-power low-frequency radiation (i.e. between 500 kHz and 1 MHz) can cause cornea shrinkage [23], [24]. Nonetheless, a narrow focused THz beam with extremely low power (e.g. -5 dBm) will be sufficient for reaching the same temperature in less than 10 minutes, causing cornea curvature changes [25]. The radiation frequency (which determines how much energy the tissue will absorb), intensity, and duration of exposure determine the thermal response on the corneal tissue.

In a healthy eye, the cornea surface temperature ranges from $31\ ^{\circ}C$ to $37\ ^{\circ}C$, and after each blink, the cornea is cooled down slowly with a rate of $-0.01\ ^{\circ}C$ per sec [26]. The minimal temperature required in TKP for cornea shrinkage was measured to be $55\ ^{\circ}C$ [27] with a maximum safe limit of $75\ ^{\circ}C$ [28]. Beyond this temperature limit, the cornea tissue



(a) (b)

Fig. 2: Two case studies: (a) the eye open and (b) the eyelid covering the eye.

could be permanently devastated due to the destabilization of the collagen structure and the breaking of heat-sensitive intermolecular bonds in the cornea. Nonetheless, corneal tissue temperatures around $40\ ^{\circ}C$ can denature proteins which may result in changes in the cornea's biomechanical characteristics, transparency, and overall health. Accordingly, the cornea of the eye is extremely sensitive to any temperature change, and its healthy temperature range should be always sustained.

The propagation of THz electromagnetic waves inside the human body is drastically impacted by the absorption of liquid water molecules [29]. Since the human eye is mainly composed of water, THz radiation is expected to be highly absorbed by the eye, introducing thermal effects. Therefore, research into how this radiation is absorbed by the cornea and the eye, in general, will help us set safety standards for devices utilizing the sub-THz frequencies in the future.

IV. NUMERICAL MODEL

A 2D bio-transfer model of the human eye is developed on COMSOL Multi-physics® that we first described in [30] then extended and partially experimentally validated in [5] when applied to human skin. This model is based on the finite element method to study thermal changes in the human eye cornea due to the radiation from antennas placed in wireless headsets. This is done by first estimating the power intensity distribution all over the defined mediums using

$$\left(\frac{1}{v}\frac{\partial}{\partial t} - D\nabla^2 + \mu_a\right)\Phi(\overrightarrow{r},t) = q_0(\overrightarrow{r},t) \tag{1}$$

Here v is the speed of light, $D = \frac{1}{3}(\mu_a + \mu_s^{'})$ is the diffusion coefficient, μ_a is the absorption coefficient, $\mu_s^{'}$ is the reduced scattering coefficient which is negligible in our case [31], [32], $\Phi(\overrightarrow{r},t)$ is the fluence rate, and $q_0(\overrightarrow{r},t)$ is the source. Then the temperature change in the exposed mediums due to the electromagnetic radiation is evaluated using

$$\rho C_p\frac{\partial T}{\partial t} + \rho C_p u.\nabla T + \nabla.q = Q + Q_{bio} \tag{2}$$

where, ρ is the density, C_p is the specific heat capacity, T is the temperature, q is the boundary heat flux, Q is the source, Q_{bio} is the bioheat source, which is neglected due to the absence of blood flow in the cornea.

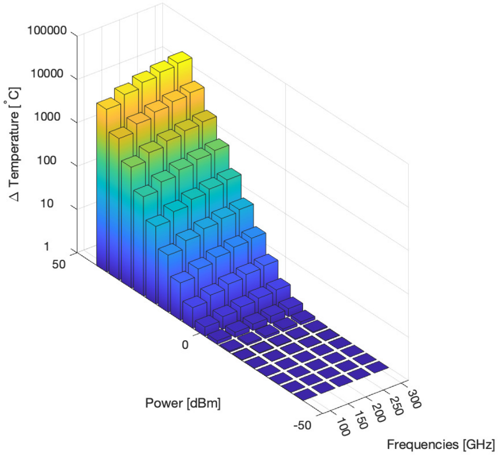


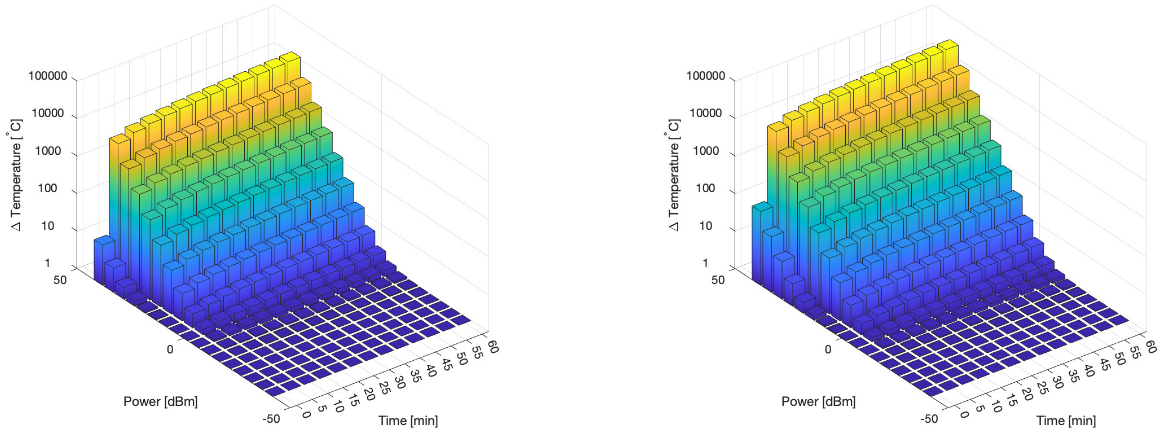
Fig. 3: Temperature change in the human cornea when exposed to sub-THz electromagnetic radiation.

The model examines two different scenarios: the eye open (i.e., the time of watching/playing) and the eye covered with the eyelid (i.e., during a blink or rest) as shown in Fig. 2. The eye is modeled as a sphere of approximately 70% water-like liquid, cornea, and lens with a cornea thickness of 600 μm [33] and an eyelid of a minimum thickness of 1.85 mm at the center of the cornea [34]. Each medium in the model is defined by its thermal and optical properties at each studied frequency, these properties were presented in [35]–[37]. The eye was impacted by a Gaussian beam that was employed to be incident on the geometry's left side. In this parametric model, the radiation's power, frequency, and duration of exposure to electromagnetic radiation are adjustable.

Antennas for smart glasses and XR headsets are frequently built into the frames or could be in other parts of the device. The antenna position usually differs to provide the best wireless connectivity while maintaining a speculative compact design. Depending on the particular design and type of device, the distance between the antenna in the headset and the eye varies greatly. In this model, this distance is assumed to be around 1 cm.

V. RESULTS AND DISCUSSION

The maximum allowed transmitted power from a GSM device is 33 dBm, and that for 3G and 4G devices is 24 dBm [38]. Additionally, cell phones, among other wireless devices, are designed to transmit power between 20 dBm and 36 dBm, and in certain situations, that power could reach 52 dBm [39], [40]. These limits were set to avoid raising the skin's temperature to a point where it might be injured or burnt at lower frequencies (600 MHz - 2.5 GHz). However, for devices designed to operate in higher frequency bands (i.e., around 60 GHz), the maximum allowable Effective Isotropic Radiated Power (EIRP) was set by the Federal Communication Commission to be around 40 dBm [41]. Therefore, the power transmitted from wearable devices is expected to vary between



(a) (b)

Fig. 4: Temperature change in the human cornea when exposed to radiation from a source of frequency = (a) 130 GHz and (b) 300 GHz.

20 and 52 dBm. This power will be emitted mostly from the antenna's main beam, so the power hitting the cornea could be less. Accordingly, in this study, the transmission power varies from -40 dBm to +40 dBm.

Fig. 3 presents the thermal impact of different frequency EM radiation on the eye cornea. While transmitting the same power, the eye cornea absorbs more of the exposed radiation when the frequency is higher; hence, its temperature rises.

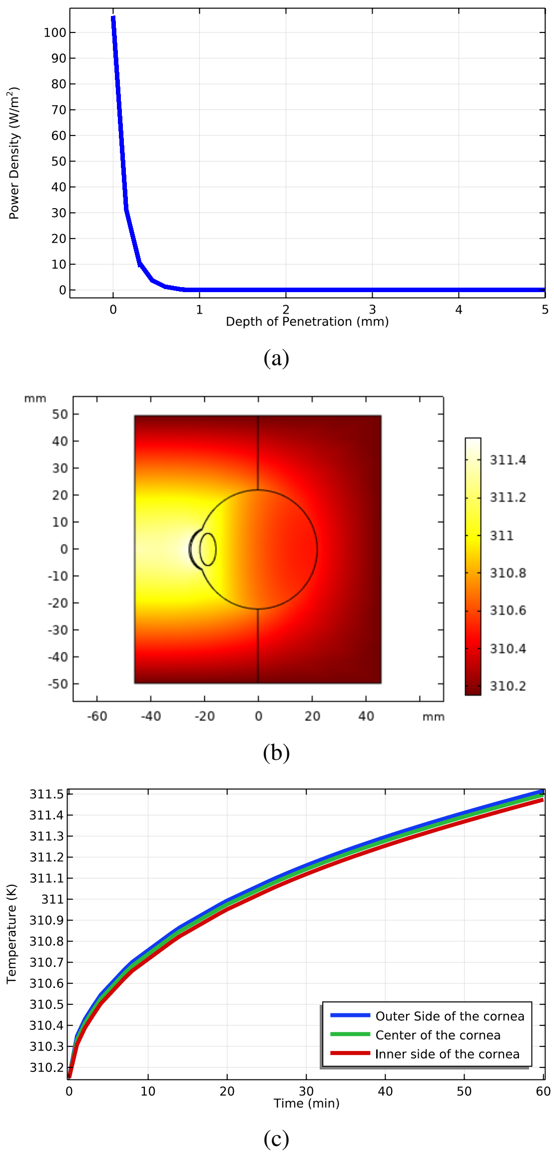
The temperature change in the eye's cornea is depicted in Fig. 4 as a function of the wearable device's transmitted power and usage time. For this analysis, the arbitrarily chosen sub-THz frequencies were 130 GHz and 300 GHz. We can infer from this that the cornea experiences a higher temperature rise with higher transmission power and this temperature rise increases with increasing the exposure time. To prevent the temperature from getting higher, a safe temperature increase limit of $1\ ^\circ C$ could be set, and accordingly, the transmitted power and the device usage time could be adjusted [42]. Taking this into account, 0 dBm would be considered as the maximum allowed power to be directed towards the eye in case of using a 130 GHz source antenna, and -5 dBm is the limit for a 300 GHz source antenna. These power values would be applicable only with a maximum usage time of 30 minutes.

To illustrate, a 130 GHz source antenna in a wearable device is directed towards the modeled human eye with a maximum power of 0 dBm. Fig. 5a manifests the power intensity variation of the EM radiation from the dipole antenna while propagating in the medium. The power was totally absorbed by the eye cornea as it dropped to $0\ W/m^2$ at around 0.6 mm (i.e., the defined cornea thickness). As a result, the cornea acted as a heating source for the surrounding mediums, increasing their surface temperature as shown in Fig 5b. It is depicted in Fig. 5c that the side of the cornea facing the antenna is more heated than the inner side by around $0.05\ ^\circ C$ after 60 minutes of using the wearable device.

The eyelid is essential in defending the eyes from potential contact with foreign environmental irritants. Eyelids are believed to lessen the exposure of the eyes to radiation and intense light. Additionally, the eyelids consist of specific glands that keep the eye's surface moist and protect it from drying out. Fig. 6 reveals the temperature variations on the surface of the eyelid and the cornea. These results establish evidence that the eyelid is incapable of protecting the cornea from EM radiation. The cornea still absorbed the radiation and acted as a heating source for the surrounding mediums. As a result, the temperature of the side of the cornea closer to the antenna and the further side are higher than the exposed eyelid temperature by around $0.2\ ^\circ C$ and $0.1\ ^\circ C$ respectively.

VI. CONCLUSION AND FUTURE WORK

The growing number of wireless devices we use on a daily basis has paved the way to investigate the use of high-frequency bands in 6G. It is anticipated that 6G wireless networks will signal significant improvements in the audio and communication capabilities of wireless headsets by enabling instantaneous latency. As we use these devices more frequently, we are exposing our eyes to more electromagnetic fields, which may heat up the cornea and result in serious damage. In this article, the thermal implications of placing the headset near the eye are presented. Potential safe limits for the power and the usage time are defined for the sub-THz frequency band, which is anticipated to be employed in 6G. The outcomes of this work serve as a foundational basis for setting safe radiation limits in future wireless devices as well as for using THz systems in scanning and imaging in ophthalmology.



(a)

(b)

(c)

Fig. 5: The propagation of a 130 GHz EM wave from a wearable headset on the eye with a transmission power of 0 dBm. (a) shows the depth of penetration of the radiation, (b) reveals the surface temperature of the eye, and (c) shows the temperature changes in the cornea.

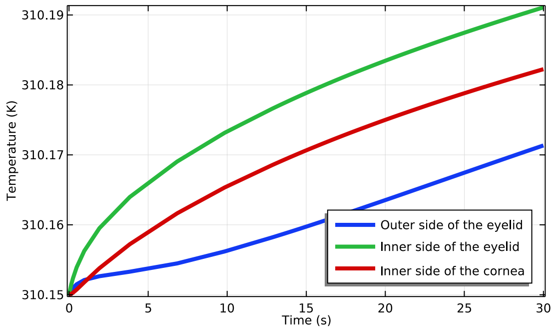


Fig. 6: Temperature changes on the eyelid and cornea surfaces.

If utilizing a wireless headset is expected to increase the temperature of the cornea, what will be the combined impact of the cell phone, laptop, and all the other wireless devices around us? This is an extremely critical question, especially after it has been established that the eyelid is unable to shield the eye against EM radiation. Future studies could look into the issue of various radiation sources affecting the eye and the human skin in general.

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