THE HUMAN EYE’S RESPONSE TO MILLIMETER-WAVE RADIATION

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Abstract

In this paper, several modeling approaches are taken to investigate the effects of 5G millimeter-wave (MMW) radiation on the human eye. As the effects of MMW radiation from 26-34 GHz on the eye have not yet been examined directly, understanding them allows for the prediction of biological damage caused by commercial devices operating in the aforementioned frequency range. Models of varying complexity are used to examine the degree to which physical fidelity and specific tissue properties (e.g., losses in different types of tissue) affect the expected overall power deposition, through the specific absorption rate (SAR). Specifically, a simplified physical geometry was used to approximate the system, namely layered dielectric slabs, before comparing it to a meshed model of an eye. The simplified model allows for the general effects of parallel and perpendicular polarization to be examined, in addition to estimating the regions in which the highest SAR will occur. Physical tests were performed to validate the ability of this model to predict the power deposition and resultant heating in layered lossy media.

Subject Keywords: electromagnetics; 5G; safety
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1. Introduction

1.1 Tissue Damage

At a fundamental level, the need to study the effects of wireless devices on the human body stems from the nature of the interactions between electromagnetic waves and the human body. While the full picture of the interactions is generally complicated and material-dependent, the work discussed in this thesis is focused on the thermal concerns that heavily dominate at millimeter-wave frequencies. Additionally, several material-related parameters can be used to understand the degree to which incident energy will penetrate the material and be absorbed.

In terms of the electromagnetic spectrum, radiation occurring at millimeter-wave frequencies has a relatively low energy from a quantum-mechanical perspective. This can be seen from Planck’s equation [1] for the energy per “quanta” of electromagnetic waves, which indicates that a higher frequency also corresponds to a higher energy. This is responsible for the delineation between “ionizing” and “non-ionizing” radiation; millimeter-wave radiation belonging to the latter of the two [2].

\[ E = hf \]  

This fact limits the biological concerns associated with millimeter-wave radiation to thermal excitation due to effective conductive losses in the tissue in question. Without exposure to electromagnetic fields, the human body’s thermoregulation mechanisms can maintain temperatures that do not result in unwanted tissue damage or destruction. Once external fields are applied however, the extra energy present may result in uncontrolled heating to the point of damage if it exceeds the tissue’s ability to transfer and dissipate it [3]. Additionally, because electromagnetic waves will penetrate a finite distance into a material with a finite amount of loss per unit distance, there is potential for the damage to occur past the outer layer of the body. This behavior is an important
motivator for investigating the eye’s response to millimeter-wave signals and will be discussed in the next section.

From electromagnetic theory, we know that EM waves in a lossy medium will decay as they propagate further into it due to energy leaving the wave and being dissipated. This dissipation occurs in the form of field amplitudes exponentially decaying smoothly with distance, in accordance with the material parameters. More specifically, a quantity called the skin depth (unrelated to human skin) captures the rate of this decay and is very useful in understanding how waves are attenuated in materials. For a general lossy medium, the skin depth is inversely proportional to frequency; tending to result in higher frequency radiation penetrating less (barring any change in effective conductivity) \[4\]. At frequencies in the microwave and millimeter-wave regions of the EM spectrum, this distance is usually small, but can still be large enough in the case of biological tissues for power deposition to occur throughout them.

While the skin depth contains important information about where the loss will be present, it does not allow for much insight into how the absorbed energy will create thermal excitation (i.e., temperature increase). The specific absorption rate (SAR) is a measure that can quantify the ability of a tissue or material to absorb energy and is the basis for exposure limits set by the IEEE and the ICNIRP\[5\][6]. The benefit of this metric is that it allows for the initial rate of temperature increase to be calculated directly from the physical properties of the material (mass density \(\rho\), electrical conductivity \(\sigma\)) and the magnitude of the incident electric field \[7\].

\[
SAR = \frac{\sigma |E|^2}{2\rho}
\]  \(1.2\)
1.2 The Eye

As was mentioned earlier, the geometry and physical properties of the eye make it a concern when investigating the effects of electromagnetic fields on bodily tissues. Regarding the geometry specifically, the curved, approximately spherical shape of the eye (Fig. 1) inherently leads to a focused lensing effect. This behavior can be easily explained via Snell’s law of refraction [1].

Given that the refractive index in the eye is higher than that of the air through which the incident radiation is propagating, the refracted wave travels at an angle directing it further inwards through the eye. As a result, any incident electromagnetic energy will be focused to varying degrees depending on the frequency of the energy, due to the frequency-dependent dielectric constant of the tissues. This focusing effect could theoretically result in constructive interference which may in turn result in higher losses and thus temperature increases in the affected region(s).

![Cross-section of the human eye](image)

*Figure 1: Cross-section of the human eye [8].*

The other key aspect of the eye that makes it a concern when investigating the dissipation of electromagnetic energy in the human body is its ability to transfer heat away from sensitive tissues. In
general, most of the regions in the eye do not receive direct blood flow [9]; a key part of many of the body’s thermoregulation mechanisms. As a result, most parts of the eye rely on conductive and convective (i.e., through fluids in the eye, or air in the case of the cornea) heat transfer to remove heat from sensitive regions. One exception to this is the choroid, which is a blood flow-rich section that runs around the outside of the inner eye (deeper than the lens).

1.3 Millimeter-Wave Radiation

Fundamentally speaking, the concerns stated above theoretically apply any time that a wireless transmission system is used to send any sort of information, regardless of the frequency or application space. However, the burgeoning interest in 5G technology, and particularly 5G mm Wave due to the high bandwidth it offers, gives a more acute concern than would be had with previous network architectures. Based on the earlier description of how electromagnetic power penetrates materials, it would be logical to conclude that the higher frequencies of 5G mm Wave (26 – 34 GHz) would result in less penetration relative to 4G (low-GHz range) as a consequence of the smaller skin depth. Despite this, other basic problems associated with 5G mm Wave result in it potentially posing a hazard depending on the specifications of the commercial device.

Due to the higher attenuation from atmospheric gases (specifically water vapor) faced by millimeter-wave radiation [10], the number of transmitters and base stations will likely have to be higher in order to maintain an acceptable system performance. As a result, the average person in a non-occupational setting (i.e., not directly working on these devices) will be more likely to have a beam steered into their eye while the transmitter scanning algorithm is searching for the next receiver.

While this factor on its own was a large motivator for the work shown in this thesis, the lack of studies surrounding the specifics of this problem also encouraged further questions. For instance, while
there is certainly no shortage of literature focused on similar problems (as will be discussed in the next section), many of these papers do not necessarily address all of intricacies of this problem.

The following chapters will outline the previous work performed to study the effects of radiation in similar situations, in addition to highlighting the conclusions of the work performed. Namely, the studies performed as part of this thesis revealed that the vast majority (if not all) of the incident power is deposited in the outermost layers, with a slight variation due to different operating frequencies.
2. Literature Review

Studies concerning the absorption of electromagnetic energy by biological tissues go back as far as the early 1970’s, and as such there is a fairly large body of work regarding the general problems being considered by this thesis. Despite this, there still exists a significant amount of variation in terms of the different approaches used, each with their advantages and disadvantages. While it was not feasible to perform testing on an actual eye for the purpose of this thesis, studies utilizing this type of testing were considered alongside simulation-based work, the latter of which being more informative for developing the approach presented in the next chapter.

As commercial systems operating in the millimeter-wave region have only started to become common recently, a large portion of the existing body of work is focused on lower frequencies, namely in the low-GHz range [11] - [13]. Since many of the important parameters governing the penetration and absorption of energy into a material are highly frequency-dependent, direct investigation of the effects on the overall structure is required.

Much of the existing literature that focuses on physically measuring the effects of electromagnetic radiation on the human eye features some form of physical substitute for the human eye. Most commonly, the substitutes used are either primate or rabbit eyes that are then instrumented to measure any temperature increases that result from the exposure [13] [14]. While they are useful for being able to characterize the power densities required to induce rapid corneal damage in these subjects, tests such as this are difficult to use to inform human exposure concerns due to the large variations induced by head geometry [9]. Furthermore, the inherent difficulty in measuring resulting temperature increases requires the usage of power densities well above typical regulatory limits, with fluences ranging as high as 8 \( W/cm^2 \) in some cases [14]. For reference, the power density limit for local exposure above 6 GHz as defined by the IEEE is 10 \( mW/cm^2 \). An additional concern associated with this method of testing is that it does not represent a typical exposure scenario, as it utilizes a high power
density for a short period of time instead of a low power density (as mandated by regulations) for a longer time period. The latter scenario is more realistic for millimeter-wave communications systems because the atmospheric attenuation mentioned in the previous chapter necessitates a higher number of transmitters in any one location. In comparison to 4G LTE technologies, millimeter-wave systems suffer from roughly 10 times more atmospheric attenuation per kilometer [10]. Additionally, since this increase in attenuation is mostly due to the water vapor content of the air, any rises in humidity or rainfall will also decrease the effective range of millimeter-wave communications. Moreover, since millimeter-wave radiation is non-ionizing, the potential for damage is highly dependent on the ability for heat to build up and thus tests cannot be performed as dosimetry studies.

In the case of simulation-based studies, there is an obvious need to utilize physical parameters that will produce results representative of what will happen with an actual human eye. Much of the existing work utilizes dielectric properties from a variety of different sources, some of which are extrapolated from lower frequency data using the Cole-Cole dielectric model [15] – [17]. The Cole-Cole model is a commonly used approximation of the behavior of dielectrics across a wide range of frequencies. It uses the high and low-frequency limits of the dielectric constant as well as the conductivity and dipole relaxation times to model how materials behave well beyond the range in which their properties were measured. The latter of these properties, relaxation time, is especially important for modeling the resonance of molecular dipoles that occurs for many biological materials due to their high water content [15]. Because this is only an approximate model and does not take into account all of the non-linearities associated with real materials, it is preferred to use actual measured data for the permittivities of materials being studied. There are some papers however that use much newer measured data, despite also featuring some extrapolation in the higher frequency ranges [18]. This thesis utilizes some of the most recent published dielectric data available, which has been measured from 500 MHz to 110 GHz [19].
An important consideration when simulating a physical structure such as the eye is the spatial resolution with which the model is discretized. This becomes even more of a concern when examining the eye because the loss occurs very close to the surface (i.e., in the cornea and aqueous humor) at millimeter-wave frequencies, and the cornea is only 0.55 mm thick (on average). Many of the existing 3D models have relatively coarse resolutions, with individual cell sizes typically greater than 0.25 mm [11] [20]. Some of the literature uses an open-source 3D model with a resolution of 0.1 mm, which provides fine enough discretization for features such as the cornea [18]. Since the dielectric slab model developed for this thesis is relatively simple and not computationally intensive, it features a variable resolution that was set to 10 µm for the results shown.

2.2 Summary
The literature on interactions between electromagnetic waves and the human body is widespread and diverse in the approaches taken by it. The aforementioned research into physical testing using phantoms or substitute eyes (i.e., rabbits or primates) demonstrates the significant variation in results associated with head geometry; more accurate human models would therefore be needed for further work. Additionally, many of the simulations shown in the papers discussed previously account for many of the intricacies of the eye, such as the heat transfer in some of the internal regions and varying exposure scenarios. While these simulations do allow for more direct comparisons with existing regulatory limits, they do not focus as much on understanding the fundamental factors that drive electromagnetic interactions with the human eye at millimeter-wave frequencies. The results presented in the next section build up from a dielectric slab model to derive a more basic understanding of how the different structures of the eye interact from an electromagnetic viewpoint, to hopefully enable further studies.
3. Description of Research Results

3.1 Slab Model

Due to the complexity of the eye’s geometry, the primary approach used to analyze the system was a simplified dielectric slab model. This effectively allows for the electromagnetic properties of the eye to be examined starting with how the relative dielectric values of each section influence propagation through the structure. The model was built in Python to allow for flexibility in simulating different types of structures. To try and capture as much of the electromagnetic behavior as possible, the dimensions of several important sections of the eye were input into the model [21]. Given that the focus of this thesis is the outer sections of the eye, the computational region was truncated at the innermost part of the eye with a perfectly matched boundary region.

3.1.1 Theory

The model works by taking the dielectric information, in addition to the thicknesses of all the layers and computes the steady-state field distribution throughout the structure. In order to take into account the effects of different sections on one another, an approach utilizing S-parameter matrices was taken. To determine what these S-matrices should be, the layered slab system was analyzed in terms of transmitted and reflected waves at each material interface.

![Figure 2: General dielectric slab model for arbitrary layered media](image)
The waves entering each interface from either direction (into the eye or from direction of initial exposure) are multiplied by an appropriate coefficient relating to reflection or transmission from the direction of interest. The contributions from the two incoming waves to each of the two outgoing waves are contained within the S-matrices for each individual interface, where the order of the indices determines the direction of propagation in which that specific coefficient is to be used.

\[
S = \begin{bmatrix}
T_{i,i+1} & F_{i+1,i} \\
F_{i,i+1} & T_{i+1,i}
\end{bmatrix} \rightarrow \begin{bmatrix}
E_{i+1,+} \\
E_{i,-}
\end{bmatrix} = S \begin{bmatrix}
E_{i,+} \\
E_{i+1,-}
\end{bmatrix}
\]

(3.1)

While the normally-incident case is important to analyze, it was important for the model to contain the ability to investigate oblique incidence and TM/TE polarizations, even if the simplified geometry does still limit its applicability.

3.1.2 Dielectric data
The dielectric data used for the different sections of the eye was obtained from the results of previous research across a wide range of frequencies [19]. This data is relatively coarse in the frequency range of interest for this thesis (10 GHz steps), but the model linearly interpolates between the measured data points to achieve reasonable fidelity from 26 - 34 GHz. Because the model was initially developed through an equivalent transmission line structure in Keysight’s ADS software, this interpolation was first performed in terms of the characteristic impedances of the materials (instead of the permittivity). When refining the model to represent dielectric slabs, it was switched to linearize permittivity instead as the previous method introduced some additional error (since the underlying dielectric values would not yield a linear characteristic impedance trend versus frequency).

3.1.3 Lossless Results
From the measured dielectric data discussed earlier, it is obvious that there is a significant amount of loss present in the eye’s tissues [19]. Because of this, lossless simulations do not present much usefulness from the perspective of understanding safety concerns. However, investigating the
structure without loss allows for intuition to be developed regarding how energy moves between the layers due to interplay between different reflection and transmission properties.

The plots of field magnitude vs. distance from the eye surface (cornea-air interface) shown above indicate that the presence of standing waves, which in turn would lead to loss, is highly dependent on frequency. More specifically, the ability for energy to be trapped in the aqueous humor tends to vary significantly, with its minimum standing wave ratio being reached at around 29 GHz. On the other hand, the lens cortex and nucleus have relatively large standing waves within them across the bandwidth of interest, indicating that they may sustain damage if energy enters and that their characteristic impedances are poorly matched to the aqueous and vitreous humors.
3.1.4 Lossy Results

In comparison with the lossless results, the field distributions in the lossy media compare well qualitatively with previous works simulating the eye [12][18]. From the distributions in Fig. 4, we can clearly see that the entirety of the initial power deposition from incident waves will occur within the cornea and aqueous humor. This is not to say that conductive and convective heat transfer would not gradually remove heat from the area, but rather that the initial temperature rise (prior to other mitigating factors beginning to dominate) would take place in this region.

![Field Penetration into Eye (normal incidence)](image)

Field Penetration into Eye (normal incidence)

**Figure 4: Lossy field distribution into the eye simulated from 26 – 34 GHz.**

To study the effect of the different thickness parameters on the penetration of fields into the eye, a Monte Carlo simulation was performed. The thicknesses were perturbed around their average value by an amount related to the typical variation seen in 20 - 65 year old humans [21]. Results from these simulations (Fig. 5) yield a very constrained random field variation profile within which all of the
results are located. This indicates that the degree to which fields are deposited in the eye is relatively insensitive to any changes in these dimensions.

In addition to understanding how fields decay within the eye, it is also important to understand the overall reflection and transmission properties of the interface for an incident wave of arbitrary power. All of the previous simulations were performed with an electric field magnitude of 1 V/m incident on the eye, which is relatively unrealistic for millimeter-wave devices but was used due to a lack of information on commercial transmitter specifications. To look at overall transmission and reflection properties of the materials in the eye, the reflection coefficient of the entire structure was simulated at normal incidence.
The trend in reflectivity seen in Fig. 6 indicates that it decreases fairly linearly as a function of frequency, at least within this band. Additionally, it is important to note that this model predicts over half of the incident power will be deposited in the eye over the entire frequency range.

3.1.4 Influence of the Iris

The layers used in most of the simulations shown in this thesis are limited to the cornea, aqueous humor, lens (both nucleus and cortex), and the vitreous humor. These were chosen by examining the effective “electrical path” looking directly into the eye at normal incidence. As a result of this choice, structures such as the iris that have the potential to reflect additional energy, especially at increased angles of incidence, were ignored. This choice was justified by the fact that lossy simulations showed that the field amplitudes have effectively decreased to zero by the time that layer of the eye has
been reached, thus resulting in an almost identical distribution. To better understand how its inclusion affects wave propagation throughout the eye, lossless simulations were conducted taking the iris into account.

The results of the simulations in Fig. 7 indicate significantly more variation in the standing wave ratio for the cornea and aqueous humor, with relatively less change in standing wave occurring deeper in the lens. Since the iris is essentially a thin annulus surrounding the pupil and lens, it would be reasonable to conclude that more energy would be deposited in the region between the iris and the air at frequencies where the penetration depth is higher. This conclusion is supported by lower frequency simulations where this can be clearly seen in the field distribution [12].

Figure 7: Influence of the inclusion of the iris on fields in the lossless eye model from 26 - 34 GHz
3.1.5 Verification of Dielectric Trends

To check the validity of the dielectric data using in the modeling approach taken by this thesis, a few comparative simulations were conducted to demonstrate the expected theoretical trends. Namely, a simulation comparing the field distributions of a lossy eye model at 30 GHz and 110 GHz was performed in the simulator. The idea behind this test was to verify the expected trends in wave transmission into the eye as well as the skin depth seen at any given frequency.

![Field Penetration into Eye (TE polarization, normal incidence)](image)

Figure 8: Comparison of lossy results at 30 GHz and 110 GHz, showing the relative difference in penetration between the frequency range of interest and the limit of the dataset.

The results of Fig. 8 indicate that the 110 GHz radiation will reflect less power than at 30 GHz but will also decay faster in the material of the eye. This intuitively makes sense, as the nature of the eye as an optical structure implies that the closer you get to optical frequencies, the less electromagnetic waves are reflected at the air-eye interface. However, the loss shown in this simulation is not indicative of the behavior of the eye at optical frequencies, as the dielectric properties are only measured up to
110 GHz and would likely undergo a significant change as the quasi-optical and optical regimes are approached (i.e., less absorptive).

3.2 Physical Verification

3.2.1 Methodology
Since the simplified model is based on a purely theoretical formulation of plane wave reflections from infinitely large dielectric slabs, some validation is needed to attempt and show how well it holds up in a controlled environment. The goal of the experiments was to show that the power from an incident plane wave is deposited primarily within several skin depths of the material (or more generally near the side closest to the exposure antenna).

An ideal setup for verifying this would be with electric field probes and phantom materials designed to mimic the properties of the eye, which would allow for SAR to be computed easily and thus directly compare the model outputs to these results. Unfortunately, due to resource and time limitations, this approach was not feasible. The closest substitute approach that had the potential for verifying the model’s validity was to attempt to measure the temperature profile in test materials of varying conductivities. Since the SAR can be directly related to the temperature rise in a material before heat conduction begins to dominate, ideally the SAR could be calculated roughly from these values to achieve correlation.

3.2.2 Testing Setup
As a consequence of attempting to measure temperature to calculate approximate SAR values within a material, there were many additional variables to be controlled when creating a test fixture. The fixture went through several iterations as additional factors that may have been influencing the
measurement were realized, but the final results were still subject to some unknown variations that will be discussed in a later section.

The setup in Fig. 9 shows the FLIR infrared camera utilized to obtain temperature profiles in the sample material, specifically water of variable salinity. Utilizing water of variable salinity allows the conductivity of the solution to be adjusted, and empirical formulas relating saline concentration to

![Image of testing setup](image-url)
electrical conductivity [22] could be used to try to predict the behavior within the slab model. The solution was then exposed via a microwave horn at an output power level of 10 dBm from the network analyzer. This signal was then fed into an inline amplifier with a gain of >21 dB, for a final incident power around 30 dBm (considering losses).

3.2.3 Results

Several different experiments were conducted with varying salinity solutions over 15-minute-long exposure periods with the temperature being recorded every 5 minutes. The salinities used varied from that of distilled water (i.e., no salt added) to approximately that of sea water, the latter of which yields a conductivity slightly higher than the cornea. Overall, these tests did not result in any significant changes in temperature within the region of interest, most likely due to the additional factors governing heat transfer within the system.

Figure 10: Heat map of temperature distribution throughout the sample. The container holding the saline is outlined by the box. The table on which the sample is resting is on the far left of the image, and the exposure antenna is radiating from the right.
Figure 11: Final temperature distribution after 15 minutes of exposure at 30 GHz.

Figure 12: Vertically-averaged temperature profiles over the boxed region shown in the heat maps. No visible temperature increases were seen at the outer portion of the water (around pixel 40).
When comparing the heat maps in Fig. 10 & 11 for the initial and final measurements, there is no visible change in the temperature distribution. This is illustrated clearly in the various temperature profiles taken over the exposure time shown in Fig. 12, consisting of vertically averaged slices of the heat map. Interestingly, the entire heat profiles were shifted down in temperature after the first two measurements, but eventually stabilized at the final one. This led to the conclusion that any potential changes in temperature that could have been induced by the exposure setup may have been overshadowed by the sample coming to thermal equilibrium with its surroundings. For the setup used in these experiments, at the closest exposure distance used, we would expect a power density at the sample of about $3 \text{ mW/cm}^2$ (assuming 15 dB of gain from the horn with the sample placed in the direction of peak directivity, 30 dBm of input power). This is much lower than the IEEE limit of 10 $\text{mW/cm}^2$ shown earlier, and significantly lower than any of the power densities used in simulations at this frequency. For instance, the usage of a simulated power density of about $100 \text{ mW/cm}^2$ (over 30 times higher) yielded a temperature change of only a few degrees Celsius [18]. Such variation leads us to believe that with the power density we could achieve using the equipment available, the theoretical temperature increase may have been small enough that it was masked by experimental error.
4. Conclusion

The results of the lossy simulations conducted with the simplified dielectric slab model show very clearly that the power deposition will occur within the cornea and aqueous humor. This matches up quite well with many of the results obtained using 3D models of the human eye [12][18], allowing us to conclude that the majority of the loss is governed by the dielectric properties rather than the geometrical properties.

Regarding the tests performed to validate this model, there is significant room for improvement in terms of the setup and execution. The first improvement would be to ensure all samples sit still in the anechoic chamber until they reach a steady-state temperature before the exposure begins. This would allow for any temperature variations in the room to be smoothed out because the saline would be heating or cooling less due to environmental conditions, thus potentially making the heating effects due to the exposure more noticeable. Additionally, a higher power amplifier or source could be used to try and increase the amount of energy deposited in the sample during a given exposure period.

To further capture and study some of the more geometry-dependent electromagnetic properties of the eye, a more realistic, 3-dimensional model would be invaluable. This work is actually in progress and is being performed utilizing an open-source model of the human body that has 100 µm resolution (version 4.3, http://lifesciencedb.jp/bp3d/). Additionally, it would be informative to incorporate a model of heat transfer within the eye to this simulation to give the most realistic picture of the eye’s behavior.
References


