Computational Model of the Influence of a 835 MHz Patch Antenna Distance on Specific Absorption Rate (SAR) and Temperature Change in the Human Head

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Abstract: Human exposure to mobile phone radio frequency (RF) radiation has caused public concern for human health. Mobile phone RF exposure depends on many different parameters. The aim of this study is to examine the effects of both the RF source distance from a human head and of output power levels on the temperature change and the Specific Absorption Rate (SAR) in the head. The peak spatially-averaged SAR over 1 g of tissue is also found in this study to compare the study results to Health Canada's Safety Code 6 exposure limits. The SAR and temperature change in the head are simulated in this study using a Specific Anthropomorphic Mannequin (SAM) head model with heterogeneous dielectric properties and a microstrip patch antenna operating at a frequency of 835 MHz. The microstrip patch antenna distance from the head is varied from 0-15mm and it is operated at three different time-averaged output power levels. The simulation is performed using COMSOL Multiphysics software and is solved with the Finite Element Analysis (FEA) method. The results show that both SAR and temperature change in the head model increase as the distance between the head model and the patch antenna decreases. The simulation with the highest output power level (2W) and closest RF source distance, 0mm, produced the maximum temperature increase (from 37°C) in the head. The maximum temperature increase in the head is 0.77°C and in the brain is 0.14°C. The peak spatially-averaged SAR over 1 g of tissue is found to triple as the phone moves from 4mm from the head to 0mm from the head. At two of the power levels used the levels exceed Safety Code 6 exposure limits until the RF source is at least 4-5.6 mm away from the head. The results from this study indicate that to mitigate possible health risks from RF radiation mobile phones should be kept at least 4mm from the head.

Key Words: Specific Absorption Rate, Electromagnetic radiation, Temperature, Conductivity, Relative permittivity

I. INTRODUCTION

Mobile phone use has increased significantly over the last couple of decades. In today's society most would consider their mobile phones as an essential item. Phone technology has evolved rapidly with its popularity and today's smartphone has many capabilities and a sleek look with compact internal antennas. Along with the increase in cell phone use and the evolving cell phone technology, there has been growing public concern about possible effects on human health from mobile phone radio-frequency (RF) radiation.

Many studies link mobile phones to various negative biological effects [1–4]. There is enough evidence of biological effects from RF radiation from peer-reviewed scientific research that in 2011 the International Agency for Research on Cancer (IARC), the cancer agency of the World Health Organization, classified electromagnetic radiation at frequencies between 30 kHz and 300 GHz as possibly carcinogenic to humans [5]. As well, the National Toxicology Program conducted the longest and most expensive study to date on the biological effects of RF radiation and found statistically significant increases in brain and heart cancer in animals exposed to 2G and 3G electromagnetic frequencies (EMF) at levels of EMF below the ICNIRP (International Commission on Non-ionizing Radiation Protection) guidelines [4].

To protect the public from the harmful effects of RF radiation, countries around the world set compliance standards for RF products. Most RF regulations use Specific Absorption Rate (SAR) to set their exposure limits.

SAR is a measure of the amount of energy absorbed by biological tissue from the electromagnetic waves passing through the tissue from the RF source. When human tissue absorbs the energy from the electromagnetic waves, the tissue increases in temperature. The temperature increase of biological tissues is considered by many to be the largest health risk from mobile phones and mobile phone exposure limits are set to reduce these thermal effects [6].

Safety Code 6 is Health Canada's guideline for RF exposure. For 300 MHz to 6 GHz these guidelines are based on average SAR metrics to prevent thermal heating in the human body. Safety Code 6 sets exposure limits for the human head based on peak spatially-averaged SAR over 1 g of tissue (SAR_{1g}). The SAR_{1g} limit for the human head in Safety Code 6 is 1.6 W/kg for uncontrolled environments [7]. To test for mobile phone compliance with Safety Code 6 limits in the head, mobile phone companies use IEEE (Institute of Electrical and Electronics Engineers) 1528 testing standards. The IEEE 1528 [8] head model for mobile phone SAR testing is called the Specific Anthropomorphic Mannequin (SAM) phantom. The SAM phantom has an outer shell made of a 2mm thick lossless material and this shell is filled with a uniform liquid that has specified dielectric properties. Test laboratories use homogeneous liquid-filled head models because heterogeneous head models are harder to make measurements in and construct. The IEEE 1528 standards also specify mobile phones must be tested in two positions called the 'tilt' and 'cheek' positions. However, these testing positions have not been updated since 2003

when mobile phone antennas extended out of the phone. Many peer reviewed studies have found that the IEEE 1528 SAR testing standards are not conservative enough [9–12].

Some of the most important parameters in determining the absorption rate of electromagnetic waves are the size of the head model, dielectric properties of the tissue, source frequency, source power control and the distance between the source and the human body [12, 13]. One of the easiest ways to reduce the SAR is increasing the distance of users from mobile phones [14]. As can be seen in the literature review below on distribution patterns of SAR and temperature in the head due to antenna distance from the head, more detailed investigations using different model parameters are still needed. This study aims to help fill this gap.

Another important parameter for affecting the measured SAR is the radiated power of the RF source. In real life situations phones do not always operate at maximum power. The mobile phone’s operator network controls the output power of each connected mobile phone and keeps it at the lowest possible level while still maintaining a good signal quality. The output power level of a mobile phone can vary more than a thousand-fold during a call [15]. However, in the IEEE 1528 testing standards and in the Canadian RF compliance standards, phones being tested for SAR limit compliance must be tested using the time-averaged maximum output power to achieve the most conservative SAR results. For mobile phones using GSM technology operating in the 800 MHz frequency range, the maximum peak output power set by the IEEE is 2W [16]. In this study I use the time-averaged maximum output powers to model the most conservative result.

The purpose of this study was to explore the relationship between cell phone distance from the head and temperature and SAR levels in head in order to provide information on how to use modern smart phones in ways that reduce possible health risks from RF radiation. To do this I use a patch antenna operating at 835 MHz frequency to represent the radiation from a mobile phone. I operate the patch antenna at IEEE peak output power and the average testing maximum time-averaged output powers in GSM850 and LTE bands 5 and 26 for the 12 most popular phones in 2020. I varied the distance of the RF source from a SAM phantom head with heterogeneous tissue and studied both the resulting temperature and SAR distribution in the head from the electromagnetic waves. To compare my results to Safety Code 6 standards I also found the peak spatially-averaged 1 g SAR in the head.

Covid-19 note: I started working on my PHYS590 thesis project in January 2020 and was originally hoping to conduct research on the possible biological effects of 5G millimeter waves. My research plan was to expose fruitflies to 6 GHz RF in a lab and see if there were any biological effects compared to fruitflies being exposed to

4G frequencies and a control group. However, due to covid-19, starting in March I was unable to access the lab. It was not confirmed until September that I would still be unable to access the lab for the Fall semester. While I had been hoping to continue with the 5G research in the lab, I was able to switch to learning how to do RF computational modeling in COMSOL Multiphysics. As a result I learned about the use and importance of computational modeling.

II. LITERATURE REVIEW

The following studies have investigated the relationship between mobile phone distance from the head and the resulting SAR and temperature levels.

Amal et al. [12] studied the importance of cell phone positioning on SAR in human head using two different mobile phone models operating in Global System for Mobile communications (GSM) frequency bands and 80 different phone positions. They used a numerical model and the well accepted finite-difference time-domain (FDTD) method to solve the SAR distribution in the human head and found that it is strongly affected by the position of the mobile phone relative to the head. They found that when the mobile phone models were operating at 900 MHz, the SAR_{1g} was 25% higher for 5-10% of the studied positions compared to the IEEE 1528 standard ‘cheek’ position.

Forouharmajd et. al [6] conducted a study to experimentally determine the effect of increasing cell phone distances on brain tissue temperature. The study used the brain tissue of a cow and placed a mobile phone 4mm and 4cm away from the tissue for 15min periods. They found that increasing the distance between the phone and the brain was an important parameter for reducing thermal effects due to the electromagnetic cell phone waves.

Christ et. al [11] used numerical analysis to show that reduced distance from mobile phone to head due to pinna (ear) compression can increase the maximum peak spatially averaged 10 g SAR by approximately 2dB in head models of both adults and children. In noisy environments users tend to hold phones against the ear with a high force that deforms the pinna beyond its normal limit. The IEEE 1528 model does not take into account the deformation of the pinna when the mobile phone is held or pressed against the ear. When the pinna is deformed the mobile phone is closer to the head and therefore the SAR in the head is increased.

Lahiri et al. [17] experimentally determined that the use of mobile phones in non-contact mode significantly lowers skin temperature rise during its use. They used the infrared thermography technique to report the skin temperature rise. They also found that the temperature rise is highest when the phone is simultaneously being charged and used for a call. As well, the temperature rise is higher for mobile devices with higher reported SAR.

Hossain et. al [18] investigated the effects of the dis-

tances between the human head and a mobile phone with an internal PIFA antenna operating at 900 MHz and 1800 MHz. The analysis was performed using Computer Simulation Technology with the finite-difference time-domain (FDTD) method to determine the SAR on a SAM phantom head model. This study found that by increasing the distance between the user head and antenna, the SAR is decreased and it recommends keeping mobile phones a minimum distance of 5mm away from the body.

Mary et. al [19] used a patch antenna operating at 900 MHz and 1800 MHz with a radiated power of 0.32 W to simulate a mobile phone operating on a homogenous spherical representation of the human head. The FEKO program they used for the simulation uses Method of Moments to solve the SAR values. They found that it is possible to support experimental findings of phantom studies with numerical models and vice versa.

All the studies used different parameters, devices and methods for their experiments but all concluded that increased SAR and temperature result from a decreased distance between the human head and an RF source. The literature shows that both experimental and computational models are needed and all the studies identify the need for more in depth research with different parameters in this field. In this study I use a computational model with different output powers at a frequency of 835 MHz to investigate the effects of RF source distance from the human head.

III. METHODS

To create the computational model for this study I used COMSOL Multiphysics software. To set up the COMSOL model for this study I started by following the COMSOL Multiphysics tutorial ‘Specific Absorption Rate (SAR) in the Human Brain’ [20] which uses both the Heat Transfer Module and the RF Module available in COMSOL Multiphysics 5.6. I then built up the model to find the SAR and temperature in the head at different output powers and different antenna distances from the head. I also modified the model to be able to calculate the peak spatially-averaged SAR over 1 g of tissue so the model results could be compared to Safety Code 6 SAR limits.

A. Numerical head model

The head model used in this study has the same geometry as the Specific Anthropomorphic Mannequin (SAM) defined in the IEEE 1528 standards for mobile phone SAR testing in the head [8]. The SAM phantom is used for mobile phone compliance measurements for FCC and for Canadian RF compliance regulations. The head model geometry was imported into COMSOL Multiphysics from the COMSOL ‘Specific Absorption Rate

in the Human Brain’ application files [20] and can be seen in Figure 1.

FIG. 1. SAM phantom head model imported into COMSOL Multiphysics.

Instead of using a homogeneous material inside the SAM phantom head, which is standard practice for mobile phone SAR testing [8], the head in this study is modeled with heterogeneous tissue properties. The heterogeneous model is based off of a Magnetic Resonance Image (MRI) study of a head containing images of 109 slices with 256-by-256 pixels [21]. A COMSOL application txt file [20] was created from this MRI data and was imported into the study. The txt file was then used as source data for a volumetric interpolation function to estimate varied material parameters and tissue types inside the head model. The variation in tissue parameters interpolated within the head model is not scientifically grounded and is only meant to show the variation of conductivity, relative permittivity, and perfusion rate as a function of position in the head. The electromagnetic characteristics of the biological tissue and organs in the head are important for understanding the interactions of electromagnetic radiation with the body because the propagation, reflection and attenuation of the electromagnetic waves depend on these electromagnetic characteristics [10].

The varying conductivity and average relative permittivity as a function of position in the head model can be seen in Figure 2 and Figure 3. The conductivity and relative permittivity values were taken from a study of dielectric properties in the brain [22]. These dielectric properties were used by an interpolation function to create the dielectric variation in the human head model based off of the MRI data. Table 1 shows the base dielectric parameters used for human brain tissue at 835 MHz.

In comparison for the homogeneous liquid specified by IEEE 1528 for mobile phone testing the dielectric properties are taken from the average dielectric properties over the whole head. For 835 MHz the IEEE 1528 target rel-

ative permittivity and conductivity is 41.5 and 0.9 S/m respectively.

FIG. 2. Average relative permittivity at 835 MHz in the head model calculated from the MRI imaging data.

FIG. 3. Isotropic conductivity (S/m) at 835 MHz in the head model calculated from the MRI imaging data.

TABLE 1. Material parameters used in different parts of the head at 835 MHz [20]. Only conductivity and permittivity depend on the frequency used. The SAM phantom homogeneous liquid dielectric parameters are also added in the Table.

Part	Parameter	Symbol	Value
Brain	Conductivity	σ	1.15 S/m
Brain	Relative permittivity	ϵ_r	58.13
Brain	Density	ρ_{br}	1030 kg/m ³
Brain	Perfusion rate	ω_b	$2 \cdot 10^{-3} (ml/s)/ml$
Bone	Perfusion rate	ω_b	$3 \cdot 10^{-4} (ml/s)/ml$
Skin	Perfusion rate	ω_b	$3 \cdot 10^{-4} (ml/s)/ml$
Blood	Heat capacity	C_{bl}	3639 J/(kg·K)
Blood	Density	ρ_{bl}	1000 kg/m ³

The perfusion rate is important for the bioheat model which is used to find the temperature distribution in the head. The heating loss in the model depends on the heat capacity, density and perfusion rate of the blood. The perfusion rate varies with different tissue types and materials (Table 1). The interpolation function used for varying dielectric parameters in the head was also used for modeling the perfusion rate between the brain tissue, bone and skin.

B. Patch antenna model

Microstrip patch antennas have a wide range of applications in satellite communications including mobile phones. This study uses a microstrip patch antenna operating at a frequency of 835 MHz to model the RF radiation emitted by a mobile phone device. The dimensions used for the patch antenna can be seen in Figure 4.

FIG. 4. The modeled microstrip patch antenna. The antenna has a microstrip feed line that is fed by a Lumped Port. It has a perfect electric conductor (PEC) ground plane and rectangular patch on either side of a dielectric substrate (permittivity 5.23).

The Lumped Port boundary condition in this model is used to mimic a connection to a transmission line feed with a characteristic impedance, Z_{ref} . The characteristic impedance was set to 75 ohms to minimize the mismatching impedance between the feed line and the antenna at 835 MHz. The resulting antenna parameters from this set up can be seen in Table 2.

TABLE 2. Patch antenna output parameters.

Parameter	Symbol	Value
Reflection coefficient	S11	-0.069 dB
Gain	G_0	2.9088
Directivity	D_0	3.5455

The 2D microstrip patch antenna electric far-field radiation pattern in the x-y plane is shown in Figure 5.

FIG. 5. The modeled patch antenna 2D far-field radiation pattern of the electric field in the x-y plane.

C. Antenna output power

The antenna input power is controlled by the incident voltage wave from the transmission line which has an amplitude equal to V_0 and is set at the Lumped Port boundary condition. To determine the Lumped Port incident voltage needed to obtain a specific output radiated power, P_{rad} , the following calculation derived from [23, 24] was used:

$$P_{rad} = \frac{G_0}{D_0} \left(\frac{V_0^2}{2Z_{ref}} \right) \left(1 - \frac{1}{10^{\frac{RL}{10}}} \right) \quad (1)$$

Where G_0 is the antenna gain, D_0 is antenna directivity, V_0 is the incident Lumped Port voltage wave amplitude, Z_{ref} is the Lumped Port characteristic impedance and RL is the return loss. The return loss is calculated from the reflection coefficient, S_{11} , by the equation:

$$RL = -20 \log_{10} |S_{11}| \quad (2)$$

The output power is an important parameter for determining SAR in the human head. This study was run at several different output power levels to represent different phone models and technologies. Table 3 shows the different output power levels used in this study. Some of the most popular cell phones of 2019 and 2020 were used to find the current industry time-averaged output powers used in head SAR testing for GSM850 and LTE

bands 5 and 26 technologies. The average output powers of these phones was obtained from FCC RF exposure compliance reports. GSM850 stands for Global Systems for Mobile communications, which is a second generation (2G) technology that operates in the 850 MHz frequency band. LTE stands for Long Term Evolution and is a high-speed wireless broadband technology. LTE bands 5 and 26 also operate in the 850 frequency band. The 12 phone models used in this study to find the average maximum output powers used in current FCC RF compliance reports are the iphone7, iphone X, iphone XS, iphone 11, iphone 11 Pro Max, Galaxy S9, Galaxy J3, Galaxy S10, Moto e5 Play, Vivo 5 Mini and Google Pixel 3. The FCC compliance RF maximum time-averaged output powers for each of these phones using GSM850 and LTE bands 5 and 26 technologies can be found in Appendix A.

D. Patch Antenna Position and Distance

The patch antenna was placed on the left side of the head model. The outer limits of the head are positioned at 0.0831 m. The antenna is positioned near the top of the ear reference point on the SAM phantom used in IEEE 1528 [8]. The model set up with the patch antenna a distance of 4mm away from the head can be seen in Figure 6.

FIG. 6. Microstrip patch antenna and head model setup with the microstrip patch antenna 4mm away from the head.

The study was run in COMSOL using a parametric sweep of the antenna distances from the head starting at 0mm and stopping at 15mm with a 0.5 mm step.

E. Wave Propagation and Finite Element Analysis

COMSOL Multiphysics is a Multiphysics simulation software that uses finite element analysis. The finite element analysis (FEA) method attains solutions to differential and integral equations and discretizes the problem with finite mesh elements. In this model a Perfectly Matched Layer (PML) was created to absorb scattered

TABLE 3. Maximum time-averaged output power levels used in this study. The industry average testing output power refers to the average maximum time-averaged output powers used by the 12 most popular phones of 2019/2020 found in Appendix A. V_0 is the Lumped Port incident voltage wave amplitude.

	Time-averaged output power level (W)	V_0
IEEE maximum power level	2	19.17 V
GSM850 industry average testing output power	1.648	16.258 V
LTE bands 5 and 26 industry average testing output power	0.276	7.128 V

radiation from the model and the mesh size was limited according to the minimum wavelength. The model solves the vector-Helmholtz equation,

$$\nabla \times \frac{1}{\mu_r} \nabla \times \mathbf{E} - k_0^2 \epsilon_r \mathbf{E}, \quad (3)$$

everywhere in the domain for 835 MHz frequency. In Eq.3 μ_r represents permeability, k_0 is the free-space wave vector, ϵ_r is the relative permittivity and $\mathbf{E}$ is the electric field.

F. SAR Calculations

SAR is defined as the rate of power dissipation normalized by density of the material and was computed using the equation,

$$SAR = \frac{\sigma |\mathbf{E}|^2}{\rho}. \quad (4)$$

Where $\mathbf{E}$ is the peak electric field strength (V/m), σ is the conductivity of the biological tissue (S/m) and ρ is the mass density of the tissue (kg/m^3).

Average SAR is a more practical quantity and is defined as the ratio of power absorbed to the weight of biological tissue and is obtained by the following expression:

$$SAR_{av} = \frac{1}{V} \int_V \frac{\sigma |\mathbf{E}|^2}{\rho}. \quad (5)$$

Many SAR standard limits for the head, including Safety Code 6, FCC and IEEE are determined using the peak SAR spatially-averaged over 1 g (SAR_{1g}) or 10-g (SAR_{10g}) of tissue. Health Canada's Safety Code 6 exposure limits only use SAR_{1g} to define limits of EMF radiation in the human head.

To calculate the SAR_{1g} in this model, the IEEE 1528 procedures were followed. The peak local SAR location was found and the average SAR was calculated over a 1 g cube of tissue at this location. The head at the peak local SAR location had a density of $1050 \text{ kg}/\text{m}^3$ and therefore the 1 g cube used had a volume of $9.52 \times 10^{-7} \text{ m}^3$.

G. Heat Transfer Calculation

To calculate the heat transfer in the biological tissue of the head, the predefined equation in the COMSOL Bio-heat Transfer interface was used. This equation follows Penne's approximation:

$$\rho C_p \frac{dT}{dt} - \nabla \cdot (k \nabla T) = \rho_b C_{p,b} \omega_b (T_b - T) + Q_e + Q_{met}. \quad (6)$$

The left side of eq. 6 accounts for thermal conduction and heat storage in living tissue and is modeled as a solid medium where ρ is the density, C_p is the heat capacity, K is the thermal conductivity and T is the temperature [25]. The convective cooling of blood perfusion is represented by the transfer term,

$$Q_{perf} = \rho_b C_{p,b} \omega_b (T_b - T). \quad (7)$$

Where ρ_b is blood density, $C_{p,b}$ is blood heat capacity, T_b is the blood temperature and ω_b is the blood perfusion rate. Q_e is the electromagnetic heat source which is found from $Q_e = \mathbf{J} \cdot \mathbf{E}$, where $\mathbf{J}$ is the electric current density and $\mathbf{E}$ is the electric field. The Q_{met} term is used to account for heat generation from metabolism and can be neglected in this model as it is much smaller than the electromagnetic heat source.

The core body temperature in this model is set to 37° .

IV. RESULTS AND DISCUSSION

In this section the distribution of temperature change and SAR in the head at the different output powers and antenna distances from the head are displayed. The local maximum temperature change and SAR_{1g} are analyzed. As well, the temperature change and SAR distributions along different planes in the head are compared.

Figure 7 shows the temperature increase distribution pattern that occurs in the head when the patch antenna is positioned 0mm from the head and operating at 1.438 W. The temperature change displayed in the plot is the temperature increase in degrees Celsius from the initial body temperature of 37°C .

The temperature increase volume and slice plots in Figure 7 reveal that the temperature change is highest

FIG. 7. Surface plot (top) and slice plot along cut line 2 (bottom) of temperature increases ($^{\circ}\text{C}$) in the head modeled via the bioheat equation (Eq. 6). In this plot the patch antenna is 0mm from the head and operating at the GSM850 average output power (1.438 W).

closest to the surface of the head model. The head is sliced at the patch antenna feed point, which is the area with the highest temperature changes, to show the distribution pattern of the temperature increase inside the head.

All the different patch antenna parameters used in this simulation yielded similar temperature change distribution patterns in the head model. However, for increased output power and decreased antenna distance the temperature change pattern had proportionally higher temperature values.

Figure 8 shows the local maximum temperature increases in the head model depending on patch antenna distance for the 3 different patch antenna output power levels. The maximum temperature increase, from 37°C , was 0.77°C and it was reached when the patch antenna was operating at the maximum output power of 2W and was 0mm from the head. All the maximum temperatures were located near the surface of the head.

It is important to note that the average core body temperature naturally varies from 0.2°C - 0.3°C daily [26] so an increase less than 1°C in the body is not considered significant. The brain is more sensitive to changes in temperature than the outer layers of the head. The maximum temperature increase in the model brain region was found to be 0.14°C . It occurred when the antenna was operating at 2W and was 0mm from the head model. This temperature is well below the threshold of temperature which can cause thermal effects on the neurons in the brain [10]. As well, since the active heat transfer in

FIG. 8. Maximum temperatures in the head versus patch antenna distance from the head.

the brain is very effective in regulating the brain's temperature, a rise up to 3.5°C in the brain will not cause any physiological damage [27].

The temperature increase in the head from the incoming waves is due to the electromagnetic radiated power being absorbed into the head. SAR is a measure of the amount of power being absorbed by the head. Similar to the temperature change distribution, the local SAR values are highest closest to the surface of the head and in the area closest to the antenna feed line (Figure 9 and Figure 10). The SAR distributions in the head are similar at all output power levels and antenna distances from head. When the local SAR values are plotted on a log scale, as in Figure 10, the SAR distribution due to different dielectric properties in the head are noticeable.

FIG. 9. SAR distribution on a surface plot of the modeled head. This plot is generated at GSM850 power levels with the patch antenna located 2mm away from head.

In order to compare the results in this study to Safety Code 6 limits, the peak spatially-averaged SAR over 1 g of tissue was also measured. The SAR_{1g} is plotted versus the antenna distance from the head in Figure 11 for the three different output power levels used in this study.

FIG. 10. Log10(SAR) in the head slice plot generated at GSM850 power levels with the patch antenna located 2mm away from head.

FIG. 11. Peak spatially-averaged SAR over 1 g of tissue versus the patch antenna distance from the head.

In the IEEE 1528 SAR in head compliance testing guidelines, a 4mm lossless ear (pinna) is added to the SAM phantom and mobile phones are tested at two positions defined as the ‘cheek’ and ‘tilt’ positions. For both positions the top part of the phone is placed on the pinna and both ends of the phone, which in modern smart phones are the areas that contain the antennas, are 4mm or more away from the head model. This distance is marked in Figure 11 as the industry standard testing distance.

Figure 11 shows that at every power level the SAR_{1g} in the head exponentially increases as the patch antenna approaches the head. At all the output power levels, the SAR_{1g} increases around 3 fold between 4mm and 0mm.

At the 2W maximum power output level specified by the IEEE, the SAR_{1g} in the head exceeds the 1.6 W/kg Safety Code 6 limit until the antenna is at least 5.6mm away from the head. When the patch antenna is operating at 1.483W output power, which is the average

GSM850 industry testing output power, the SAR_{1g} in the human head exceeds the Safety Code 6 limit until the antenna is at least 4mm from the head. The LTE bands 5 and 26 average testing output power levels power level, 0.276 W, is significantly lower than the other output power levels. As a result the LTE bands 5 and 26 SAR_{1g} do not exceed the Safety Code 6 limit even when the antenna is 0mm from the head.

The relationship between SAR and temperature change in the head is important for understanding the electromagnetic affects on the human head. In this study the SAR and temperature change distributions were compared along different cut lines in the head model. Figure 12 shows the position of the 3D cut lines that are used in this study.

FIG. 12. Head model with the 3D cut lines used for SAR and temperature evaluation.

Both cut lines 2 and 3 are normal to the plane of the microstrip patch antenna. Cut line 2 is at the level of the feed line intersection with the rectangular patch. At this cross section of the head, the brain tissue is located around 7mm into the head. Cut line 3 intersects the brain in the model at around 20mm into the head along the arc length. Cut line 1 is parallel to the patch antenna and close to the surface of the head model.

The temperature increase in the head along cut lines 1, 2 and 3 with increasing antenna distance can be seen in Figure 13, Figure 14 and Figure 15, respectively. Only the temperature increases for the GSM850 industry average testing output power are displayed because the temperature increase curves are the same at all power levels just with different maximum temperatures.

Figure 13 shows that the maximum temperature occurs closest to the feed point of the patch antenna and decreases along the skin surface in either direction. Figure 14 shows that along cut line 2, where the maximum temperatures occur, the temperature decreases more slowly until 0.007 m along the cut line’s arc length where it starts to fall off more rapidly. Similarly, in Figure 15 the temperature decreases slowly along cut line 3’s arc length until about 0.02 m when the temperature declines at a faster rate. Both graphs begin decreasing more rapidly

FIG. 13. Temperature distribution along cut line 1 from Figure 12 versus the distance of the patch antenna from the head. The legend shows the distance of the patch antenna in mm from the head. The patch antenna is operating at GSM850 industry average output power (1.438 W).

FIG. 14. Temperature distribution along cut line 2 from Fig 12 versus the distance of the patch antenna from the head. The legend shows the distance of the patch antenna in mm from the head. The patch antenna is operating at GSM850 industry average testing output power (1.438 W).

FIG. 15. Temperature distribution along cut line 3 from Fig 12 versus the distance of the patch antenna from the head. The legend shows the distance of the patch antenna in mm from the head. The patch antenna is operating at GSM850 industry average testing output power (1.438 W).

FIG. 16. Local SAR distribution along cut line 1 from Fig 12 versus the distance of the patch antenna from the head. The legend shows the distance of the patch antenna in mm from the head. The patch antenna is operating at GSM850 industry average testing output power (1.438 W).

FIG. 17. Local SAR distribution along cut line 2 from Fig 12 versus the distance of the patch antenna from the head. The legend shows the distance of the patch antenna in millimeters from the head. The patch antenna is operating at GSM850 industry average testing output power (1.438 W).

FIG. 18. Local SAR distribution along cut line 3 from Fig 12 versus the distance of the patch antenna from the head. The legend shows the distance of the patch antenna in millimeters from the head. The patch antenna is operating at GSM850 industry average testing output power (1.438 W).

in the brain region (starting around 0.07m along cut line 2 and at around 0.02m along cut line 3). The brain has the largest blood-flow rate in the head, so near the brain the temperature rise slows down rapidly [27].

Figure 16, Figure 17 and Figure 18 show the local SAR values along cut lines 1, 2 and 3, respectively. Figure 16 shows that, like the temperature change, the SAR peaks at the antenna feed point and drops off along the surface of the head model. Figure 17 shows that SAR decreases much more rapidly in the head along cut line 2 than the temperature change does. Along cut line 2 the SAR levels out at around 0.04m along the arc length whereas the temperature does not level out until around 0.07m into the head. This difference in SAR and temperature patterns in the head shows that SAR and temperature are not directly proportional. This is because SAR is a measure of the instantaneous energy absorption of tissue and therefore a representation of the instantaneous heating of tissue. The temperature distribution in the head has different heat transfer mechanisms that affect thermal conduction and heat storage such as heat capacity and perfusion rate. Figure 18 shows that the SAR_{1g} significantly increases at 0.02m along cut line 3. This is the same point along cut line 3 that the temperature change begins to decrease more rapidly. The spike in SAR_{1g} occurs at the start of the brain tissue region because of the different dielectric properties between the cortical bone tissue and the brain tissue.

From this comparison of the temperature change and SAR distributions in the head from an RF source, it is evident that although they are related they are not directly proportional. As such it is important to examine both the temperature change and the SAR to understand the risks to human health from RF radiation.

Some of the limitations in this study that must be noted are the following:

1. A mobile phone's maximum time-averaged output power level is not used continuously during calls and is only reached in certain operating conditions. The time-averaged power of a GSM850 device under real operating conditions was found to be 1/8 of its maximum power [28]. Therefore the maximum output powers used in this study produce more conservative results than real devices in real operating conditions.
2. The COMSOL interpolation of dielectric properties in the head were not done scientifically but as a means to approximate the heterogeneous nature of human heads and its effect on the SAR and temperature distribution within the head. As well numerical models are limited in size and resolution and are implemented with several simplifications regarding the environmental or geometrical setup.
3. The microstrip patch antenna in this model is not inside a mobile phone model. As such the effects from a mobile phone's materials, shape and size

are not accounted for. The antenna inside a mobile phone can be placed towards the back of the phone meaning that there is a slightly increased distance between the antenna and the human head when a mobile phone is touching the head. Even an increase in distance of 1mm makes a marked difference in the measured SAR_{1g} values. As well it has been reported that metal-glass mobile casings can reflect electromagnetic energy which would also lower the SAR levels in the head [18].

Although there are limitations to this study, it still provides useful information for experimental investigations and results. This study is meant to give insight into the SAR and temperature patterns in the head due to electromagnetic radiation at 835 MHz and the relationship with distance and power in the context of Safety Code 6 and modern mobile phones. The results from this study indicate that it is better to keep your mobile phone at least 4mm away from the body. The IEEE 1528 mobile phone standard testing positions may not indicate the most conservative SAR estimates for modern mobile phones as the antennas located in the bottom and top of the phone in most modern smart phones are at least 4mm from the SAM phantoms during compliance testing. As well, Figure 11 shows that at 835 MHz the GSM850 band which is used for phone calls and texts has a much larger output power and therefore SAR than the LTE bands which are used for data calls. Using the speaker phone option or headphones for phone calls, especially when using GSM850 technology, would mitigate risk from SAR in the head that exceeds the Safety Code 6 limits.

V. CONCLUSION

The purpose of this study was to analyze the relationship between RF antenna distance from the head and the resulting Specific Absorption Rate in the head. It is useful to understand that the IEEE 1528 test position standards may not be the most conservative positions and that keeping your phone at least 4mm from your body could mitigate the risk from radiation absorption in the head. It is important to be aware of RF radiation and absorption patterns in an age that relies so heavily on mobile phone communications and RF technology.

The IEEE 1528 standard SAM phantom with heterogeneous material parameters and a microstrip patch antenna operating at 835 MHz were used to perform this study. Both the antenna distance from the head and the radiated powers were varied. The SARs and heat transfer induced by the various configurations were calculated in COMSOL Multiphysics using the FEA method.

At all power levels, the SAR in the head increased exponentially as the antenna approached the head. At the IEEE maximum output power level the SAR in the head exceeded the 1.6 W/kg SAR_{1g} limit set by Safety Code 6 until the antenna was 5.6mm away from the head. When looking at the most popular phones used in 2019/2020

the SAR_{1g} at the average maximum radiated power level for the GSM850 band were above the SAR limit until the antenna was 4mm from the head. For the same phones operating in LTE bands 5 and 6, the radiated output power levels produced a SAR_{1g} below the SAR limit even when the antenna was at the closest distance to the head.

The temperature change distribution also increased as the patch antenna approached the head. There was not a direct relationship between SAR and temperature change distribution and therefore it is important to look at both to understand how electromagnetic radiation interacts with the human body.

This research provides evidence that mobile phones should be kept at least 4mm away from the head during calls in order to mitigate possible health risks from electromagnetic absorption. Using phones operating at a constant maximum time-averaged output power level is a conservative model because mobile phones in reality operate at varying output levels. However, it is important for standards to be set for human health and safety based on the most conservative configurations possible.

Finally, the research conducted in this study could be furthered by placing the antenna into a mobile phone model in the simulation and expanding the study to include higher frequencies. Understanding how SAR in the human head changes with higher frequencies will be important for mitigating health risks in the future with the proposed roll out of 5th generation (5G) technology.

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Appendix A: 2019/2020 Mobile Phone RF Exposure Compliance Reports

TABLE 4. popular 2019/2020 mobile phone FCC reports on maximum time-averaged power. LTE refers to bands 5 and 26 which are in the 831.5-850 MHz frequency range. GSM850 is in the 850 MHz frequency band.

Phone Model	FCC ID	Maximum Output Power (dBm)	
		LTE	GSM850
iphone 7	BGC-E3309A	25.7	32.25
iphone X	BCG-E3161A	24	29.8
iphone XS	BCG-E3218A	25.5	32
iphone 11	BCG-E3309A	25.7	32.25
iphone 11 Pro Max	BCG-E3306A	25.7	32.25
Galaxy S9	A3LSMG960U	21.57	32.8
Galaxy J3	A3LSMJ337A	24	32.15
Galaxy S10	A3LSMG973U	26	32.34
Moto e5 Play	IHDT56XC4	23.13	27.5
Vivo 5 Mini	YHLBLUVIVO5MIN	23.17	32.45
Pixel 3	A4RG013A	24.1	29.9

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