Modeling of Electromagnetic Wave Penetration in a Human Head due to Emissions from Cellular Phone

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Abstract – In recent years, there has been an increasing public concern about possible health hazard resulting from exposure to electromagnetic (EM) waves. Much attention has been paid to the induced of SAR in the human head for exposure to EM waves emitted from commercial cellular phone antennas. Therefore, the computation of the electric fields and SAR generated by cellular phone inside a four-tissue phantom head model is presented in this paper. The phone was considered working at 900MHz to 1800MHz bands according to the Global System of Mobile Communication (GSM). The penetration of the E-fields and averaged SAR values in 1g and 10g of tissue were computed inside the model of human head using Finite Difference Time Domain (FDTD) technique. The E-fields and SAR are then evaluated using CST Microwave Studio as it capable to do an accurate 3D simulation. The CST Microwave Studio results show that magnitude of EM field decreases exponentially with the penetration distance at a rate specified by the attenuation constant, α. Besides, the SAR is affected by operational frequency of the phone and the distance of the antenna to the human head. An experimental technique on SAR distribution needs to be done to validate the results from simulation technique.

Keywords:Specific Absorption Rate (SAR), International Commission on Non-Ionizing Radiation Protection (ICNIRP), Global System for Mobile Communication (GSM)

1. Introduction

Today, cellular phone becomes a necessity for human being due to its mobility, small size and some useful applications provided in the chip. Widespread use of this kind of hand-held transceivers has led to increased concerns about possible health hazards, particularly concerns about an Alzheimer and brain cancer, as the antennas for these phones lie along the transmission towers. Increasing exposure from the use of devices such as cellular phones and base stations are a growing concern for the community. This is because cellular phone, at distances within a wavelength from a RF transmitter is a region known as the near field. Since cellular phone radiation has a wavelength of 30 cm at 900 MHz (GSM phone) the users head will be within this near field region. The head disturbs the field and alters the manner in which RFR interacts with tissue.

Therefore, it is important to model the behavior of the electromagnetic waves as they interact with the complex tissues of the human due to GSM frequency. Thus, this research is performed to calculate the propagation of the electromagnetic fields in a human head due to the emissions from cellular phone and to study the effects of SAR due to the operational frequency of the cellular phone, the electrical properties of a human head and the position of cellular phone. Numerical technique has been used in this report as one of the computational methods for analyzing electromagnetic problems.

2. Methodology

This section is divided into two parts; mathematical analysis and the other one is simulation. All the steps are taken to evaluate the electromagnetic fields penetration in a 2D human head model. The mathematical results are used to validate the output from the simulation technique. All the results are simulated using CST Microwave Studio software.

2.1 Derivation of Maxwell's Equations

The propagation of EM waves in a biological medium is studied mathematically by solving Maxwell's equation under appropriate boundary condition [1]. For simplicity, the biological medium is assumed to be infinite extent, source-free, isotropic, and homogeneous. The medium is isotropic if ε is a scalar constant, so **D**

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and **E** are the same in every direction. A homogeneous medium is one for which ε, σ and μ are constant. For this case, Maxwell's equations become

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad (1)$$

$$\nabla \times H = J + \frac{\partial D}{\partial t} \quad (2)$$

$$\nabla \bullet B = 0 \quad (3)$$

$$\nabla \bullet D = 0 \quad (4)$$

Further, since the medium is assumed to be isotropic and homogeneous, its permittivity, permeability, and conductivity are scalars constant. After going through some mathematical processes, both **E** and **H** satisfy the equation (called the *wave equation*):

$$\left(\nabla^2 - \mu\sigma\frac{\partial}{\partial t} - \mu\varepsilon\frac{\partial^2}{\partial t^2}\right)\begin{pmatrix}\mathbf{E}\\ \mathbf{H}\end{pmatrix} = \begin{pmatrix}0\\0\end{pmatrix} \quad (5)$$

In view of the fact that equations governing **E** and **H** in the biological material (Maxwell's equations) are linear and keeping in mind that any arbitrarily time-varying function can be expressed as a sum of number of sinusoidal functions, time dependence of the fields, **E** and **H**, can be given by the factor e^{jwt} so that

$$\frac{\partial}{\partial t} \equiv j\omega \qquad \frac{\partial^2}{\partial t^2} \equiv -\omega^2 \quad (6)$$

By applying both relationships in equation (5), the wave equation becomes

$$\nabla^2\mathbf{E} + \gamma^2\mathbf{E} = 0 \quad (7)$$

where

$$\gamma^2 = \omega^2\mu\varepsilon - j\omega\mu\sigma \quad (8)$$

$$= \omega^2\mu\varepsilon_O\left(\varepsilon' - j\frac{\sigma}{\omega\varepsilon}\right)$$

$$= \frac{\omega^2}{c^2}\left(\varepsilon' - j\varepsilon''\right)$$

where c is the free space velocity ($3\text{x}10^8$ m/s), $\varepsilon' = \mu_r\varepsilon_r$, $\varepsilon'' = \frac{\sigma\mu_r}{\omega\varepsilon_o}$ and γ is the propagation constant. Thus is, in general, a complex quantity and may be written in the form

$$\gamma = \alpha + j\beta \quad (9)$$

2.2 Finite Difference Time Domain (FDTD)

The FDTD method [2] is used for investigating the interaction between the human body model and EM waves. Information about the properties of tissues is found in the literature which is taken from Gabriel and Gabriel 1996 [5]. It consists of the electrical properties of some tissues inside a human head at 900 and 1800 MHz. FDTD was chosen because it is stable and accurate, doesn't require enormous computational resources and can handle complex geometries.

2.3 CST Commercial Software

At the final stage of research work, a commercial EM modeling codes is applied to validate the results form FDTD technique. CST Microwave Studio is one of the EM modeling code which can be used for bioelectromagnetic purpose. A partial-body of human head with four tissues (skin, fat, bone, brain) is distinguished. The model of cellular phone is put parallel with the head and the electromagnetic wave is assumed to propagate in z-direction. Figure 1 illustrates 2D of a partial body of human head model. CST is capable to calculate various kinds of electromagnetic properties such as electric field, magnetic field, power low, SAR and etc. However, this paper only focuses on the electric fields and SAR that penetrate into a human head. The distribution of the local SAR values can be calculated directly from the electric field distribution, which results from the computer run. This was achieved using equation (10) as the sinusoidal source leads to a steady-state electric field, numerically analogous with the same sinusoidal variation.[6]

$$SAR = \frac{\sigma E_{\max}^2}{2\rho} \text{ (W/Kg)} \quad (10)$$

where σ is the conductivity (S/m) and ρ is the density (Kg/m^3) of a human head.

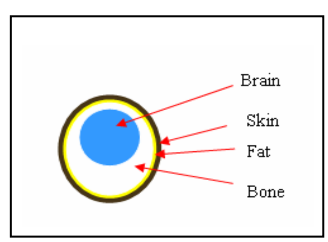


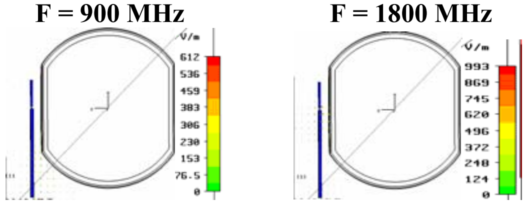
Figure 1: Front view of four-tissue phantomead model in CST Microwave Studio

3. Results and Discussion

The main interest of this research is to investigate the behavior of electromagnetic wave propagation in a human head due to the frequency and the position of the cellular phone from the human head model with the same constitutive parameters (conductivity, and permittivity), thus to evaluate the SAR values in (W/Kg).

3.1 Distribution of electric field

F = 900 MHz **F = 1800 MHz**

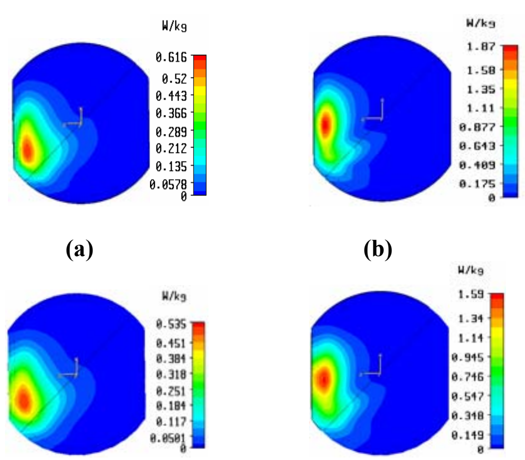


(a) (b)

Figure 2: Distribution of E-field in xz-plane (a) f=900MHz, (b) f=1800MHz

Figure 2 shows the distribution of electric fields inside a human head model at 900 and 1800 MHz respectively. It is observed that the intensity of the electric fields are considered high at the portion close to the source of radiation and these fields attenuate as the waves propagate along the z-axis.

3.2 Distribution of SAR at different frequency



(a) **(b)**

(c) **(d)**

Figure 3: (a) SAR $_{1g}$ at 900 MHz, (b) SAR $_{1g}$ at 1800 MHz (c) SAR $_{10g}$ at 900 MHz, (d) SAR $_{10g}$ at 1800MHz

Table 1: The peak SAR at various frequencies

SAR (W/Kg)	Frequency (MHz)	
	900	1800
Peak SAR_{1g}	0.616	1.87
Peak SAR_{10g}	0.535	1.59

Figure 3 presents for comparison, the *Specific Absorption Rate*, SAR in the specified conditions. Maximum values averaged over a volume corresponding to 1g of tissue, SAR_{max} (1g) and to 10g of tissue, SAR_{max} (10g) are displayed for checking the compliance with exposure standard. High SAR values are in red, low SAR values are in blue. The results can be described as follow:

i. The region with high absorption values is small and close to the feedpoint of the antenna. In most part of the head, the EM field is relatively low.

ii. With the frequency dependence of the equivalent electric conductivity and dielectric permittivity, the SAR_{max} for both 1g and 10g of tissue is higher at 1800 MHz rather than 900 MHz.

iii. The value of max SAR is different for each plane base on the averaging mass of a human head model. From Table1, SAR_{max} for 10g of tissue is slightly lower than SAR_{max} for 1g of tissue for both frequencies.

iv. Based on Figure 3(a), it is interesting to note that the intensity of electromagnetic wave as it penetrates into a human head at 900 MHz is deeper rather than the penetration of EM wave at 1800 MHz as shown in Figure 7. For a uniform plane wave traveling in the +z-direction, the electric field can be expressed as $\tilde{E}(z) = \hat{x}E_{xo}e^{-\gamma z} = \hat{x}E_{xo}e^{-\alpha z}e^{-j\beta z}$ and from this equation, the magnitude of $\tilde{E}_x(z)$ is given by $\left|\tilde{E}_x(z)\right| = \left|E_{xo}e^{-\alpha z}e^{-j\beta z}\right| = \left|E_o\right|e^{-\alpha z}$ which decreases exponentially with z at a rate specified by the attenuation constant, α as shown in Figure 4.

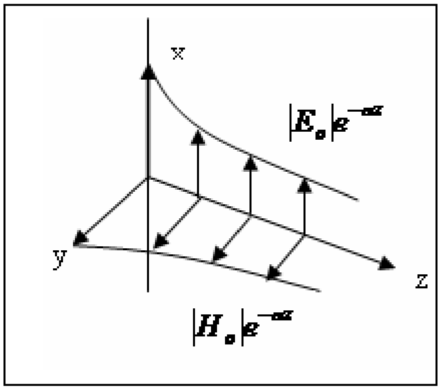


Figure 4: Propagation of EM wave in a lossy medium

Through a distance z = δ such that $\delta = \frac{1}{\alpha} = \frac{1}{\omega\sqrt{\frac{\mu\varepsilon}{2}\left[\sqrt{1+\left[\frac{\sigma}{\omega\varepsilon}\right]^2}-1\right]}}$ where α represents an attenuation constant of a lossy medium, the wave magnitude decreases as it goes deeper into a human head. Thus, this distance δ , called the *skin depth* of the medium or in bioelectromagnetic point of view it is called as *depth of penetration* (D_p), characterizes how well an electromagnetic wave can penetrate into a human head. Value of D_p varies from a small fraction of a millimeter at the upper frequency of RFR range, to a few centimeters from high water content tissues at lower frequency and to more depths for low water content tissues. As a result, the value of *skin depth* of a medium decreases as the operational frequency of the cellular phone increases.

v. Based on the recommendations made by the International Commission on Non-Ionizing Radiation Protection (ICNIRP Guidelines 1998), the limit of SAR for 10g of tissue is equal to 2.0 W/Kg while SAR for 1g of tissue is 1.6 W/Kg. Therefore, the maximum value of SAR as shown in Figure 3 is lower than the standard limit and it is considered to be in a safety condition.

3.3 Distribution of SAR at different position

This subsection discusses the local peak SAR averaged over 1g and 10g of tissues. Figure 5 illustrates the penetration of SAR in a 2D human head model due to different position of the phone. Based on these figures, it shows that the peak SAR not around the region that closes to the feedpoint of the antenna but appears at the center of the head. This inconsistency is due to the increased in frequency and the distance between the antenna and the human head.

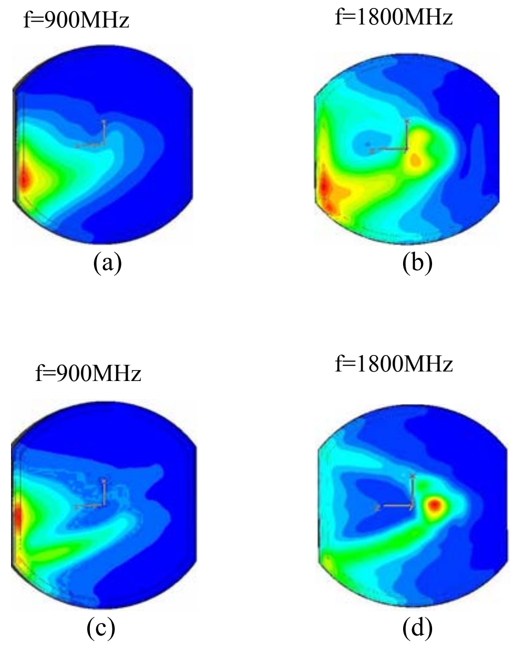


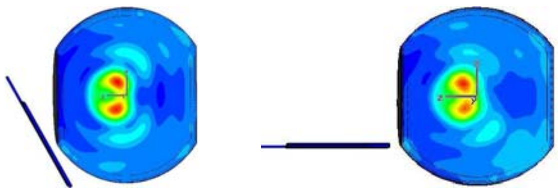
Figure 5: (a) SAR_{1g} at z=5, (b) SAR_{1g} at z=100, (c) SAR_{1g} at z=5, (d) SAR_{1g} at z=100

Table 2: Peak SAR at different position along z- axis

SAR (W/Kg)	f = 900MHz		
	Translation vector		
	z = 5	z = 25	z = 100
Peak SAR_{1g}	0.315	0.124	0.0143
Peak SAR_{10g}	0.269	0.109	0.0127

Table 2 lists the value of the peak SAR at the distances of 5, 25 and 100 units. Note that the antenna positions where SARS are calculated denoted in z-axis, and the origin in the coordinate system is located at the antenna feeding point. The cellular phone is assumed to be operated at 900MHz. It is also interesting to point out that the peak SAR for both average volume decreases as the distance increases.

f = 900MHz



(a) **(b)**

Figure 6: Distribution of SAR_{1g} at different angle (a) θ = 30°, (b) θ = 90°

Table 4: Value of peak SAR at angle of 30° and 90°

SAR (W/Kg)	f = 900MHz	
	θ = 30°	θ = 90°
Peak SAR_{1g}	$9.35e^{-5}$	$8.7e^{-5}$
Peak SAR_{10g}	$6.62e^{-5}$	$6.38e^{-5}$

Besides that, SARs are also evaluated based on the angle between the phone and the model. The results are illustrated in Figure 6. From the observation, it shows that the region with high absorption values is no more close to the feedpoint but around the center of the human head model. Table 4 lists the peak SAR for 1g and 10g average values. It shows that the peak SAR decreases as the feedpoint is not too close to the human head.

5. Conclusion

In conclusion, the important parameters affecting the Specific Absorption Rate (SAR) in the human head exposed to cellular phone radiation were the operational frequency of the phone and the distance between head and antenna of the cellular phone. The peak SAR increases as the operational frequency increases but it will decrease if the antenna of the phone is not too close with the human head. Thus, for safety purpose, the users are advised to use their handfree or turn on their phone speaker while they are talking through the cellular phone. Hence, by increasing the distance of the phone to the head, the peak SAR will be very much lower than the limit SAR as set by ICNIRP and the results basically confirm the conclusion that the SAR is affected by the operational frequency [4] and the distance of antenna of the phone to the human head

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