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SAR Analysis in a Spherical Inhomogeneous Human Head Model Exposed to Radiating Dipole Antenna for 500 MHz – 3 GHz Using FDTD method

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***Abstract*- Analysis of specific absorption rate (SAR) generated by half wave radiating dipole antenna inside a spherical inhomogeneous human head model at the frequency range 500 MHz to 3 GHz using finite difference in time domain (FDTD) method is presented in this paper. The human head is modeled as an inhomogeneous sphere of 19 cm diameter consisting of a uniform core representing human brain, surrounded by two spherical shells representing skull and skin with their respective electromagnetic properties. Maximum local SARs are obtained for the distance between head and antenna in the range of 1.0 cm to 3.0 cm using a dipole antenna of length 14.5 cm. As the distance is increased over 1.0 cm then the value of maximum local SAR induced in the head goes below FCC and IEEE's upper safety limit for input power of 0.6 Watt. Resonant dipole antennas of appropriate length corresponding to several spot frequencies have also been used to observe the maximum local SARs at their resonance frequencies.**

***Index Terms*-** FDTD, SAR, dipole antenna, biological hazards.

I. INTRODUCTION

The radiofrequency (RF) hazard due to the electromagnetic absorption in the human head is becoming a burning issue [1-7]. During the last several years, there have been increasing interests in the application of numerical techniques to calculate the intensity of electric fields in the human head models. Numerical simulations hold very significant role since it is not possible to actually measure the distribution of electromagnetic fields or *SAR* values inside a human head and the FDTD method [4] is used to carry out most of the numerical calculations. The *SAR*s induced in a homogeneous human head model due to the fields irradiated from a half-wave dipole antenna at 835 MHz for a set of distance between the head and dipole antenna are available in the literature [5]. The *SAR*s induced in a multilayered human head model for a band frequency at a constant distance for electromagnetic plane wave source are also available in the literature [6,14-15]. However *SAR* vs. frequency for a set of distance between inhomogeneous head model and antenna is not available in the literature. In this work, *SAR*s induced in an inhomogeneous head model have been calculated for a set of distance between the head and the dipole antenna at a band of frequencies. Instead of *SAR*, maximum local *SAR* induced in the human head model has been calculated which gives more information regarding the biological effects of the electromagnetic fields inside the head. FDTD code is developed to implement the head model along with a dipole antenna to calculate maximum local SAR using MATLAB 7.1 [7].

II. FINITE DIFFERENCE IN TIME DOMAIN

The FDTD method is one of the most successful and versatile technique for computations involving the electromagnetic waves in three dimensional structures [4,8-9]. The Maxwell's time-dependent curl equations may be written as:

$$\vec{\nabla} \times \vec{E} = -\mu \frac{\partial \vec{H}}{\partial t} \tag{1}$$

$$\vec{\nabla} \times \vec{H} = \sigma \vec{E} + \varepsilon \frac{\partial \vec{E}}{\partial t} \tag{2}$$

where, the parameters σ, μ and ε are conductivity, permeability and permittivity, respect tively.

Equations (1) and (2) have been solved by discretizing the space into a number of Yee cells and assigning each cell to the corresponding permittivity and permeability in a time-marching sequence to obtain the components of the electric and magnetic fields [4]. Following Yee's notation at each grid points all the components of the electric and magnetic fields are calculated.

The method follows the propagation, reflection and absorption of an electromagnetic (EM) wave in a domain comprising the target and surrounding space. It requires the use of absorbing boundary conditions (ABC) to accurately terminate the computational domain which allow the propagation of electromagnetic waves out of the computational space but at the same time reduce the reflections from the edges of the region of interest. In this work Berenger Perfectly Matched Layer (PML) [10,11] has been used as the absorbing boundary.

To obtain the frequency dependent reflection coefficient $S_{11}(f)$, the incident and the reflected waveforms must be known at the feeding point of the antenna. $S_{11}(f)$ is determined from the ratio of the Discrete Fourier transform (DFT) of these transient waveforms by:

$$S_{11}(f) = \frac{DFT\left[E_{ref}\right]}{DFT\left[E_{inc}\right]} \tag{3}$$

where, E_{inc} = incident electric field and E_{ref} = reflected electric field.

$|S_{11}|$ is computed in dB by:

$$|S_{11}| = 20\log_{10}\left(|S_{11}|\right) \tag{4}$$

From the converged solutions the local SAR at $(i,j,k)^{th}$ cell inside the head is obtained from the following equation [12]:

$$SAR(i,j,k) = \frac{\sigma(i,j,k)\left|E(i,j,k)\right|^2}{2\rho(i,j,k)} \quad (\mathrm{W/Kg}) \tag{5}$$

where, E = r.m.s value of the electric field (V/m), σ = conductivity of the head (S/m) and ρ = mass density of the head (Kg/m³).

Maximum local SAR is obtained by finding the maximum value of $SAR(i,j,k)$ for the whole head model at each frequency and the location of maximum local SAR may or may not be same for a different frequency.

III. SYSTEM MODEL

For simplicity the human head along with antenna is modeled as shown in Fig. 1, where the Yee cell length δ = 0.5 cm. The inhomogeneous spherical human head model is comprised with three layers. It has a uniform content at its core (representing the human brain) of diameter 17 cm. The core is surrounded by two spherical shells each having width of 0.5 cm representing the skull (bone) and the skin with their respective electromagnetic properties. The outer boundary area as shown in the figure consists of Berenger PML. In this study, variation of relative dielectric constant (ε_r) and conductivity (σ) of brain, bone and skin of human head at the different frequencies have been taken into consideration to calculate both SAR and reflection coefficient (S_{11}). The mass density of the brain ρ_b = 1050 Kg/m^3, bone ρ_{bn} = 1180 Kg/m^3 and skin ρ_s = 1080 Kg/m^3 have been taken during calculation [12-15]. Average values of ε_r and σ of the human head at the desired frequency range were interpolated from the Table 1 [12-15]. The human head is coupled with radiation antenna to represent accurate FDTD simulations of real-life communication scenarios and also provide information concerning the SAR for power absorbed in human head. A metallic material having length L and diameter of 0.5 cm is used as the radiating dipole antenna. The value of L of the resonant dipole antenna is appropriately varied corresponding to several spot frequencies following the relation:

$$f_{res} = \frac{c}{2L} \tag{6}$$

where, f_{res} = resonant frequency of the dipole antenna and c = speed of light in free space (3×10^8 m/s). The values obtained for L are 18.5 cm (37δ), 14.5 cm (29δ), 10.5 cm (21δ) and 5.5 cm (11δ) for approximate resonating frequencies 700 MHz, 1.0 GHz, 1.6 GHz and 2.5 GHz, respectively.

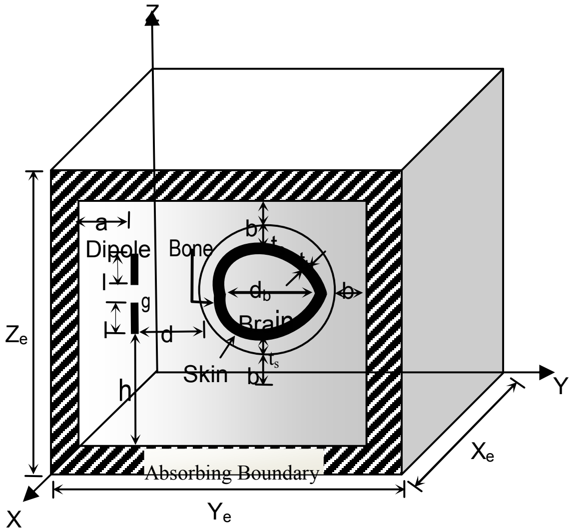


Fig. 1. Geometry of the dipole antenna and the human head used for simulation by the FDTD method. [$X_e = 54\delta$, $Y_e = 58\delta$, $Z_e = 62\delta$, $a = b = 2\delta$, $l = 5\delta$ to 18δ, $g = 1\delta$, $d_b = 34\delta$, $t_s = 1\delta$, $t_b = 1\delta$, $d = 4\delta$ to 6δ, $L = (2l+g)\delta$].

Table 1: Relative Dielectric constant (ε_r) and conductivity (σ) of the human brain, bone and skin at the different frequencies.

Frequency (MHz)	Brain		Bone		Skin	
	ε_r	σ (S/m)	ε_r	σ (S/m)	ε_r	σ (S/m)
100	82.0	0.53	7.50	0.067	24.50	0.55
350	60.0	0.65	5.70	0.072	17.60	0.44
900	56.8	1.10	20.90	0.340	41.41	0.87
1800	51.8	1.50	19.34	0.590	38.87	1.88
2450	48.9	1.81	18.55	0.820	38.01	1.46
6000	30.0	5.30	6.00	0.300	23.00	2.60

IV. SOURCE MODEL

A Gaussian pulse is applied as the excitation because its frequency spectrum is obtained over a wide range and will therefore provide frequency domain spectrum from dc to desired cut-off frequency by adjusting the width of the pulse as necessary. To obtain S_{11}, Gaussian pulse of unit amplitude is used. Whereas in case of *SAR* analysis Gaussian pulse is used with the amplitude following the equation:

$$V = \sqrt{2R_a P} \tag{7}$$

where, P = radiated power from the antenna, R_a = equivalent antenna input impedance and V = maximum value of voltage. In case of layer wised *SAR* analysis sinusoidal pulse of amplitude (V) is used. For all the cases, the calculations have been made by placing the excitation at the center gap of the dipole antenna considering R_a = 50 Ohm and input power of 0.6 Watt.

V. RESULTS

Presence of the human head in the vicinity of the radiating dipole antenna acts like a dielectric scatterer which alters the input impedance and also the resonant frequency of the dipole antenna. Variations of $|S_{11}|$ with frequency for the half wave dipole antenna of length 14.5 cm placed in free space and in front of head at a distance of 2.0 cm are shown in Fig. 2. The fundamental resonance frequencies obtained with and without head are 915 MHz and 952 MHz, respectively. Due to fringing field at two open ends of dipole antenna, the resonating frequency is obtained at 952 MHz instead of 1.0 GHz for the antenna without head. The head acts as a part of antenna since it is present in the reactive near field so the effective length of the antenna further increases. As a result the resonant frequencies of both fundamental and higher order modes are reduced during the presence of head.

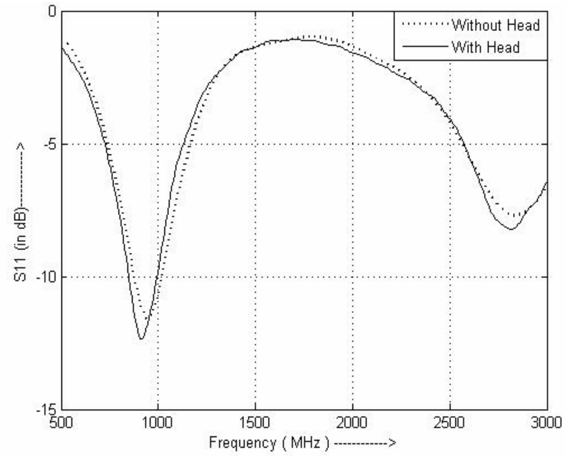
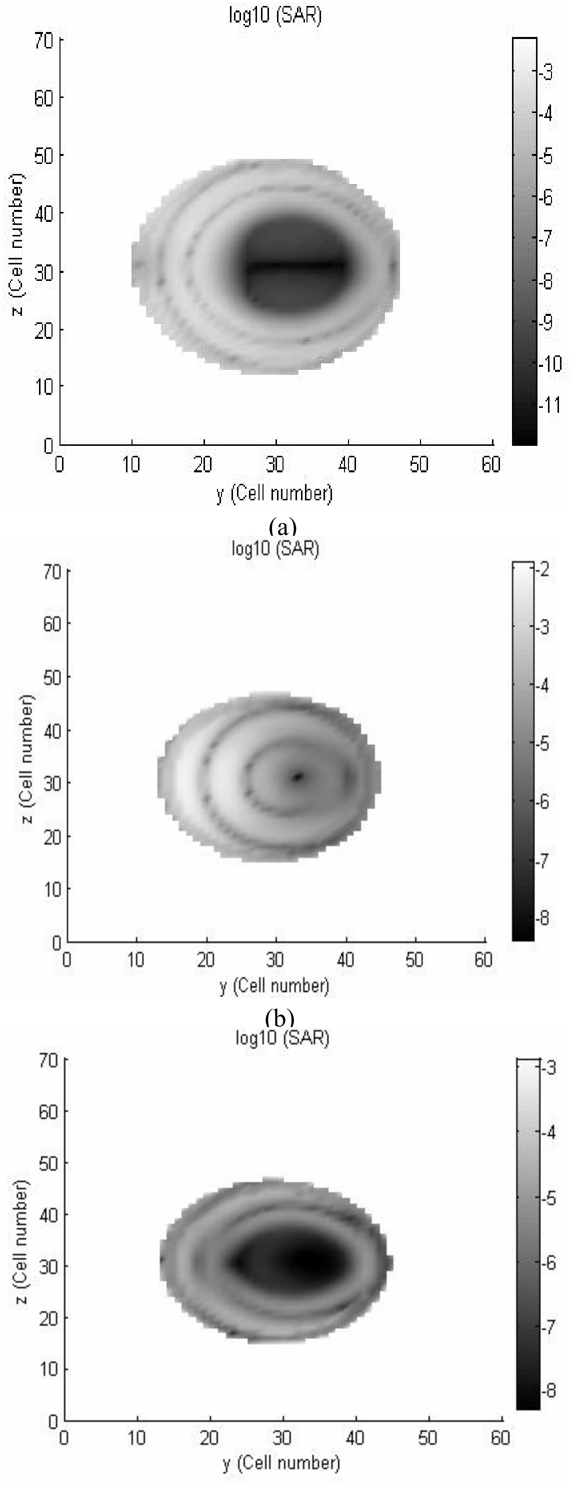


Fig. 2. Variation of $|S_{11}|$ vs. frequency of the dipole antenna of length 14.5 cm for with and without head.

Shifting of resonant frequency towards left is about 37 MHz at the fundamental mode due to presence of the head. Values of $|S_{11}|$ are -12.35 dB and -11.56 dB at the resonant frequencies 915 MHz and 952 MHz, respectively. From Fig. 2, it is also seen that the value of $|S_{11}|$ remains below -10 dB in the GSM-900 band (890MHz – 960MHz) for both with and without head for antenna length of 14.5 cm.

SAR distributions at various layers obtained within the head for 2.0 cm distance between the head and antenna at frequency of 915 MHz using a sine wave as the source of excitation are shown in the Fig. 3. (a) - (c). From the figures it is found that the *SAR* value decreases gradually as the distance from the antenna increases. It is seen from figures, higher values of *SAR*s are induced in the outer layer of head consisting of skin and muscle tissues closest to the antenna. Lower values of *SAR*s are induced in the core region of head consisting of brain tissue. The nature of SAR distribution in human head changes from layer to layer.

Maximum local SAR vs. frequency for *d* equal to 1.0 cm, 2.0 cm and 3.0 cm and *L* = 14.5 cm is shown in Fig. 4. When *d* is less than or equal to 1.0 cm then the maximum local SAR is above FCC and IEEE's upper safety limit 1.6 W/kg [16,17]. As *d* increases over 1.0 cm then the value of the maximum local *SAR* goes below the upper safety limit. The curve shows three major peaks near the resonant frequencies. For each



(a)

(b)

(c)

Fig. 3. SAR distribution in the yz plane of head phantom (a) middle layer (X = 27 Yee cell), (b) front layer (X = 17 Yee cell) and (c) end layer (X = 37 Yee cell).

value of *d*, the maximum value of maximum local *SAR* has been found at fundamental resonant frequency near GSM-900 band due to large amount of energy transfer from antenna to head for good impedance matching. But at the other resonant frequencies the value of maximum local *SAR* decreases significantly due to higher reflection of electromagnetic wave from the surface of the head which results in smaller absorption. *SAR* also decreases faster in higher frequency range due to smaller penetration depth. *SAR* is linearly proportional to conductivities of brain, skin and bone but conductivities are nonlinear function of frequency. As a result the frequency at which peak of maximum local *SAR* obtained doesn't match with the frequency for minima of $|S_{11}|$.

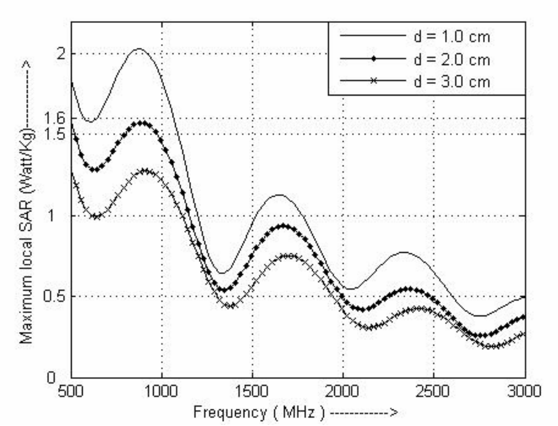


Fig. 4. Maximum local SAR distributions in the human head model for different '*d*'(Antenna length = 14.5 cm).

Maximum local *SAR*s induced in the human head by the half wave resonant dipole antennas of different length (*L*) near their resonance frequencies for a set of *d* are shown in Fig. 5. It is seen that for all antennas maximum local *SARs* are obtained near their resonance frequencies. For *L* = 10.5 cm and *L* = 5.5 cm, the values of maximum local *SAR*s remain lower than the FCC and IEEE's upper safety limit of 1.6 W/kg even when *d* = 1.0 cm.

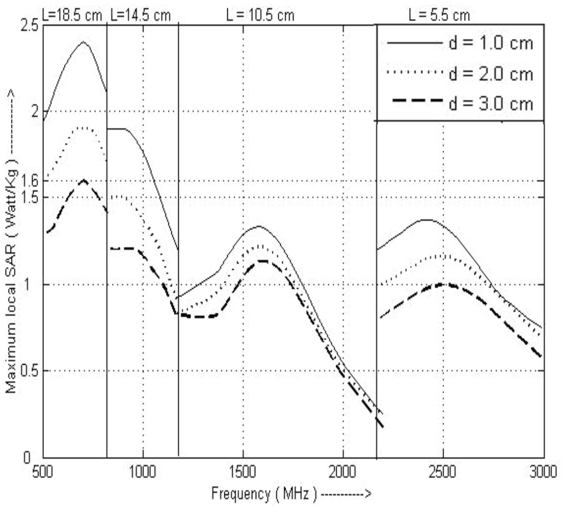


Fig. 5. Maximum local SAR distributions in the human head model for different '*d*' and Antenna length (*L*).

VI. CONCLUSION

The presence of the human head in the vicinity of the radiating antenna acts like a dielectric scatterer which alters the input impedance of the antenna. The distribution of the absorbed energy is important to determine the biological effects due to electromagnetic radiation. Absorption of electromagnetic energy into the human head depends on the operating frequency, polarization and the distance of the radiating antenna from the human head. In this work both SAR and $|S_{11}|$ have been calculated considering human head as a three layered spherical shaped inhomogeneous dielectric medium consisting of only three different types of tissues for the frequency range from 500 MHz to 3 GHz using FDTD method. Variation of $|S_{11}|$ with frequency for the half wave dipole antenna of length 14.5 cm placed in free space and at 2.0 cm distance from the head model has been studied. The resonant frequencies for both fundamental and higher order modes of the dipole antenna move toward lower frequencies during the presence of head. Variation of maximum local *SAR* with frequency has been obtained for a set of distance between the radiating dipole antenna and the head in the range of 1.0 cm to 3.0 cm. Maximum local *SAR* induced in the head model is found more than the FCC and IEEE's upper safety limit 1.6 W/Kg for the distance between head and dipole antenna less than 1.0 cm for input power of 0.6 Watt. With the increase of the distance maximum local *SAR* decreases.

Due to huge complexity of the human head, limitations of FDTD method and computational resources, many assumptions have been made in calculations of *SAR* and S_{11} [18]. In this work both *SAR* and S_{11} have been calculated considering human head as three layered spherical shaped inhomogeneous dielectric medium consisting of only three different types of tissue but it is actually consisting of several tissue types of varying dielectric properties. Again it is also assumed that the dipole antenna is radiating the carrier power continuously but in case of actual handsets discontinuous transmission of power is used to save the power consumption of the handsets. In future, the assumptions made should be modified to obtain better realistic analysis.

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