SAR Analysis for Handheld Mobile Phone Using DICOM Based Voxel Model

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***Abstract*—In this paper, Specific Absorption Rates (SAR) inside the human head and hand have been analyzed for a handheld mobile phone operated at GSM 900 band. Both the head and hand are modeled electrically using Digital Imaging and Communication in Medicine (DICOM) formatted CT Scan voxel data considering the electrical parameters of different internal anatomical structures. Three-dimensional Finite Difference in Time Domain (FDTD) method has been used to simulate SAR induced in the head and hand. Maximum peak 1-g and 10-g SARs of 1.33 W/kg and 0.388 W/kg are found at antenna resonance frequency of 930 MHz for 0.6 W applied input power which are below the limits set by ANSI/IEEE and FCC, respectively.**

***Index Terms*—** FDTD, near-field, peak 1-g and 10-g SARs, DICOM data, CT scan, human head and hand models.

I. INTRODUCTION

The effect of non ionizing radiation on human health has become one of the common areas of interest for both technical and clinical researchers as a result of rapid growth in the use of mobile phones throughout the world. Mobile phone users are exposed to significant amount of electromagnetic (EM) energy radiated from the transmitting antennas and directly or mutually coupled headsets and it is seen that absorption of EM waves in human head and other body parts causes adverse biological effects [1]-[5]. Absorption of radio frequency (RF) fields emitted from the mobile phone may change the proliferation rate of cells, enzyme activity and affect the genes in the DNA of cells and may form tumor in living tissues [6]. It has also been reported that the opening of the blood brain barrier due to low level EM radiation emitted from a mobile phone causes to release the dangerous chemicals into the brain, leak hemoglobin and building up of which can cause heart diseases and kidney stones [7].

The dose rate at which RF electromagnetic energy imparted into the human head and other body parts is measured in terms of SAR. It is defined as the rate at which a person absorbs EM energy per unit mass [8]. SAR is used to quantify biological adverse effects and formulating safety guidelines or

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standards on exposure to RF fields [9]-[10]. For safety evaluation, SAR is averaged over a tissue volume which is still not harmonized among the different countries and states [11]. SAR averaged over *X*-g of tissue can be denoted by *X*-g SAR. In this way, local peak SAR averaged over 1-g of tissue is called peak 1-g SAR. In USA, the SAR limit is specified as 1.6 W/kg, averaged over one gram of tissue in the shape of a cube [9]-[10]. But in Europe and Japan, the SAR limits are specified as 2.0 W/kg, averaged over any ten gram of tissue [12].

Direct measurement of SAR is very difficult inside a living human head or body parts using the experimental technique. In the experimental method, actual phone with the equivalent homogeneous head or other body parts are used in the measurement, but these homogeneous models are not a faithful representation of the complex heterogeneous human organs because actual electrical properties of different tissues are not considered. Therefore, the numerical techniques are used to calculate EM field components and SAR inside human head or body parts [13]. To calculate SAR, full wave electromagnetic numerical techniques like FDTD, Finite Element Method (FEM) or Moment Method (MoM) are utilized to solve Maxwell's equations in a heterogeneous electrical model of human body parts. FDTD method [14] is one of the widely used techniques to simulate the EM field distributions in complex three dimensional structures [15]-[20]. SAR induced in human head model due to EM waves emitted from a dipole antenna in the frequency range of 900 MHz to 2.45 GHz is calculated through the FDTD method, and temperature rise in the model has been obtained by substituting the SAR values into Penn's bioheat equation [21].

In this work, variation of peak 1-g and 10-g SARs with distance has been studied using three-dimensional FDTD method for a realistic human head model including hand consisting of eleven types of tissues exposed to EM waves radiated from a mobile phone model designed for GSM 900 band (890 MHz – 960 MHz). Simulated peak 1-g and 10-g SARs have been compared with the corresponding measured values for two typical commercial mobile phones working at GSM 900 band. For all simulations the mobile phone is placed touching the head model holding with the right hand. For all simulations in-house FDTD code is developed using commercially available MATLAB [22] software. Commercially available FDTD based EM simulation software CST Microwave Studio (MWS) [23] is used to validate the performance of in-house FDTD code.

II. MODEL AND METHOD FOR ANALYSIS

Numerical voxel-based computational models of biological structures are used in calculations for electromagnetic interaction between electronic equipments such as mobile phones and biological structures in the computer environment. Initially mathematical models of adults and children were used for this purpose [24]-[25]. These models were represented by equations for planes, spheres, cones, ellipsoids, elliptical cylinders or cylinders and do not conform to the shape of real anatomical organs. Therefore, the voxel-based high resolution anatomical computational models are constructed from the Computed Tomography (CT), Magnetic Resonance (MR) or ultrasound scan data [26]-[27].

A. DICOM File Format

In this study, voxel-based computational models for the human head and hand have been constructed from DICOM files for SAR calculation. DICOM format is used extensively in CT, MR and ultrasound devices and combines images and metadata to create a rich description of a medical imaging procedure. Each DICOM file header contains a Service-Object Pair (SOP) instance related to Information Object Definition (IOD) [28] which is useful for voxelization of scanned organ. The voxel-based tomographic computational model can be constructed by stacking up the medical images embedded within the DICOM files [29].

1) Construction of Voxel models using CT scan DICOM files

The header of the DICOM file used for modeling the human head is shown in the Table I [29]-[30]. The examination was performed with a CT machine (Philips). The data is stored as a 512 × 512 × 460 two-byte pixel array with slice thickness of 1.5000 mm and 0.7000 mm spacing between slices. Original three-dimensional geometry of the human head model obtained from the DICOM files is shown in the Fig. 1(a).

TABLE I. INFORMATION SAMPLES OBTAINED FROM HEADER OF DICOM FILE USED FOR HEAD MODEL

Rows	512
Columns	512
Dimensions	[512 512 460]
Slice Thickness	1.5000
Spacing Between Slices	0.7000
Rescale Slope	1
Pixel Dimensions	[0.4883 0.4883 0.7000]
Rescale Intercept	-1000

TABLE II. INFORMATION SAMPLES OBTAINED FROM HEADER OF DICOM FILE USED FOR HEAD MODEL

Rows	512
Columns	512
Dimensions	[512 512 134]
Slice Thickness	2
Spacing Between Slices	0.7000
Rescale Slope	1
Pixel Dimensions	[0.9766 0.9766 1.5000]
Rescale Intercept	-1024

The header of the DICOM file, used for modeling the hand is shown in the Table II [29]-[30]. The examination was performed with a CT machine (SIEMENS). The data is stored as a 512 × 512 × 134 two-byte pixel array with slice thickness of 2 mm and 0.7000 mm spacing between slices. Original three-dimensional geometry of the hand model obtained from the DICOM files is shown in the Fig. 1(b).

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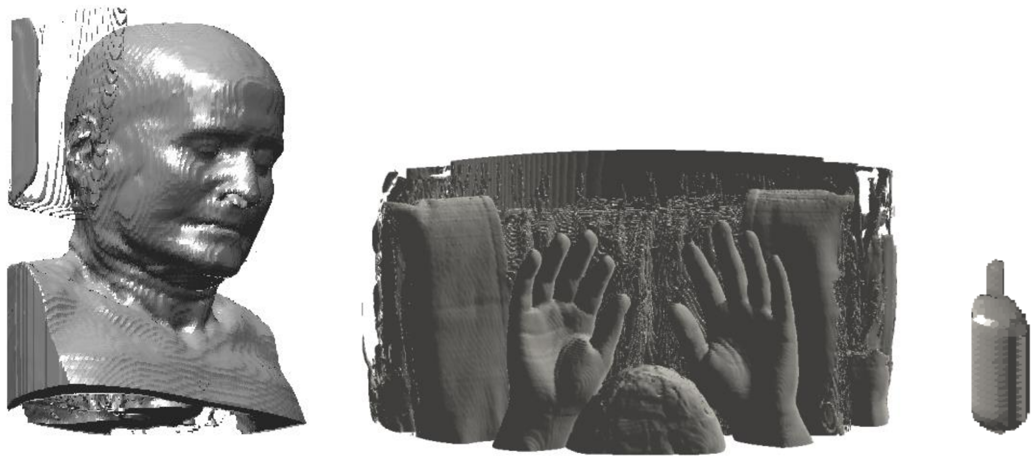

(a) (b) (c)

Fig. 1. Three-dimensional geometrical view of (a) human head, (b) hand and (c) mobile phone model.

2) Tissue Identification and Separation of Header from the DICOM files

Image pixel data is stored as the value of the pixel data element within the DICOM file in the form of pixel cell. A pixel cell is the container for a pixel sample value and optionally additional bits. A pixel cell exists for every individual pixel sample value in the pixel data. As the sample pixel cells are encoded in byte streams so to construct voxel-based computational models the pixel cells are decoded using in-house MATLAB program.

Pixels in an image obtained by CT scanning are displayed in terms of relative radiodensity. Hounsefield scale proposed in 1972 by Godfrey Newbold Hounsefield is a quantitative measure of radio-density [31]. The pixel corresponds to the mean radio attenuation by the tissue is represented on a Hounsfield scale using a value from -1024 to +3071. Using a linear transformation, the pixel values found in CT data can be converted in the Hounsefield Units (HU) [32]:

$$\mathrm{HU} = \left(\mathrm{pixel\_value} \times \mathrm{slope}\right) + \mathrm{int\,ercept} \tag{1}$$

where, slopes and intercepts are obtained from the header.

Each different tissue has different of HU values and the pixels correspond to a particular tissue can be identified and distinguished from pixels belonging to other tissues. HU used in the simulation corresponding to the tissues are listed in the Table III [31]-[34]. Due to huge complexity of the human head and hand, limitations of FDTD method and computational resources, many assumptions have been made during the calculations of SAR. In this study, SAR has been calculated considering the head and hand models are assumed to be consisted of only eleven types of tissues i.e., skin, bone, muscle, fat, blood, cartilage, CSF, white matter, grey matter, water and mouth cavity/sinuses.

TABLE III. HU OF THE TISSUE USED FOR HEAD AND HAND MODELS

Tissue Type	HU	
	Lower limit	**Upper limit**
Skin	-100	+200
Bone	+400	+3000
Muscle	+5	+40
Fat	-100	-50
Blood	+40	+40
Cartilage	-140	-120
CSF	+15	+15
White Matter	+20	+30
Grey Matter	+37	+45
Water	0	0
Mouth cavity/sinuses	-1000	-1000

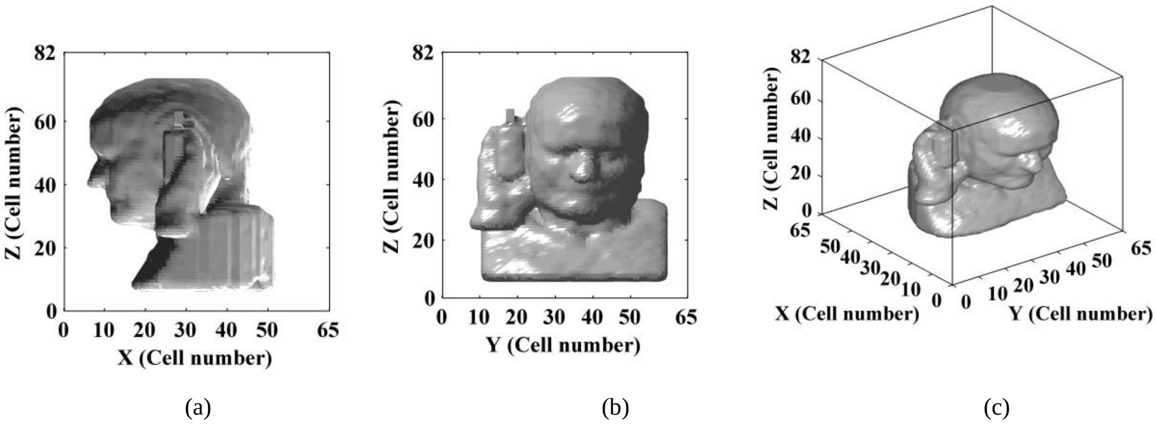

Fig. 2. (a) Sagittal plane, (b) coronal plane and (c) three-dimensional geometrical view of human head model along with hand and mobile phone.

3) Simulation Model

To simplify the numerical calculations raw data obtained from the DICOM files for both the head and hand models has been processed using in-house MATLAB program. The metallic parts of the CT machines as shown in Fig. 1(a) and (b) are discarded completely. Resolutions of the volume head and hand are reduced by 10% and 20%, respectively. Excluding the left hand, the right hand is placed at the side of the right ear of the head model holding the mobile phone.

Sagittal, coronal and three-dimensional geometry of the human head model along with the mobile phone holding with right hand used in the simulation are shown in Fig. 2 (a-c). Mass density (ρ), relative dielectric constant (ε_r) and conductivity (σ) of different tissues are obtained from the literature [35]. Relative dielectric constant, conductivity, mass density and mass of one 4 mm × 4 mm × 5 mm volume cell for different tissues are shown in Table IV. Frequency dependent ε_r and σ are determined by interpolating the available data.

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TABLE IV. DIELECTRIC CONSTANT (ε_r), CONDUCTIVITY (σ) AND MASS DENSITY (ρ) OF THE HUMAN HEAD AND HAND TISSUES

Tissue Type	Dielectric Constant (ε_r) [930 MHz]	Conductivity σ (S/m) [930 MHz]	Mass density ρ (kg/m^3)	Mass of one cell (g)
Skin	48.0980	0.6657	1010	0.1263
Bone	13.2700	0.0869	1850	0.3313
Muscle	57.5960	0.7834	1040	0.1300
Fat	5.6000	0.0403	920	0.115
Blood	64.8200	1.3320	1060	0.1325
Cartilage	46.0430	0.5690	1100	0.1375
CSF	36.0650	0.4329	1040	0.1300
White Matter	42.8100	0.4290	1030	0.1287
Grey Matter	58.5500	0.7150	1050	0.1312
Water	78.00	1.59	1000	0.1250
Mouth cavity/sinuses	1.0000	0.0000	1.300	0.0002

B. Mobile Phone Model

The mobile phone used in the simulation consists of a monopole antenna made with aluminum having length (L) of 4.0 cm and 5 mm × 5 mm cross sectional area placed on a metallic rectangular box of dimension: 3.2 cm × 4.6 cm × 9.9 cm as shown in the Fig. 1(c). In this study, classical one-cell gap model or delta gap model feeding used for thin-wire antenna has been applied in the design of the mobile phone. H field components around the gap of the feeding point are given by [36]:

$$\begin{aligned} &H_x^{n+1/2}(i, j+1/2, k+1/2) = H_x^{n-1/2}(i, j+1/2, k+1/2) \\ &+\frac{\Delta t}{\mu_0 \Delta}[\{E_y^n(i, j+1/2, k+1) - E_y^n(i, j+1/2, k)\} - \{E_z^n(i, j+1, k+1/2) + V^n/\Delta\}] \end{aligned} \tag{2}$$

where, ($i,j,k+1/2$) is location of the gap and V is the input voltage as a function of time.

Frequency dependent reflection coefficient $S_{11}(f)$ of the mobile phone is determined from the ratio of the Discrete Fourier Transform (DFT) of incident and reflected waveforms [17]:

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

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

S_{11} is computed in dB by:

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

C. FDTD Method

The simulation domain obtained using in-house MATLAB program containing head, hand and mobile phone consists of 65×65×82 Yee cells with cell dimension of 4 mm × 4 mm × 5 mm is directly exported in CST MWS to calculate the SAR of different resolutions induced inside the head and hand models at 930 MHz. In CST MWS the computational domain is terminated with 4-layer Generalized Theory-based Perfectly Matched Layer (GTPML) with reflection factor of 0.0001.

D. Source Model

To obtain $S_{11,}$ a Gaussian pulse of unit amplitude is applied as the excitation of the mobile phone antenna both in MATLAB and CST MWS. S_{11} has been obtained in MATLAB using equations (2-4) and by placing the excitation at the gap of the monopole antenna and the box of the mobile phone considering equivalent antenna input impedance of 50 Ω. But in CST MWS, S_{11} has been obtained directly by using the *Transient Solver* and S-parameter type *Discrete Edge Port* input impedance of 50 Ω.

E. SAR Calculation

Commercially available software MATLAB and CST MWS have been used to calculate SAR induced in the head and hand for a hand held mobile phone of applied input power 0.6 W [37]. During calculation of SAR in MATLAB, a sinusoidal signal with amplitude V is applied as the excitation of the mobile phone antenna. The value of V is obtained using the following equation:

$$V = \sqrt{4R_a P} \tag{5}$$

where, P = radiated power from the antenna (0.6 W), R_a = equivalent antenna input impedance (50 Ω), V = peak value of voltage.

In MATLAB when the simulation obtained steady-state condition then the local SAR at $(i,j,k)^{\text{th}}$ cell inside the head and hand is obtained from the following relation [20]:

$$\begin{aligned} SAR(i,j,k) &= \frac{\sigma(i,j,k)\left|\hat{E}(i,j,k)\right|^2}{2\rho(i,j,k)} \\ &= \frac{\sigma(i,j,k)\left\{\left|\hat{E}_x(i,j,k)\right|^2 + \left|\hat{E}_y(i,j,k)\right|^2 + \left|\hat{E}_z(i,j,k)\right|^2\right\}}{2\rho(i,j,k)} \quad \text{(W/kg)} \end{aligned} \tag{6}$$

where, $\hat{E}_x$, $\hat{E}_y$ and $\hat{E}_z$ are the peak values of the electric-field components (V/m), σ = conductivity (S/m) and ρ = mass density of the head tissues (kg/m³).

In MATLAB, peak 1-g and 10-g SARs have been obtained considering irregular volume averages [38]. In irregular volume averaging technique, peak 1-g SAR is obtained by finding the maximum value of local SAR in an FDTD cell and then finding the neighbor cell with next higher local SAR, and so on. The process is repeated until total mass of the FDTD cells becomes equal to the required mass of 1-g. Similarly peak 10-g SAR is calculated.

In CST MWS, SAR is calculated as a post-processing step after the simulation setting the power loss density monitor to calculate the SAR values and fields [23]. It is also recommended to use the FPBA mesh type for SAR simulations. For the local SAR calculation, specify the mass in gram over which the SAR should be averaged. Typical values are 1-g or 10-g. Applied input power of the mobile phone antenna is rescaled using the SAR Special Settings Dialog Box option.

III. RESULTS

Return loss of the mobile phone is computed using the MATLAB program and compared that with CST MWS result. Variations of S_{11} with frequency for the mobile phone placing in free space

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computed using MATLAB and CST MWS are shown in Fig. 3. Nature of variation of S_{11} obtained using in-house FDTD based MATLAB program follows closely with that obtained using CST MWS. For both the cases, at the fundamental mode, the antenna of the mobile phone antenna resonates at 930 MHz and the value of S_{11} remains below –10 dB within GSM 900 band. Value of S_{11} at the fundamental resonance frequency obtained by the MATLAB program and CST MWS are –22 dB and –15 dB, respectively.

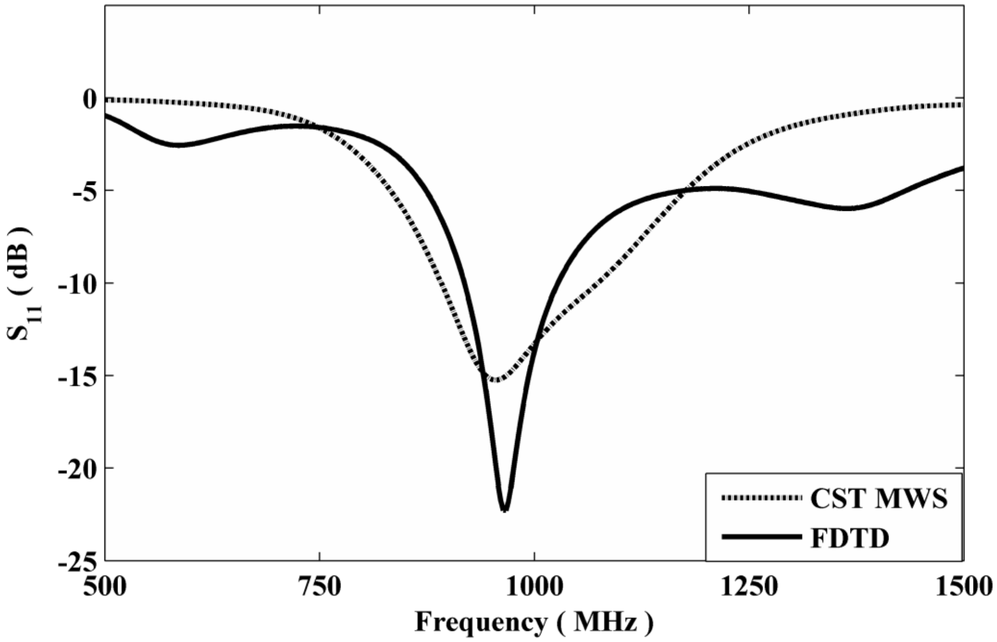
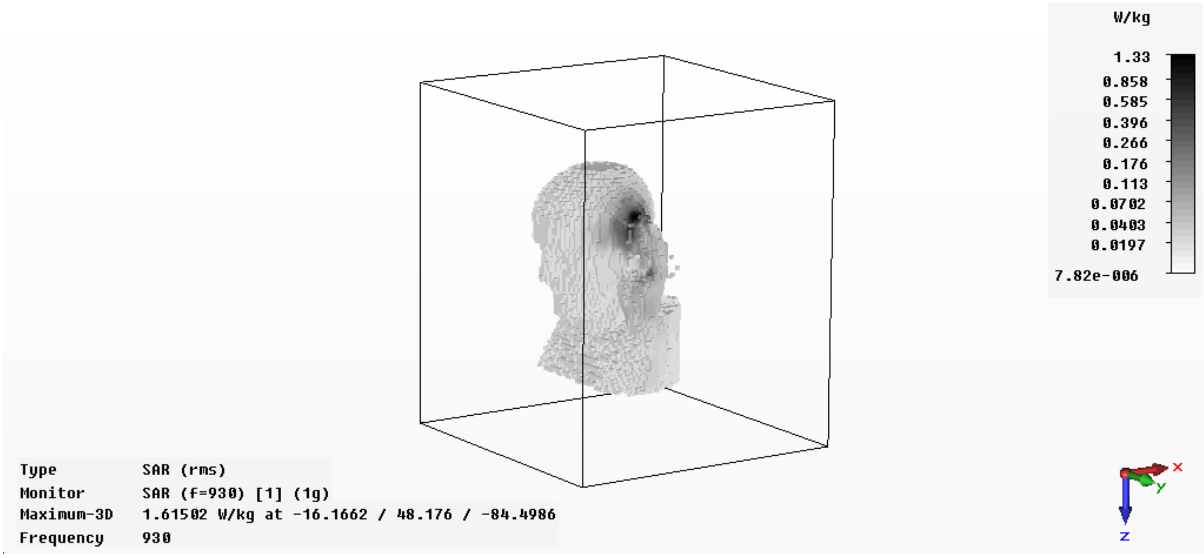


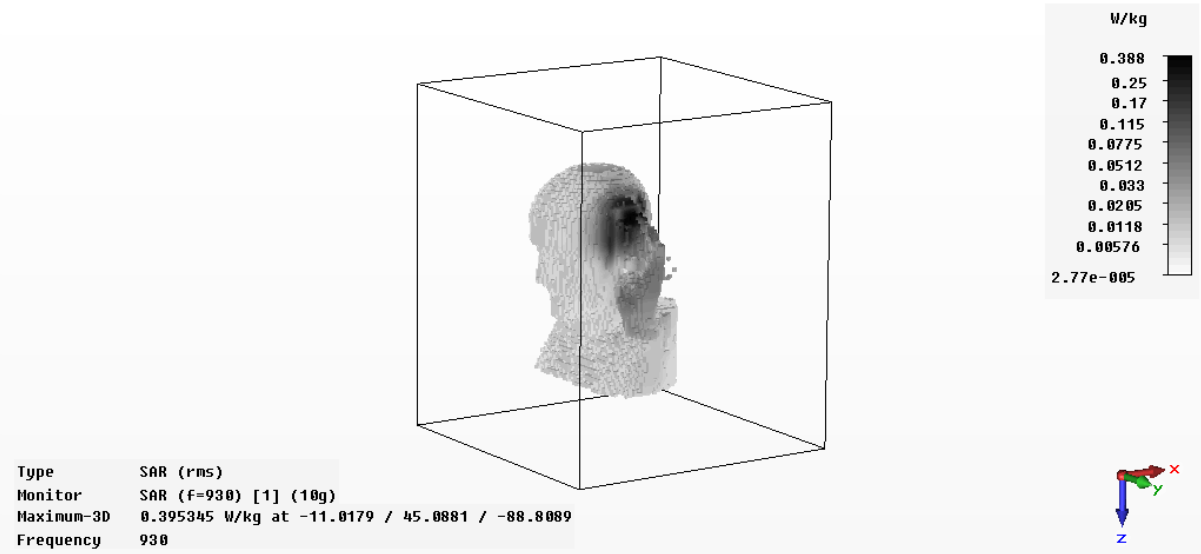
Fig. 3. Variation of S_{11} vs. Frequency of the mobile phone placed in free space.

Finishing return loss calculation, head model along the handheld mobile phone is simulated for SAR calculation at 930 MHz which is fundamental mode resonance frequency of the mobile antenna. Three-dimensional 1-g and 10-g SAR distributions inside the human head model including hand model at 930 MHz obtained by CST MWS are shown in the Fig. 4 (a-b). Higher value of 1-g and 10-g SAR are found in the vicinity of the mobile phone antenna and their value decreases periodically with continuous decrease in the average level for the increase of distance from the mobile phone antenna and vice-versa.

Variations of peak 1-g and 10-g SARs with distance *D* measured along Y-axis in the mid-coronal plane at 930 MHz obtained using CST MWS are shown in Figs. 5 (a-b). The stem plots of peak gram averaged SAR vs. *D* contain a number of hotspots. From the Figs. 5 (a-b), it is seen that the density of the hotspots decreases with increase of SAR value and vice-versa. Only one hotspot is found corresponding to each maximum peak 1-g and 10-g SAR with the value of 1.33 W/kg and 0.38 W/kg respectively.



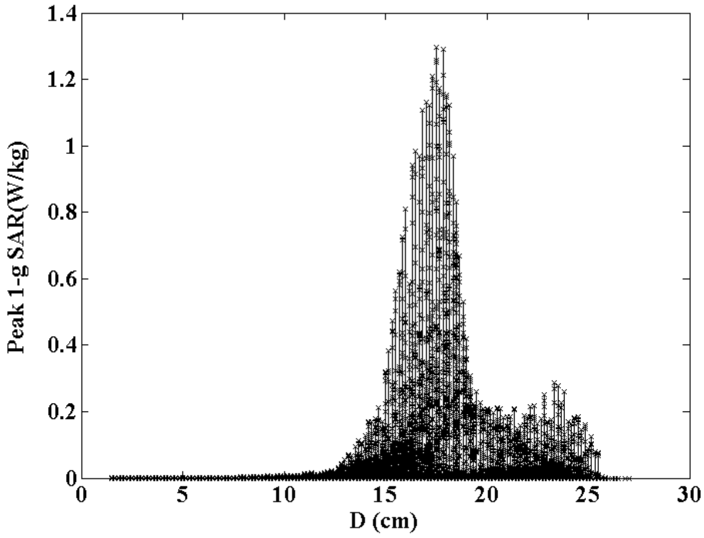
(a)



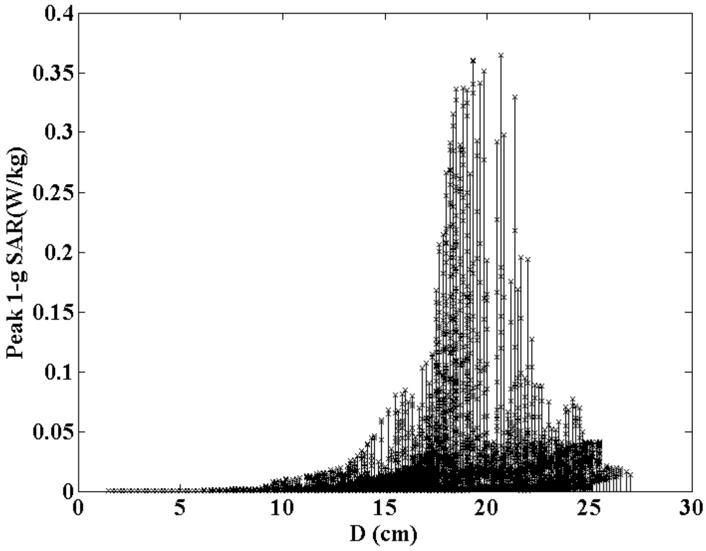
(b)

Fig. 4. Three-dimensional (a) 1-g and (b) 10-g SAR distributions inside the human head model using CST MWS.

Maximum value of peak 1-g and 10-g SARs for different type of tissues at 930 MHz obtained using MATLAB are listed in the Table V. From the table, it is seen that maximum peak 1-g and 10-g SARs obtained in skin are 1.3238 W/kg and 0.3882 W/kg respectively. The minimum peak 1-g and 10-g SARs obtained in CSF are 0.0084 W/kg and 0.0014 W/kg respectively. Mouth or sinuses cavities are filled with air and therefore have zero conductivity so no SAR is induced in it.



(a)



(b)

Fig. 5. Variations of Peak (a) 1-g and (b) 10-g SARs vs. *D* at 930 MHz.

TABLE V. PEAK ONE AND TEN GRAM SAR INDUCED IN THE HUMAN HEAD AND HAND TISSUES AT 930 MHZ

Tissue Type	Peak 1-g SAR (W/kg)	Peak 10-g SAR (W/kg)
Skin	1.3238	0.3882
Bone	0.0168	0.0028
Muscle	0.7803	0.1323
Fat	0.0176	0.0029
Blood	0.0465	0.0078
Cartilage	1.0512	0.1783
CSF	0.0084	0.0014
White Matter	0.0779	0.0132
Grey Matter	0.0503	0.0085
Water	0.0339	0.0057
Mouth cavity/sinuses	0.0000	0.0000

Measured values of peak 1-g and 10-g SAR at GSM 900 band for a typical commercial handheld mobile phone have been obtained from the literature [39]. Comparison between the available measured and simulated values of the gram averaged SARs are shown in the Table VI. From the table, it is observed that the peak 1-g and 10-g SARs obtained by simulation are close to each other and lower than the corresponding Measured values within the ANSI/IEEE and FCC safety limits. The differences between simulated and measured data obtained are possibly due to the head and antenna model differences.

TABLE VI. COMPARISION OF SIMULATED SAR WITH MEASURED SAR

SAR	Simulated	Measured
Peak 1-g SAR (W/kg)	1.3238	1.41
Peak 10-g SAR (W/kg)	0.3882	0.96

IV. CONCLUSION

In this work SAR distributions and peak SAR averaged over 1-g and 10-g mass of head and hand tissue induced inside the DICOM data based human head and hand models consisting of eleven types of tissues exposed to a mobile phone designed for GSM 900 band (890-960 MHZ) have been studied using FDTD method without considering modulation type or duty cycle of mobile communication systems. Calculation of SAR has been performed using commercially available software MATLAB and CST MWS. At 930 MHz, variation of peak 1-g and 10-g SARs with distance shows that both peak 1-g and 10-g SAR value attain to maxima near the position of the mobile phone antenna and decreases gradually with increase of the distance from the mobile phone antenna. Results obtained by the simulation show that maximum peak 1-g and 10-g SARs obtained in skin are 1.3238 W/kg and 0.3882 W/kg respectively whereas the minimum peak 1-g and 10-g SARs obtained in CSF are 0.0084 W/kg and 0.0014 W/kg respectively for 0.6 W antenna input power. Variations of peak 1-g and 10-g SARs with distance *D* measured along Y-axis in the mid-coronal plane at 930 MHz obtained using CST MWS are observed. The stem plots of peak gram averaged SAR vs. *D* contain a number of hotspots and it is seen that the density of the hotspots decreases with increase of SAR value and vice-versa.

Simulated peak 1-g and 10-g SARs for human head with hand held mobile is compared with measured SARs available in the literature and it is observed that obtained simulated and measured SAR values are close to each other and lower than the corresponding measured values within the ANSI/IEEE and FCC safety limits.

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