

Electromagnetic Radiation Hazards on Humans Due to Mobile Phones

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Abstract

There is an escalation in the amount of mobile phone users day by day with the availability of low cost, highly featured mobiles in the market. In the present investigation, the radiation characteristics of cell phone hand set is being analyzed at the frequency of 900 MHz and the interaction of these radiations with the human body is to be evaluated. The effects of radio frequency (RF) energy are related to the rate of energy absorption and it is computed using the parameter specific absorption rate. The specific absorption rate (SAR) of EM radiation from cell phones on human body is being analyzed at the regions of skin, muscle and heart. A novel method for the modeling of human body is carried out using the MATLAB software, which uses the finite difference time domain (FDTD) method for the SAR calculations. Further its effects are being analyzed from our investigation and it is reported that the measured SAR are within the FCC limits.

Keywords: EM (Electromagnetic Radiation), MOM (Method of Moments), RF (Radio Frequency), Radiation Hazards, SAR (Specific Absorption Rate)

1. Introduction

There is an increasing demand for the use of wireless communication systems along with the concern for human's contact to EM radiation. This is mostly evident in the usage of mobile phones. Many countries have set various guiding principles and standards for limits for exposure to RF radiation.

EM Radiation can be defined as waves of electric and magnetic energy radiating through space. Cell phones and its base stations produce EM radiations. These radiations are observed by their frequency and power. The frequency range for the cell phone is around 800 MHz to 1900 MHz with a maximum power of 2 watts. The power emitted is expressed in units of milli watt per cm^{2-1} .

When human body is unprotected to EM radiation an internal field is generated in the body. The absorption of power by the tissues will cause a temperature rise which is dependent on the cooling mechanism of the tissue. The field produced due to heating depends on the frequency, tissue dielectric properties and source configuration². When the thermo regulatory capability of the system

exceeds, tissue damage results. The Electromagnetic energy absorbed per unit mass of tissue is called Specific Absorption Rate (SAR)

$$\text{SAR} = \sigma E^2 / 2\rho$$

Where σ = Conductivity (m /m)
 ρ = Density of the tissue (Kg/m^3)
E = Internal Electric Field (V/m)

The SAR of EM radiation from cell phones on the human body is being studied. A novel method for the modeling of human body is being carried out by using MATLAB software which employs the FDTD method for SAR calculations. There are several techniques available for measuring the full body electromagnetic absorption, but there is no specific technique to calculate SAR within the body. MOM is a frequency domain method which was followed, still MOM requires storage memory of the order of $(3N)^2$ and time for computing of $(3N)^3$ where N is the number of cells.

The FDTD has been used extensively in computing the interaction of EM fields with complex, lossy dielectric bodies. This method has memory and time requirements

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proportional to N . This Paper describes the FDTD method and utility of the FDTD method is demonstrated by a 3D model of the human body model using MATLAB software. The acquired results validate that the FDTD method is capable of computing internal field distribution with acceptable accuracy.

2. Electrical Properties of Biological Substances

The Electrical properties of the biological substances can be classified as the active properties and passive properties. Active defines the capability to generate electrical potentials and fields while the passive describes the responses to externally applied electrical stimuli.

The absorption of EM waves in full body depends on frequency and the positioning of the electric field 'E' to the dimension 'L' of the body, where L is major length of the body. The highest rate of energy absorption happens for E || L (E orientation) for frequencies where major length is approximately 0.36 to 0.4 times the free space wavelength (λ) of radiation. Understanding about the electrical properties is needed to investigate the interaction mechanism of EM fields.

The human brain creates electrical signals and along with chemical reactions with which the body parts communicate. The human brain weigh up to about 3 pounds (1300-1400 gm)³. The brain entails gray matter (40%), white matter (60%) contained inside the skull. The blood is an opaque rather viscid fluid. Its specific gravity is about 1.06 and temperature is generally about 37 degree centigrade. The heart is a bioelectrically controlled blood pump. The heart of all mammals contracts or beats in response to an electric potential difference across it which reaches a maximum value just prior to the start of the blood pumping contraction. Electrical properties are needed to assess the rate of the energy absorption. The SAR is used to measure the effects of EM fields on humans. The SAR is considered sufficient in most cases to quantify the effects of the deposition of thermal energy in the biological systems.

3. RF Exposure Limit

Frequency and intensity of the incident EM field decides the exposure limit. The limits are set considering the average whole body SAR not exceeding 0.4 wkg^{-1} for workers and 0.08 wkg^{-1} for general public, along with experimentally determined threshold of 4 wkg^{-1} .

There is a major difference between the NRPB and the IEEE specifically in the 10 to 1000 MHz range as shown in Figure 1. ICNIRP figures are reduced half when compared to the two standards above 1 GHz. The Figure 2 shows a comparison for the public category.

As per the standards given by FCC, ANSI/IEEE and NCRP, there is a limit on EM absorption in humans and emission from RF devices given in terms of SAR. By FCC, RF absorption limits are upto 1.6 watts/Kg, over one gram of tissue^{4,5}.

4. FDTD Method

The FDTD method was proposed by YEE and then developed by Taflove¹. It is the solution for Maxwell's equations^{6,7}.

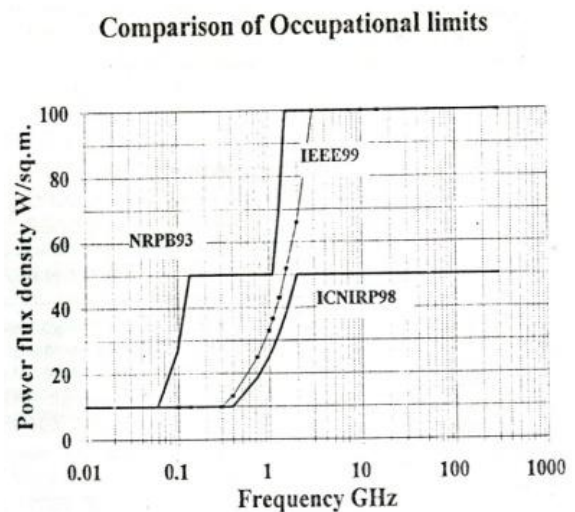


Figure 1. Comparison of occupational limits.

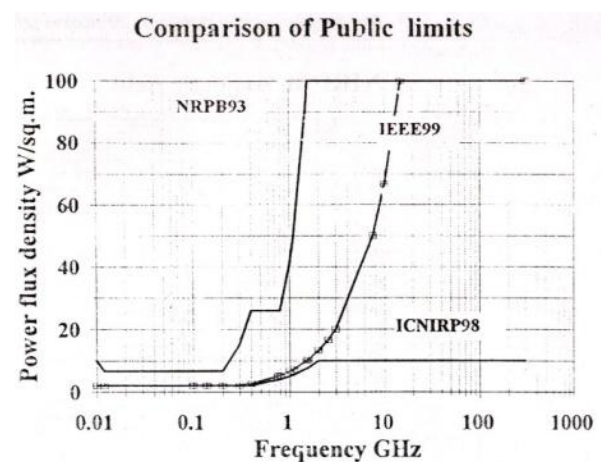


Figure 2. Comparison of public limits.

Approximation of derivatives in discrete form is done using FD and the time domain simulations indicate TD. In this method, the region considered is divided into number of cubic cells in which the fields are defined at fixed locations. Maxwell's equations are discretized by using the FD approximation. After discretizing the Maxwell's equation, it is solved by providing the excitation field to the cells as a function of time, the initial conditions and the boundary conditions.

- ❖ Extensively used method for approximating EM.
- ❖ No matrices are involved in implementing.
- ❖ Quick learning time.
- ❖ Wave interaction and coupling mechanisms can be studied.
- ❖ It is robust, flexible, efficient, versatile, user friendly to solve Maxwell's equations in time domain.
- ❖ It is widely used for solving open region scattering, electromagnetic interference (EMI), Electromagnetic compatibility (EMC).

Advantages

- (a) It is simple.
- (b) No need of integral equations, inversion of matrices.
- (c) Simple to implement
- (d) Less memory requirement.
- (e) Easy to convert to frequency domain from time domain.

Disadvantages

- (a) Modeling of surrounding is needed along with the object modeling.
- (b) Execution time is large.
- (c) Accuracy is less when compared to method of moments.
- (d) Computation cannot be done for curved surfaces.
- (e) The field quantities are known only at grid points.

Applications

- Antenna/Radiation problems
- Eigenvalue problems
- EM Absorption in human tissues

5. Electromagnetic Simulation in Free Space

The EM waves simulation generated by a Pulse is studied. Maxwell's equations in free space are given by

$$\frac{\partial E}{\partial t} = \frac{1}{\epsilon_0} \nabla \times H \quad (1)$$

$$\frac{\partial H}{\partial t} = -\frac{1}{\mu_0} \nabla \times E \quad (2)$$

Both E and H denote the electric field and magnetic field. Equations (1) and (2) can be expressed using del operator,

$$\nabla = i \frac{\partial}{\partial x} + j \frac{\partial}{\partial y} + k \frac{\partial}{\partial z}$$

Let $E = (E_x, E_y, E_z)$. The cross product of ∇ and E is given below

$$\nabla \times E = \begin{vmatrix} i & j & k \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ E_x & E_y & E_z \end{vmatrix}$$

Using the above expressions we rewrite (1) and (2) as

$$\begin{bmatrix} \frac{\partial E_x}{\partial t} \\ \frac{\partial E_y}{\partial t} \\ \frac{\partial E_z}{\partial t} \end{bmatrix} = \frac{1}{\epsilon_0} \begin{vmatrix} i & j & k \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ H_x & H_y & H_z \end{vmatrix} = \frac{1}{\epsilon_0} \begin{bmatrix} \frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} \\ \frac{\partial H_z}{\partial z} - \frac{\partial H_z}{\partial x} \\ \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} \frac{\partial H_x}{\partial t} \\ \frac{\partial H_y}{\partial t} \\ \frac{\partial H_z}{\partial t} \end{bmatrix} = -\frac{1}{\mu_0} \begin{vmatrix} i & j & k \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ E_x & E_y & E_z \end{vmatrix} = -\frac{1}{\mu_0} \begin{bmatrix} \frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} \\ \frac{\partial E_z}{\partial z} - \frac{\partial E_z}{\partial x} \\ \frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} \end{bmatrix} \quad (4)$$

E field is in the direction of xz plane and waves travels in the z direction ($E_y = 0$). $E_z = H_z = 0$, and hence $E = (E_x, 0, 0)$. The E field and H field travel at right angles to each another and hence $E \cdot H = 0$. Since $E_x \neq 0$ and by zero factor property $H_x = 0$. As $H_z = 0$, we have $H = (0, H_y, 0)$. Equations (3) and (4) changes to

$$\begin{bmatrix} \frac{\partial E_x}{\partial t} \\ 0 \\ 0 \end{bmatrix} = \frac{1}{\epsilon_0} \begin{bmatrix} \frac{\partial H_y}{\partial z} \\ 0 \\ 0 \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} \frac{\partial H_y}{\partial t} \\ 0 \\ 0 \end{bmatrix} = -\frac{1}{\mu_o} \begin{bmatrix} 0 \\ \frac{\partial E_x}{\partial z} \\ 0 \end{bmatrix} \tag{6}$$

Equations (5) and (6) indicates the wave propagation in z direction, as shown in (Figure 3)

6. The Algorithm

Having got the system, we need to approximate E_x and H_y . Δx corresponds to the change along the z axis and a time change is denoted by Δt . By central difference approximation in both space and time, we modify (5) and (6) as

$$\frac{(E_x)_k^{n+\frac{1}{2}} - (E_x)_k^{n-\frac{1}{2}}}{\Delta t} = -\frac{1}{\epsilon_o} \frac{(H_y)_{k+\frac{1}{2}}^n - (H_y)_{k-\frac{1}{2}}^n}{\Delta x}$$

$$\frac{(H_y)_k^{n+\frac{1}{2}} - (H_y)_k^{n-\frac{1}{2}}}{\Delta t} = -\frac{1}{\mu_o} \frac{(E_x)_{k+\frac{1}{2}}^n - (E_x)_{k-\frac{1}{2}}^n}{\Delta x}$$

where

$$v = -\frac{1}{\epsilon_o} \frac{\Delta t}{\Delta x} \text{ and } v = -\frac{1}{\mu_o} \frac{\Delta t}{\Delta x}$$

The Figure 4 below represents the FDTD grid created^{8,9}. The E_x approximations are represented by orange triangles while the H_x approximations by violet triangles. Each row relates to a specific instant in time, at half time steps and each column indicates a one whole time step. The whole and half steps are denoted by the gray and blue grid line. The initial values considered are set as green circles and the borders are shown as orange and violet circles.

FDTD Approximation Grid

Every triangle has three arrows pointing towards it (Figure 4)^{8,9}. Of the three arrows, one arrow emerges from

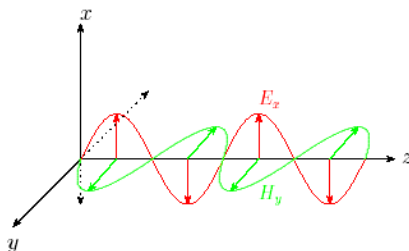


Figure 3. Propagation of Transverse Plane-Polarized EM Waves.

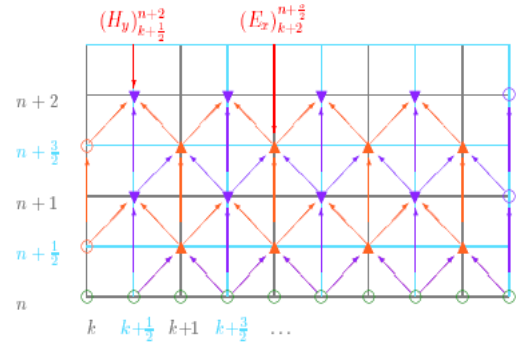


Figure 4. The FDTD Approximation Grid.

the previous time step. The remaining two comes from a half-step down and a half-step to the right or left. It is clearly evident that the algorithm is inter weaved in spatial and time domain similar to partial differential equations in time and space. This technique is also named as leap frog method. Imagine a frog as triangle, for instance

$(E_x)_{k+\frac{1}{2}}^{n+\frac{1}{2}}$ and leaping his legs to jump up to the triangle, $(E_x)_{k+\frac{1}{2}}^{n+\frac{3}{2}}$. The path it makes first moves outward and then inward making a triangle and the path drawn by his legs make a triangle.

The magnitudes of (5) and (6) are not equal because of the permittivity of free space and the permeability of free space, ϵ_o and μ_o . Since the values are modified as,

$$\tilde{E} = \sqrt{\frac{\epsilon_o}{\mu_o}} E$$

$$E = \sqrt{\frac{\mu_o}{\epsilon_o}} \tilde{E}$$

and substituting this in equations (7) and (8) we have

$$(\tilde{E}_x)_k^{n+\frac{1}{2}} = \eta \left[(H_y)_{k+\frac{1}{2}}^n - (H_y)_{k-\frac{1}{2}}^n \right] + (\tilde{E}_x)_k^{n-\frac{1}{2}}$$

$$(H_y)_{k+\frac{1}{2}}^{n+1} = \eta \left[(\tilde{E}_x)_{k+\frac{1}{2}}^{n+\frac{1}{2}} - (\tilde{E}_x)_{k+\frac{1}{2}}^{n-\frac{1}{2}} \right] + (H_y)_{k+\frac{1}{2}}^n$$

where $\eta = \frac{1}{\sqrt{\epsilon_o \mu_o}} \frac{\Delta t}{\Delta x}$

This method is being implemented in our project by generating an incident wave and the equations for E and H are solved. Human body model was created using the dielectric properties and the conductivity.

7. Body Model

The calculated E and H fields (Figure 5.) are categorized into,

- The Total field
- The Scattered field

The incident wave is created along one edge of the total field, propagates through the field and is subtracted out the other end. Hence, E and H fields to reach the scattered field volume are those which are scattered off the scatterer. This explains the implementation of the radiation condition. This explains the implementation of the radiation condition.

8. Constraints and Limitations

The constraint in this method is the radiation condition is not implicit ie. outgoing scattered waves may reflect back into the scattered object. This problem can however be overcome by introducing an absorption condition around the edge of each E field matrix which absorbs the outgoing scattered waves. This is based on a two-pole expansion method according to Bayliss and Turkel, which results in error given by,

$$Error = O \left[\frac{c}{2\pi fr} \right]^{2.5} \quad (7)$$

Where f - incident frequency

r - distance from center of the scattering body to the boundary of the computing field.

When low incident frequency is used, large volume surrounding the body is needed to overcome the error due to imperfect truncation conditions.

The stability can be ensured by taking the step size as

$$\delta t = \delta / 2c \quad (8)$$

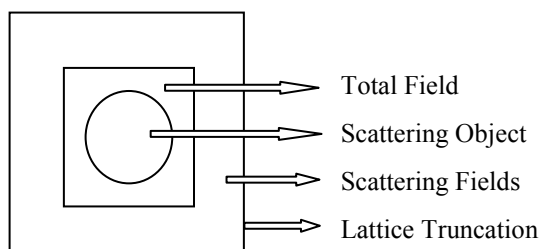


Figure 5. A. Division of FDTD lattice into Total and Scattered fields.

Where δt - the time step

δ - the cell size

c - speed of the electromagnetic waves

The equation (8) indicates that the smaller step size leads to more number of time steps (high resolution).

9. Results for Human Body Model

The Model for the Human body is being done by MATLAB software based on FDTD method. The results obtained are accurate, efficient and versatile. Here the SAR distribution is obtained using incident frequencies at 900 MHz. The tabulation for conductivity, relative permittivity and mass density of heart, muscle and skin at 900 MHz frequency are shown in Table 1.

The SAR distribution in human model is shown below in Figure 6.

10. Conclusion

For cell phones operating at 900 MHz, the maximum value of electric field is calculated to be 400 V/m for 2W power output. But we have found the Electric field strengths inside the body with the incident field of 1V/m. In order to compare our results accurately, we do the following calculations.

Assuming the cellphone is cylindrical and considering the antenna length $l = \lambda$ (lambda),

$$\begin{aligned} \text{We know, } C &= f\lambda, \\ \lambda &= C / f, \\ &= (3 \times 10^8) / (900 \times 10^6) \\ &= 0.33 \text{ m} \end{aligned}$$

The Power density at a distance $r = 2.2\text{cm}$, from the antenna is roughly equal to $p/2\pi rl$, since nearly all the radiated power has to pass through a cylinder of area $2\pi rl$. We know the power radiated by a cell phone at 900 MHz is 2 watts, and hence $p = 2$ watts. Substituting the above values

Table 1. Tabulation for conductivity, relative permittivity and mass density

Tissue Name	Frequency	Conductivity (s/m)	Relative Permittivity	Mass Density of the Tissue (Kg/m ³)
Skin	900MHz	0.86674	41.405	1100
Muscle	900 MHz	0.94294	55.032	1041
Heart	900 MHz	1.2298	59.893	1060

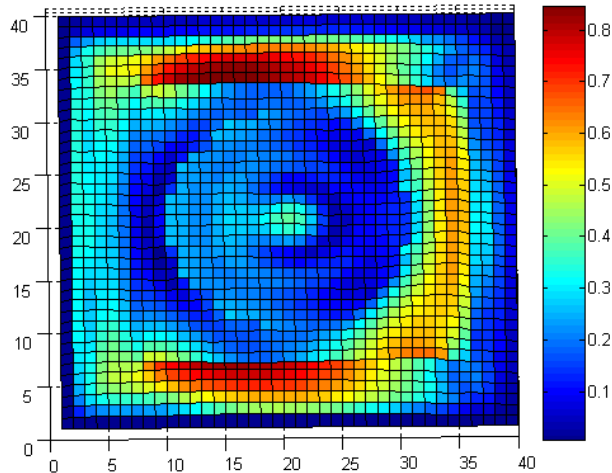


Figure 6. Field Distribution at 900 MHz - Skin, Muscle, Heart in human body.

At distance of 10 cm - Skin
 At distance of 13 cm - Muscle
 At distance of 16 cm - Heart

the power density is found to be 43.86 watts. Now we have to find the Electric field from power density. We know,

$$E^2 / R = \text{power density}$$

$$E = (43.86 \times 377)^{0.5}$$

$$= 129.59 \text{ V/m}$$

This will be the incident field to the human body at 900 MHz and hence we can multiply with the result which we obtained for, with 1 V/m. Thus the Electric field strength obtained at different tissue layers Skin, Muscle, Heart are found to be 33.43 V/m, 28.28 V/m, 36 V/m and are shown in Figure 6, 7.

The obtained SAR of Skin, Muscle, and Heart are shown in Figure 8 and tabulated below in Table 2.

These results are compared with the (Federal Communication Commission) FCC limits for general uncontrolled/exposure (100 KHz – 6 GHz)^{10,11}.

- < 0.08 W/Kg Full Body
- ≤ 1.6 W/Kg Partial Body

The obtained Specific Absorption rates are within the FCC limits.

11. Future Development

EM radiation is all over spread among the environment. Because of the emergence of various wireless services

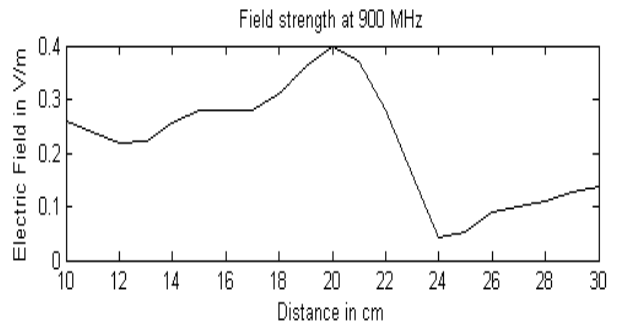


Figure 7. Field Strength at 900 MHz.

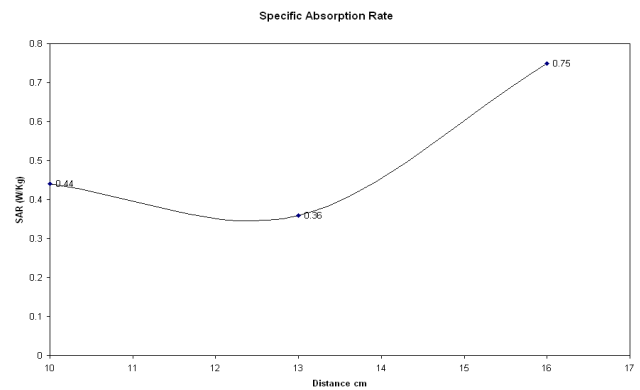


Figure 8. Specific Absorption Rate.

Table 2. Specific Absorption Rate

Frequency (MHz)	Skin	Muscle	Heart
900	0.44 W/Kg	0.36 W/Kg	0.75 W/Kg

EM radiation is part and parcel of the environment. The number of mobile users has been drastically increased. It was predicted to have 1.2 billion wireless device users around the world by 2005¹² and 2.7 billion in 2015. There is no way to control this change. EM radiation is also a kind of pollution which should be controlled.

Currently all the researchers are working towards the production of harmless wireless devices. Smaller cell size, improved base station antennas and some advanced technologies will make the cell phones to radiate less power. It is huge research topic which needs to be investigated further.

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