

Estimation of Electromagnetic Radiation Distribution in the Human Heart Rate at Different Frequencies

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Abstract

The health implications of electromagnetic radiation have been extensively debated due to the sharp increase in the usage of cell phones, Wi-Fi transmitters and other microwave equipment. Electromagnetic radiation affects the autonomic nervous system, heart rate, blood pressure and other cardiovascular functions. This study aims to present a Numerical Simulation of Electromagnetic Radiation (EMR) on the human heart tissue and to explore the effect of different frequencies in the spectral range (900, 1,800 and 2,400 MHz) on Specific Absorption Rate (SAR), power density, the Distribution of Electromagnetic Fields by Matlab program, and Finite-Difference Time-Domain (FDTD) method in One Dimension (1D). A 1-dimensional finite difference method was used to solve Maxwell's equations in heart tissue. The heart model was subjected to electromagnetic radiation that has dielectric properties according to frequency. Frequency was chosen and the operation of the software program as Matlab and the dielectric attribute has been calculated. Concurring with the Frequency in a private program, are the conductivity, relative permittivity, wavelength and infiltration profundity. The amplitudes of the reflected and transmitted sinusoid waves, relative to the occurrence wave, were portrayed by the reflection coefficient and the transmission coefficient, which relate to the amplitudes of the electric field wave. The electric field, magnetic field and power density were simulated along the line $X = Y = 0$. The study showed that the impact of electromagnetic radiation depends on the frequency of the wave which hit the heart. It was found that the heart tissue reacts more at 900 MHz compared to 1,800 and 2,400 MHz, and the tissue absorption is higher at the lower frequency. There was a relation between the magnetic field in the y-dimension and the time step the in x-dimension.

Keywords: Electromagnetic radiation, Heart rate, Maxwell's equations, FDTD method

Introduction

The health implications of electromagnetic radiation have been extensively debated due to the sharp increase in the usage of cell phones, Wi-Fi transmitters and other microwave equipment. In the current day, it seems like most people have cell phones. Thus, electromagnetic radiation sources are often held quite close to the body. The effects of electromagnetic radiation on the autonomic nervous system, heart rate, blood pressure and other cardiovascular functions are still poorly understood [1].

According to several studies, radiofrequency (RF) and (electromagnetic fields) EMF may be harmful to both the cardiac cycle of isolated hearts and animal brain function [2,3]. Heart rate (HR) [4], blood pressure (BP) [5], and heart rate variability (HRV) [6-9], in humans have all been associated with exposure to radiofrequency electromagnetic fields (RF, EMF). These findings are still debatable, though. Despite the fact that heart rate remained unaffected when subjects were asleep [10,11], numerous effects were observed in conscious subjects, including an increase in sympathetic nerve tone and an increase in blood pressure [12]. In the contrast, different studies did not show such effects [13,14]. The difference in obtained results may be due to the variability of physical and biological factors in the study subjects. It has been demonstrated that exposure to EMR could slightly alter heart rate [15,16]. The circulatory system's performance may be changed by the radiated EMR, which may impact the autonomic nerve tone [17].

In situ measurements provide the most accurate means of doing dosimetric evaluation and estimating electromagnetic exposure. However, using theoretical estimations is necessary to gain an understanding of the potential effects of electromagnetic radiation. However, there are several issues with these theoretical estimations that are related to the human body's characteristics and the accuracy of the

electromagnetic radiation distribution parameters. As a result, a commitment is made between the final correctness of the results and the computational complexity in terms of calculation time. There are many different techniques to calculate electromagnetic radiation distribution, just as there are many different ways to depict the human body. The most accurate method to perform dosimetric estimation is directly solving Maxwell’s equations, which describe the electric and magnetic fields in heat tissue.

Knowing the power density and temperature distributions in biological human tissues (i.e. heart) in response to electromagnetic exposures is critical for assessing the biological impacts and medicinal uses of electromagnetic radiation [18]. We need to locally solve the governing equations in order to model the interactions between systems generating electromagnetic radiation and the human body. In the present study, we assessed the effects of electromagnetic radiation on heart rate through electromagnetic compatibility analysis, experimentally and by numerical modelling. The system of electromagnetic equations that are based on Maxwell equations was expressed mathematically in diverse forms depending on the problem of this study.

Materials and methods

Mathematical formulation

Theory and model

One dimensional Finite-difference method (FDTD) is used to solve Maxwell’s equations which describe the electric and magnetic fields in heat tissue. The time and space stages are sufficiently modest. The dielectric properties of tissue are different according to differ the frequencies, we consider the heart tissue under the effect of different radiation with 900, 1,800 and 2,400 MHz, the dielectric properties of different frequencies determine in **Table 1**. The chart of 1-dimensional 1-layer tissue demonstrated is illustrated in **Figure 1**.

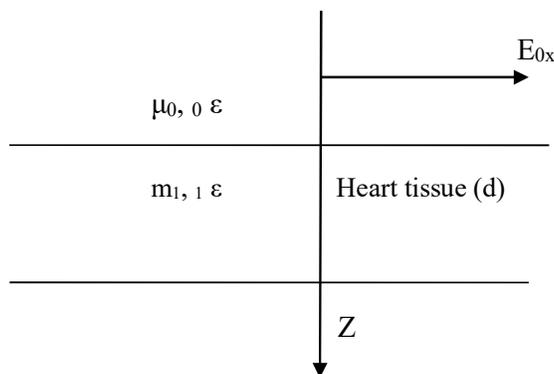


Figure 1 The chart of 1-dimensional 1-layer heart tissue.

Table 1 Insulating attribute of cardiac tissue at 900, 1,800 and 2,400 MHz.

Tissue name	Frequency [MHz]	Conductivity [S/m]	Relative permittivity	Loss tangent	Wavelength [m]	Penetration depth [m]
Heart tissue	900	1.2298	59.893	0.41013	0.042198	0.034074
Heart tissue	1,800	1.7712	56.323	0.31405	0.02193	0.022763
Heart tissue	2,400	2.2159	54.918	0.30221	0.016671	0.017951

At first, the work will illustrate FDTD solution of Maxwell’s curl equation in 1-dimension free space formulation, it begins from the time-dependent Maxwell’s curl equations in free space, and we will expansion of the vector components in 3 dimensions as we did in the former chapter. It is assumed that only “Ex” and “Hy” components subsist, regular with modeling flat wave spread out away from a source, the equations become as follows:

$$\frac{\partial E_X}{\partial t} = -\frac{1}{\varepsilon_0} \frac{\partial H_Y}{\partial z} \quad (1)$$

$$\frac{\partial H_Y}{\partial t} = -\frac{1}{\mu_0} \frac{\partial E_X}{\partial z} \quad (2)$$

A planar wave with the electric field oriented in the x-direction and magnetic field oriented in the y-direction and travelling in the z-direction is described by these equations. We will take the central difference approximations for both the temporal and spatial derivatives approved by the FDTD method, the previous equations become as follows:

$$\frac{E_x^{n+\frac{1}{2}}(k) - E_x^{n-\frac{1}{2}}(k)}{\Delta t} = -\frac{1}{\varepsilon_0} \frac{H_y^n(k+\frac{1}{2}) - H_y^n(k-\frac{1}{2})}{\Delta z} \quad (3)$$

$$\frac{H_y^{n+1}(k+\frac{1}{2}) - H_y^n(k+\frac{1}{2})}{\Delta t} = -\frac{1}{\mu_0} \frac{E_x^{n+\frac{1}{2}}(k+1) - E_x^{n+\frac{1}{2}}(k)}{\Delta z} \quad (4)$$

In these 2 equations, n is the time index and k is the spatial index. Time index is written as a superscript, and the spatial index is within brackets, times $t = n\Delta t$ and distances $z = k\Delta z$. The term $n + 1$ means a 1-time step later. Δt and Δz represent increments step in time and distance, Eqs. (3) and (4) becomes:

$$\tilde{E}_x^{n+\frac{1}{2}}(k) = \tilde{E}_x^{n-\frac{1}{2}}(k) - \frac{1}{\sqrt{\varepsilon_0\mu_0}} \frac{\Delta t}{\Delta z} \left[H_y^n\left(k + \frac{1}{2}\right) - H_y^n\left(k - \frac{1}{2}\right) \right] \quad (5)$$

$$H_y^{n+1}\left(k + \frac{1}{2}\right) = H_y^n\left(k + \frac{1}{2}\right) - \frac{1}{\sqrt{\varepsilon_0\mu_0}} \frac{\Delta t}{\Delta z} \left[\tilde{E}_x^{n+\frac{1}{2}}(k+1) - \tilde{E}_x^{n+\frac{1}{2}}(k) \right] \quad (6)$$

These equations are utilized more than once in a circle to modify the field amounts at each position at all spaces, as time advances. Rewriting Eqs. (5) and (6), we get:

$$\tilde{E}_x^{n+\frac{1}{2}}(k) = \tilde{E}_x^{n-\frac{1}{2}}(k) - 0.5 \left[H_y^n\left(k + \frac{1}{2}\right) - H_y^n\left(k - \frac{1}{2}\right) \right] \quad (7)$$

$$H_y^{n+1}\left(k + \frac{1}{2}\right) = H_y^n\left(k + \frac{1}{2}\right) - 0.5 \left[\tilde{E}_x^{n+\frac{1}{2}}(k+1) - \tilde{E}_x^{n+\frac{1}{2}}(k) \right] \quad (8)$$

The computer code equations writing as the following equation:

$$ex(k) = ex(k) + 0.5[hy(k-1) - hy(k)] \quad (9)$$

$$hy(k) = hy(k) + 0.5[ex(k) - ex(k+1)] \quad (10)$$

We observe that the time-index (n, $n + 1/2$, $n - 1/2$) within the superscripts does not appear. The 'ex' on the rt side of the equal sign of Eq. (1) is the former value at $n - 1/2$, and the 'ex' on the lt part is the new value $n + 1/2$, which will be calculated.

At the hy in the condition of the locative index ($k + 1/2$, $k - 1/2$) are exchanged by (k, $k - 1$) respectively, that specify an integer position in an array. All the same, it is grasp from the derivation, that the value stored in $hy(k)$ is the magnetic field value at position $k + 1/2$.

In this study, we fined time-dependent Maxwell's curl equations in a lossy dielectric medium such as heart tissue. This study will start with the time-dependent Max's curl equations but here will be in a lossy Dielectric Medium. Based on the equations mentioned above, we expansion of the vector components in 3 dimensions. In this model 1-dimensional, it is assumed that only E_x and H_y components exist so the equations expansion are reduced to just 2-equation. The equations become as the following:

$$\frac{\partial E_X}{\partial t} = -\frac{1}{\varepsilon_0 \varepsilon_r} \frac{\partial H_Y}{\partial z} - \frac{1}{\varepsilon_0 \varepsilon_r} \sigma E_X \quad (11)$$

$$\frac{\partial H_z}{\partial t} = -\frac{1}{\mu_0} \frac{\partial E_y}{\partial x} \quad (12)$$

where:

ϵ_0 is the permittivity of free space.

μ_0 is the permeability of free space.

ϵ_r is the prorated permittivity of the material.

μ_r is the prorated permeability of the material.

ϵ is the prorated permittivity of a lossy isolation middle.

$\epsilon\mu$ is the prorated permeability of a lossy isolation middle.

Then we took the central variance parataxis for the interim and locative derivatives approved by the FDTD method, we have:

$$\frac{E_x^{n+\frac{1}{2}}(k) - E_x^{n-\frac{1}{2}}(k)}{\Delta t} = -\frac{1}{\epsilon_0 \epsilon_r} \left[\frac{H_y^n(k+\frac{1}{2}) - H_y^n(k-\frac{1}{2})}{\Delta z} \right] - \frac{\sigma}{\epsilon_0 \epsilon_r} \left[\frac{E_x^{n+\frac{1}{2}}(k) + E_x^{n-\frac{1}{2}}(k)}{2} \right] \quad (13)$$

$$\frac{H_y^{n+1}(k+\frac{1}{2}) - H_y^n(k+\frac{1}{2})}{\Delta t} = -\frac{1}{\mu_0} \left(\frac{E_x^{n+\frac{1}{2}}(k+1) - E_x^{n+\frac{1}{2}}(k)}{\Delta z} \right) \quad (14)$$

Rearranging

$$E_x^{n+\frac{1}{2}}(k) = \frac{(1 - \frac{\sigma \Delta t}{2\epsilon_0 \epsilon_r})}{(1 + \frac{\sigma \Delta t}{2\epsilon_0 \epsilon_r})} E_x^{n-\frac{1}{2}}(k) - \frac{2\Delta t}{2\epsilon_0 \epsilon_r + \sigma \Delta t} \left[\frac{H_y^n(k+\frac{1}{2}) - H_y^n(k-\frac{1}{2})}{\Delta z} \right] \quad (15)$$

$$H_y^{n+1}(k + \frac{1}{2}) = H_y^n(k + \frac{1}{2}) - \frac{1}{\mu_0} \frac{\Delta t}{\Delta z} \left[E_x^{n+\frac{1}{2}}(k + 1) - E_x^{n+\frac{1}{2}}(k) \right] \quad (16)$$

While working simulation to lossy Dielectric medium equations, will note E_x values on the right-hand side equation at time step are not supposed stocked in the computer's memory, therefore, when taking the central difference approximations, and to solve this problem, we resorted to using the semi-implicit approximation. Where E_x values at timestep are supposed to be plain the mathematic middle of the stocked values of E_x at the time-step $n - 1/2$ and the yet-to-be calculated new values of E_x at time-step $n + 1/2$.

Power density

Energy is transmitted from the source to other objects when an electromagnetic wave moves through a medium. The intensity of the Electromagnetic field components determines the pace of energy transmission. The resultant of the electric field strength (E) times the magnetic field strength (H), is power density, which is defined as the rate of energy transfer per unit area.

The immediate Poynting vector and the time-dependent power density of the electromagnetic wave for time-varying fields, the time-dependent power flow density is given by:

$$P(t) = E(t) \times H(t) \quad (17)$$

$$\langle P(t) \rangle = \frac{1}{T} \int_0^T E(t) \times H(t) dt \quad (18)$$

Where:

$P(t)$ is the time-dependent power density.

$E(t)$ is the time-dependent E-field strength in volts per meter.

$H(t)$ is the time-dependent M-field strength in amperes per meter.

T is the time period of the EM wave.

Results and discussion

This study aims to evaluate the effect of electromagnetic fields produced from electromagnetic radiation at 900, 1,800 and 2,400 MHz on layered biological tissues (heart model) by the FDTD method. A 1-dimensional finite difference method is used to solve Maxwell's equations in heart tissue. The heart model is subjected to electromagnetic radiation that has dielectric properties according to frequency. We focused the electric field, magnetic field and power density in layered biological tissue at the same frequencies mentioned above. A 1-dimensional finite difference method is used to solve Maxwell's equations in heart tissue. The heart model is subjected to electromagnetic radiation that has dielectric properties according to frequency. This work aims to evaluate the effect of electromagnetic fields produced from electromagnetic radiation at 900, 1,800 and 2,400 MHz on layered biological tissues (heart model) by the FDTD method. It will study the electric field, magnetic field SAR and power density in layered biological tissue at the above frequencies.

Frequency is chosen and the program is operated, the dielectric attribute has been calculated. Concurring to the Frequency in a private program, are the conductivity, relative permittivity, wavelength and infiltration profundity. An electromagnetic beat is emitted from a source in free space. The simulated radiation source is a persistent sinusoidal waveform, with Matlab programs acting as directed dipoles. This wave voyages in open space and strikes human heart tissue. When a sinusoidal wave hits the interface, it reflects a division of the oncoming wave and transmits a division into the heart tissue layers.

The amplitudes of the reflected and transmitted sinusoidal waves, relative to the occurrence wave, are portrayed by the reflection coefficient and the transmission coefficient, which relate to the amplitudes of the electric field wave. The electric field, magnetic field, SAR and power density are simulated along the line $X = Y = 0$, i.e. propagation along the z-axis during free space and the heart tissue layer.

Figures (1) - (3) show a simulation of the electromagnetic pulse that radiated from a source located in free space and then strikes the heart tissue model interface in the XY plane, and 300 iterations, at a frequency equal to 900, 1,800 and 2,400 MHz respectively. After a 30 time step, the wave enters the human heart tissue which has dielectric properties that change with frequency. When the electromagnetic pulse strikes the heart tissue at a frequency 900 MHz has dielectric properties such as conductivity = 1.2298, relative permittivity = 59.893, and penetration depth = 0.034074. The wave propagates in the tissue and absorption starts at 30 and then decreases all the way. The highest absorption of the electric field is the beginning of the tissue at 31 then decreases at 32 and then returns to high at 35, and then the wave gradually fades.

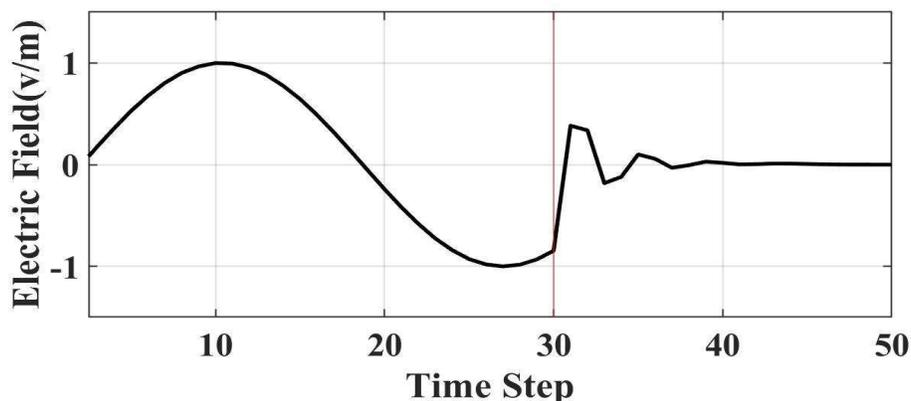


Figure 1 Simulation of electric field at 300 repetitions in heart tissue for a distance of 30 cm at frequency 900 MHz.

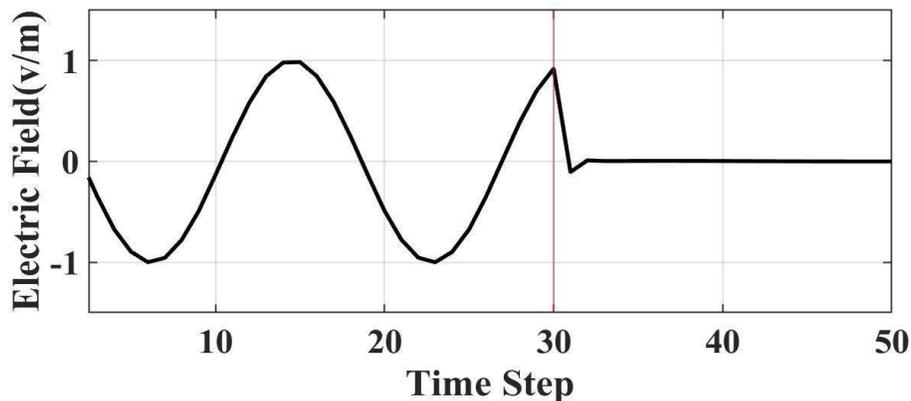


Figure 2 Simulation of electric field at 300 repetitions in heart tissue for a distance of 30 cm at frequency of 1,800 MHz.

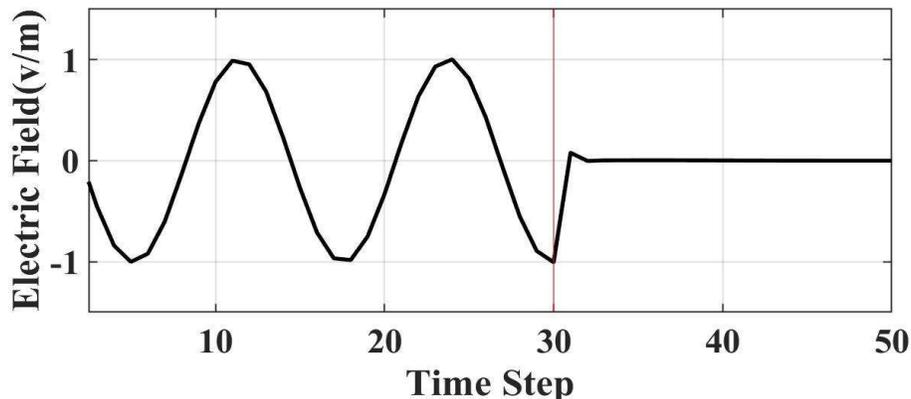


Figure 3 Simulation of electric field at 300 repetitions in heart tissue for a distance of 30 cm at a frequency of 2,400 MHz.

When the frequency of the wave is 1,800 MHz, the dielectric properties changed as follows, conductivity = 1.7712, relative permittivity = 56.323 and penetration depth = 0.022763. It is clear that the highest absorption of the wave is at 30, then it decreases at 31, then the wave is damped. When the frequency equals 2,400 MHz, a small peak is shown at the beginning of the tissue, then pulse length is shorter until the wave decays at around 33. The electric field is a high value when striking the tissue at 900 MHz compared with frequencies 1,800 and 2,400 MHz in the heart tissue model.

Also, we found a relation between the magnetic field in y-dimension and the time step in x-dimension, where simulation of the magnetic field in the heart tissue model after distance 30 at different frequencies. At 900 MHz, the range from 0 to 30 represents the free space, and when the wave strikes heart tissue is turbulent and variable amplitude between 30 to 45 in the time steps, then amplitude decreases until reaching 0 (**Figure 4**). At 1,800 MHz, the turbulence appears about 30 to 38 before the wave fades, and we have a rather large peak at 30 (**Figure 5**). At frequency 2,400 MHz, we have a small peak at about 31, then the wave gradually fades until it reached 0 (**Figure 6**). The results showed that the maximum peak of the magnetic field was at $f = 900$ MHz.

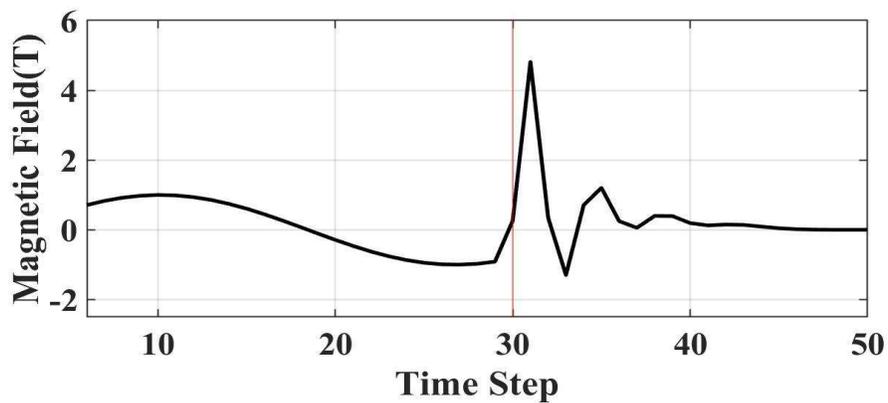


Figure 4 Simulation of the magnetic field at 300 repetition in heart tissue for a distance of 30 cm at frequency 900 MHz.

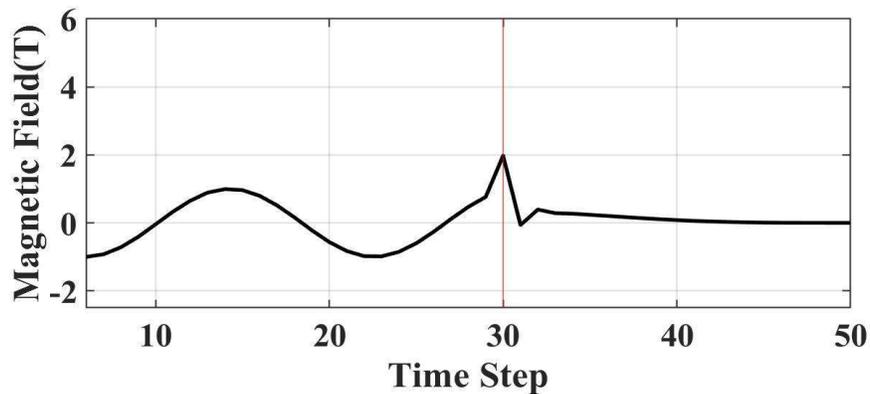


Figure 5 Simulation of the magnetic field at 300 repetition in heart tissue for a distance of 30 cm at frequency 1,800 MHz.

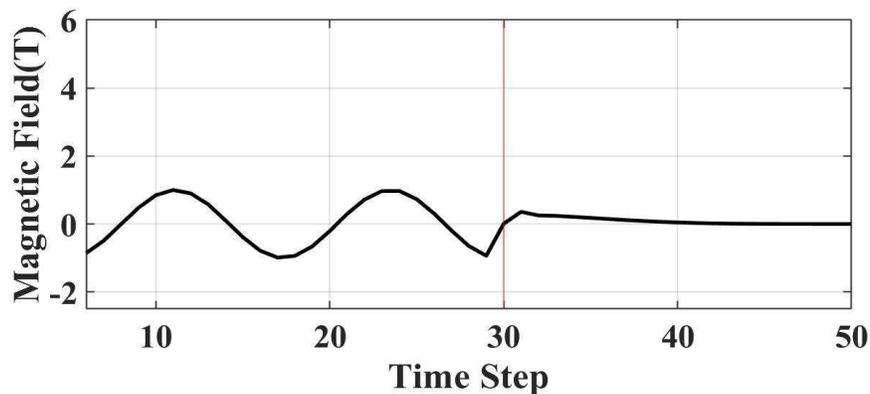


Figure 6 Simulation of the magnetic field at 300 repetition in heart tissue for a distance of 30 cm at frequency 2,400 MHz.

Figures (7) - (9) showed the relation between power density and time steps after 30-time steps but do not show it in the free space 0 to 30. Usually, power density is zero in free space and increases in tissue. As clearly shown, the power density is increasing to a maximum at the starting of the wave entering the tissue equal to 0.49 W, then it fluctuates between increases and decreases until it eventually and finally reaches to a value of 0 after 35-time. When the wave enters at frequency 1,800 MHz, it

changes when it enters the tissue, and then the power decreases to reach 0 after 32-time steps. The waves with frequency 2,400 MHz, show that the effect is at the beginning of the tissue and then decreases to reach 0 after 31-time steps.

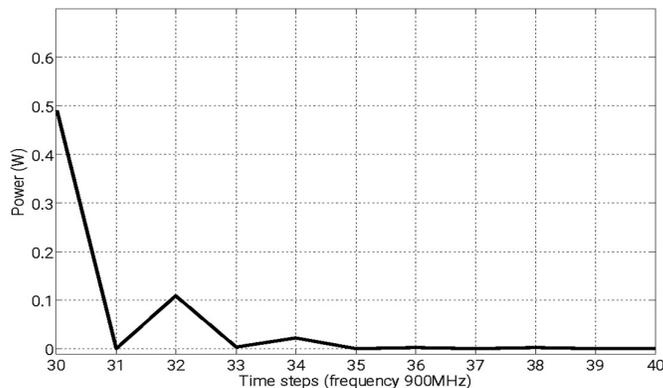


Figure 7 Simulation of power density at 300 repetitions in heart tissue for a distance of 30 cm at frequency 900 MHz.

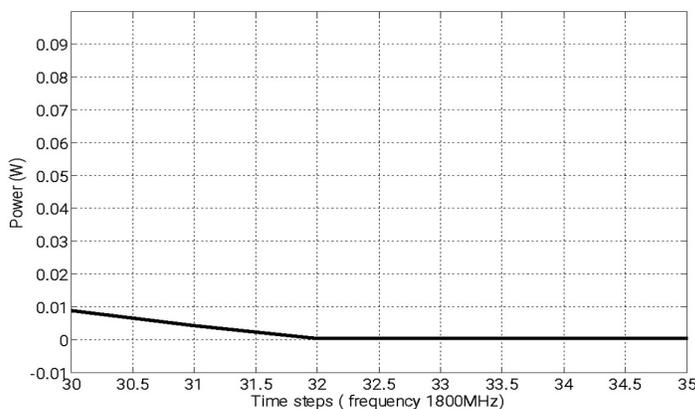


Figure 8 Simulation of power density at 300 repetition in heart tissue for a distance of 30 cm at frequency 1,800 MHz.

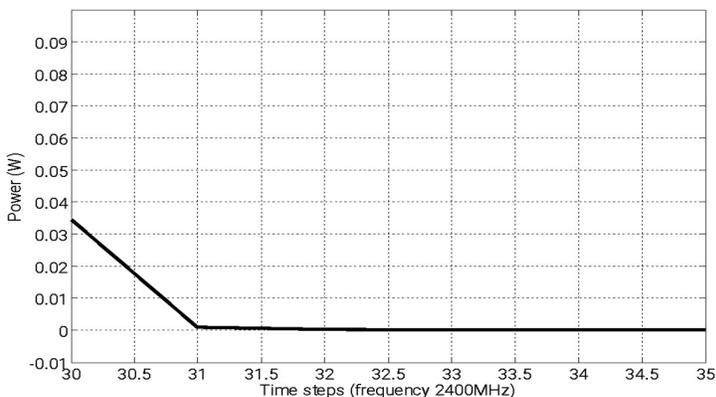


Figure 9 Simulation of power density at 300 repetitions in heart tissue for a distance of 30 cm at frequency 2,400 MHz.

Conclusions

In this study, we theoretically evaluated the effect of electromagnetic fields produced from electromagnetic radiation at 900, 1,800 and 2,400 MHz on layered biological tissues (heart model) by the FDTD method. The heart may produce its own rhythm because it is a contractile organ. Due to the excitability of the heart, electromagnetic radiation may affect the rhythm or contraction of the heart. The study showed that the impact of electromagnetic radiation depends on the frequency of the wave which hit the heart. There was a relation between the magnetic field in the y-dimension and the time step in the x-dimension. The impact of electromagnetic radiation depends on the frequency of the wave which hit the heart. Also, the wave enters the human heart tissue which has dielectric properties that change with frequency. The dielectric properties of the human heart tissue change according to the wave frequency.

Future work

Study of numerical simulations of EMR on human heart tissue in 2 dimensions or 3 dimensions using the FDTD method, and determine the thermal effect, power density and SAR on the human heart layers by FDTD. Making a study on every single layer of the heart separately using numerical simulations of EMR in 1 dimension, 2 dimensions and 3 dimensions using the FDTD method. Study numerical simulations of EMR on other tissues of the human body as ear tissue, hand tissue, oral and dental tissues and tissues of internal organs. Studying the effect of EMR with its different frequencies on the tissues of the human body in cooperation with research doctors.

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