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SAR Simulation of Human Head Tissues Exposed to Mobile Radio Waves Using FDTD Method

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Abstract:
Increasing the exposure time of radio wave radiation to human tissues is an important factor affecting the SAR (the specific absorption rate) values. This leads to the question of whether overlapping or interfering with electromagnetic waves has a negative impact on our health. Specific absorption rates (SAR) were calculated for the multilayered model of a human head model through different exposure times (30 min, 45 min, 1 hour, 1.5 hours, and 2 hours) at radio wave frequencies of 0.9 GHz and 1.8 GHz emitted from the mobile phones with planer inverted-F antenna (PIFA) and planar monopole antenna. The electromagnetic wave equation was solved using the Finite-Difference Time-Domain Method (FDTD). Different physical phenomena (penetration and interference) were considered for the flow of radio waves penetrating the tissues. Increasing the exposure time of RF waves increased the SAR values in the human head model tissues. The results showed that the cerebrospinal fluid (CSF) was the most affected. The interference effect is very clear. Some values exceeded the safety boundaries set by the Federal Communications Commission (FCC), indicating the close relationship between long-term exposure and the probability of biological damage due to increasing SAR values in tissues. The long exposure period contributes to the interference between the pulses emitted from the antenna.

Keywords: Simulation, Radio waves , Health Hazards, Human Head Tissue, SAR

محاكاة *SAR* لأنسجة رأس الإنسان المعرضة لموجات الراديو المتنقلة باستخدام طريقة *FDTD*

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الخلاصة
تعد زيادة فترة تعرض الأنسجة البشرية لإشعاع التردد اللاسلكي عاملاً مهمًا يؤثر على قيم SAR (معدل الامتصاص المحدد). وهذا يقودنا إلى التساؤل عما إذا كانت الموجات الكهرومغناطيسية المتداخلة لها تأثير سلبي على صحتنا. تم حساب معدل الامتصاص النوعي (SAR) للنموذج متعدد الطبقات لرأس الإنسان خلال

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فترات تعرض مختلفة (30 دقيقة، 45 دقيقة، ساعة واحدة، 1.5 ساعة، وساعتين) عند تردد 0.9 جيجا هرتز و1.8 جيجا هرتز المنبعث من الهواتف المحمولة المزودة بهوائي PIFA وهوائي أحادي القطب المستوي. تم حل معادلة الموجات الكهرومغناطيسية باستخدام طريقة المجال الزمني للفرق المحدود (FDTD). يشير تدفق الموجات التي تخترق الأنسجة إلى الاهتمام بالظواهر الفيزيائية المختلفة (الاختراق والتداخل). تؤدي زيادة فترة التعرض لموجات التردد اللاسلكي إلى زيادة قيم SAR في أنسجة رأس الإنسان. أظهرت النتائج أن أنسجة السائل الدماغي الشوكي كانت أكثر تأثراً. تأثير التداخل واضح جدًا. تتجاوز بعض القيم حدود الأمان التي تشير لها لجنة الاتصالات الفيدرالية (FCC) ، مما يشير إلى العلاقة الوثيقة بين التعرض طويل الأمد واحتمال حدوث ضرر بيولوجي بسبب زيادة قيم SAR في الأنسجة. تساهم فترة التعرض الطويلة في التداخل بين النبضات المنبعثة من الهوائي.

1- Introduction:

The last few years have witnessed the development of electronic devices that emit radio waves. Mobile phones are the most frequently used of these devices. The discomposure with the increased exposure time to radio wave radiation emitted from mobile phone devices increases, whereby long-term exposure increases in the probability of health hazards in tissues [1-7]. Most of the studies on the effect of electromagnetic radiation did not refer to the effect of wave interference at the interfaces between tissues or the effect of the time factor [1-9].

Specific absorption rate (SAR) measures the energy absorbed by a certain mass of human tissues. It determines the probability of biological effects on the human tissues due to exposure to RF radiation. SAR is defined as [10-16]:

$$\mathrm{SAR}\, {}^{W}\!/_{kg} = \frac{\mathrm{P}}{\rho} \tag{1}$$

Where: P is the power density in W/m^3 , and ρ is the density of each tissue in Kg/m^3. The specific absorption rate (SAR) parameter represents the safety guidelines placed by many ceremonious miens interested in this domain. The Federal Communications Commission (FCC) regulates the standards of the safe exposure levels to RF radiation emitted from a mobile phone. The allowed level of SAR as set by the FCC is 1.6 watt/kg for each 1 g of mass tissue [8, 9, 11, 17].

Many researchers have studied the effect of radio rays emitted by the antenna used in mobile phones on different human tissues, employing various methods [1, 2]. One of these methods is the Finite-Difference Time-Domain (FDTD) [18-25].

In this paper, the SAR was calculated corresponding to the increase in exposure time to 0.9 GHz and 1.8 GHz radio wave frequencies emitted from the planer inverted-F antenna (PIFA) and the planar monopole antenna to the multilayered model of the human head. The work is based on physical foundations, including each layer permittivity and permeability, regarding the wave interference and velocity changes at material interfaces, in addition to the mathematical basis of the FDTD method. The human head layers and their thicknesses were adopted according to the Atlas of Human Anatomy [26].

2- Mathematical method:

Human tissue is heterogeneously designed in a very complicated way to perform complex functions. Electromagnetic waves, including radio waves, change in two dimensions, temporal and spatial, through which researchers can calculate the determinant of SAR values for any human tissue [21, 23]. Numerical analysis is the best way to determine the SAR for the complicated tissue structures of the human organs. However, selecting a suitable numerical method is crucial for obtaining good results. The finite-difference time-domain (FDTD) method is one of the best numerical analysis techniques to solve and model computational electrodynamics problems [19, 27, 28, 29].

The FDTD method uses central difference approximations to solve the Maxwell's equations' temporal and spatial derivatives. It also depends on the Yee algorithm to solve electromagnetic problems [2, 18].

For a one-dimensional space (the x-direction variations), the electric field has a z-component only. Faraday's law can be written as follows:

$$-\mu\frac{\partial H}{\partial t} = \nabla \times E = \begin{vmatrix} \hat{a}_x & \hat{a}_y & \hat{a}_z \\ \frac{\partial}{\partial x} & 0 & 0 \\ 0 & 0 & E_z \end{vmatrix} = -\hat{a}_y\frac{\partial E_z}{\partial x} \quad (2)$$

Where: E and H are the electric and magnetic fields, respectively, μ represents the electromagnetic permeability [2,30, 31].

The FDTD algorithm provides a method to obtain future fields from past fields.

$$H_y^{q+\frac{1}{2}}\left[m+\tfrac{1}{2}\right] = H_y^{q-\frac{1}{2}}\left[m+\tfrac{1}{2}\right] + \frac{\Delta t}{\mu\Delta x}\left(E_z^q[m+1] - E_z^q[m]\right) \quad (3)$$

This is known as the updated equation for the H_y field, to be general with applicability to any node for magnetic field calculations. Where index m is the spatial step, effectively the spatial location, and the index q is not an exponent, it is the temporal step

By the same way as Ampere's law, the updated equation for the $E_z$field can be obtained from the formula, which is the updated generic equation for the E_z field::

$$E_z^{q+1}[m] = E_z^q[m] + \frac{\Delta t}{\varepsilon\Delta x}\left(H_y^{q+\frac{1}{2}}\left[m+\tfrac{1}{2}\right] - H_y^{q+\frac{1}{2}}\left[m-\tfrac{1}{2}\right]\right) \quad (4)$$

Many studies that simulate the propagation of mobile phone radiation in biological tissues depend on implementing FDTD codes in a purely mathematical form. They ignore the physical nature of the biological tissues, which strongly affects all major parameters. For example, the wavelength in the different tissue layers is not constant; it varies with the wave velocity in the different tissues, as shown in the following equation [32]:

$$\lambda_0 = \frac{c_0}{f_0} \quad (5)$$

Where: C_o *is* the speed of radio waves in air, f_o represents the frequency of radio waves in air before entering tissues.

In previous studies, the effect of the relative permittivity of tissues was ignored. This paper addresses this gap in the calculation to correct the resulting SAR values.

3- Results and discussions:

The simulation of a head model was performed using the FDTD method to calculate the SAR. The simulated head layers were (skin, dura, cerebrospinal fluid (CSF), and brain). The selected mobile antennas were a PIFA and a planar monopole antenna. This study calculates the SAR values in the human head tissues when the separation distance between the mobile phone and the antenna is zero for different exposure times of 30 min, 45 min, 1h, 1.5h, and 2h. Figures (1) and (2) show the simulation results of the propagation of the electric field in the skin, dura, CSF, and brain tissues for the human head model. The x-axis ranges from 0 to 40, 40 to 70, 70 to 90, and 90 to 130, representing the skin, dura, CSF, and brain, respectively.

The simulation of the electric field propagation, power density, and SAR values in the head tissue for exposure to 0.9 GHz frequency radio wave.

The influence of exposure to 0.9 GHz radio waves, for long-term exposure is discussed to represent the effect of exposure time on the electric field amplitude, power density, and SAR values of the pulse that penetrates the skin, dura, CSF, and brain tissues; the amplitude of these pulses change at the tissue interfaces, due to differences in the dielectric properties of the tissues.

Figures (1 and 2) shows the behavior of the electric field of 0.9 GHz frequency radio waves in the simulated head model.

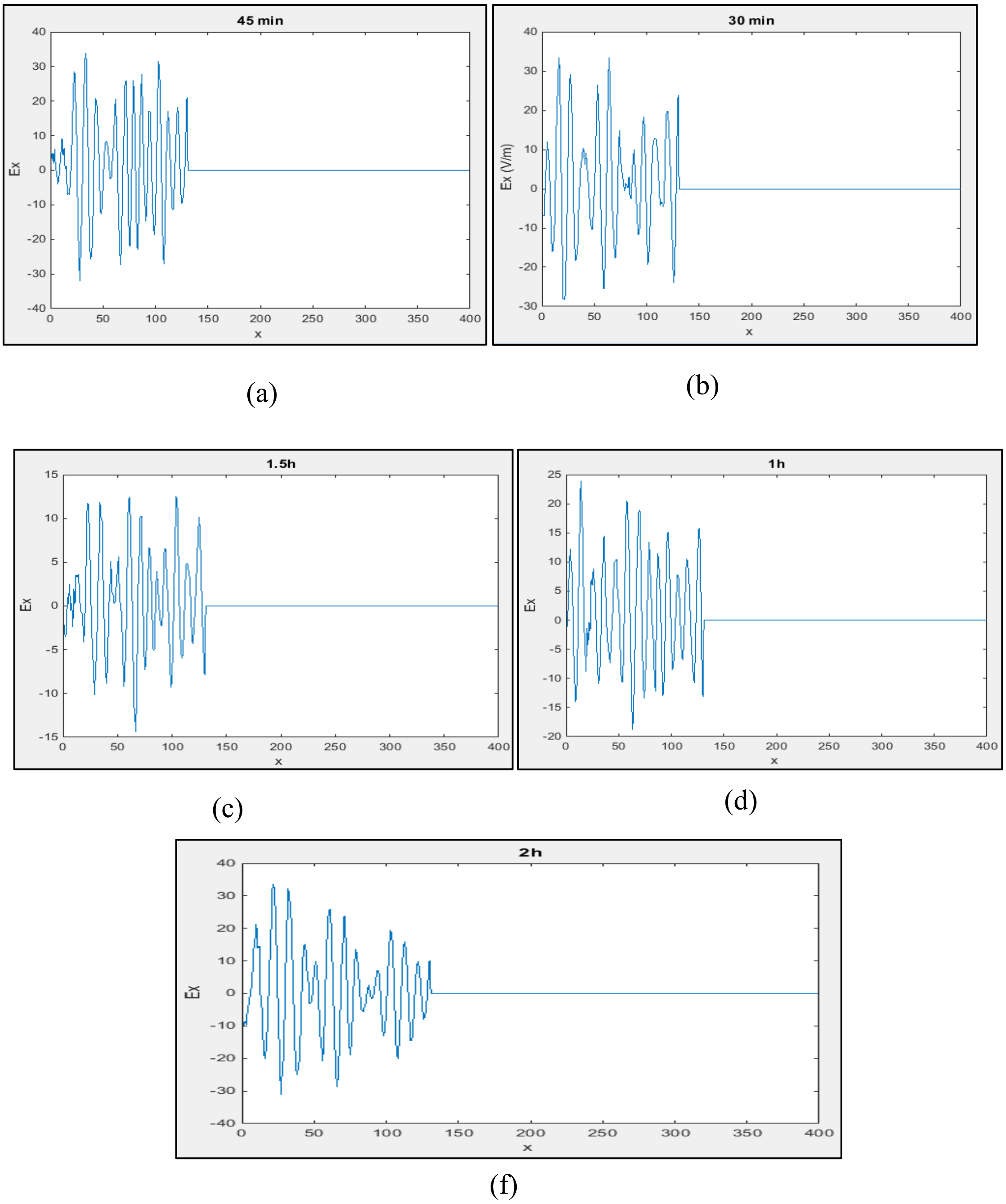

Figure 1: The simulation of the electric field of 0.9 GHz radio waves propagation in the head tissues for exposure times of (a) 30 min, (b) 45 min, (c) 1h, (d) 1.5h and (f) 2h.

Figure (2) shows the changes in the electric field due to increasing the exposure time from 30 min to 2 h on the skin tissue; in general, a rise of amplitude values with increasing exposure time to the skin was noticed; at an exposure of 30 min the amplitude was 29.22 V/m, after exposure of 2h the amplitude increased to 32.35 V/m, but there are exceptions in some values, which is due to the interference of waves in the tissue that results in a decline in the amplitude values, as shown in Figure (2), which ends after exceeding the interference points, and the amplitude of values rises again with increasing exposure time. The electric field amplitude in the dura tissues, CSF, and brain tissues has the same behavior as in the skin tissues.

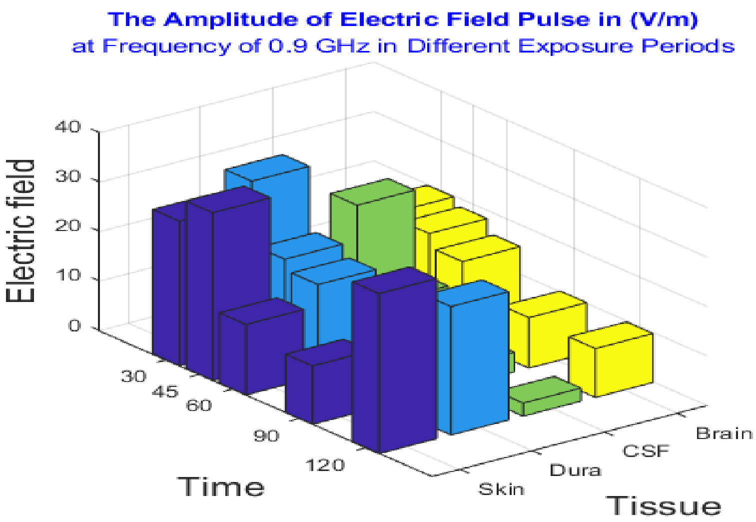

Figure 2: Electric field pulse amplitude in (V/m) at 0.9 GHz radio wave frequency for different exposure times.

Figure (3) displays the development of the power density in the simulated head model due to exposure to 0.9 GHz frequency radio waves. In Figure (3), the power density values decreased and increased by increasing the exposure time when passing through the different head tissues. This behavior follows the increasing and decreasing behavior of the electric pulse amplitude. The highest power density was in the CSF, equal to 932.7 W/m^3. Generally, the power density values in the skin increased with the increase in exposure time.

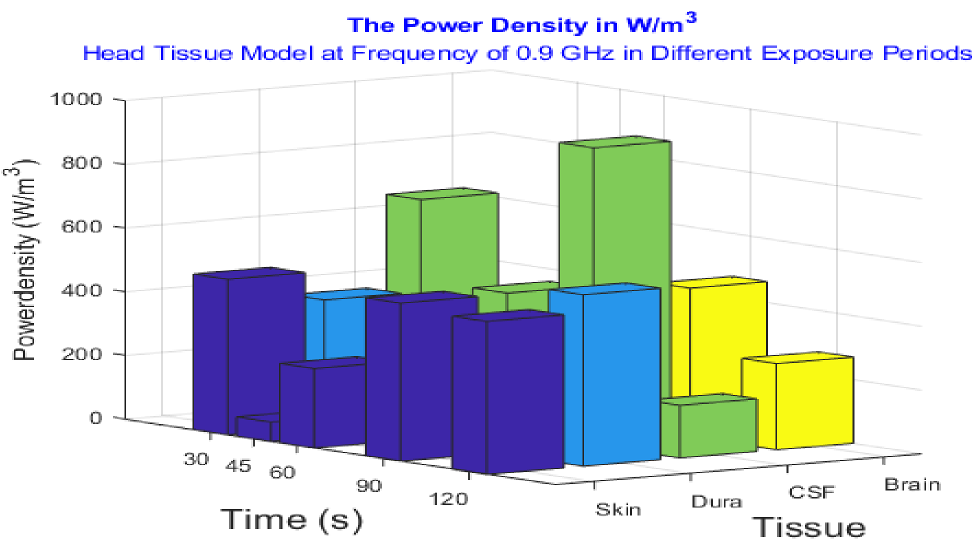

Figure 3: Power density in (W/m^3) at 0.9 GHz frequency

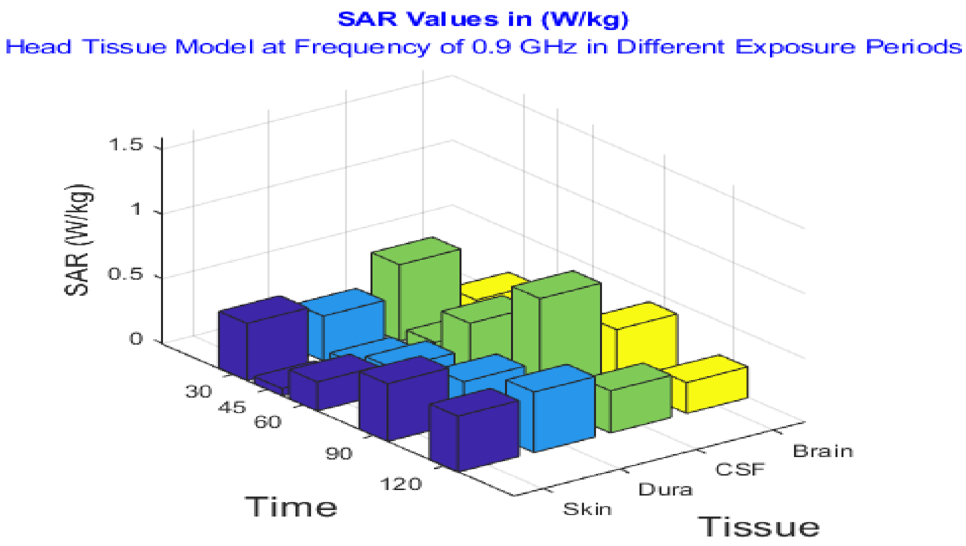

Figure 4 : shows the simulated SAR values in the simulated head model due to exposure to 0.9 GHz radio waves at a separation distance of zero. The maximum SAR values were in the CSF after an exposure time of 2 h equal to 0.5922 W/kg.

Figure (4): SAR in (W/kg) at 0.9 GHz radio wave frequency for different exposure times. The above results for the electric field and, accordingly the other variables (power density, and SAR) change, agreed with those of Rashid [1]and Whittow [33] for the first exposure period (30 min). Meanwhile, this research considered the exposure time as an important factor in SAR calculations, previous researches studied the electromagnetic effects on human head tissues without considering the effect of increasing exposure time. They also did not calculate the effect of the wave amplitude changes at tissue interfaces.

The simulation of the electric field propagation, power density, and SAR values in the head tissue for exposure to 1.8 GHz radio waves:

The influence of long-term exposure to 1.8 GHz radio waves on head tissue is discussed. The columns in Figures (6, 7, and 8) show the changes in the amplitude, power density, and SAR values of the pulse that penetrates the skin, dura, CSF, and brain tissues, which increase or decrease due to the differences in the dielectric properties of the tissues.

Figures (5) show the behavior of the electric field of 1.8 GHz radio waves in the simulated head model. Rises in amplitude values with increasing exposure time to the skin were noticed. At an exposure of 30 min, the amplitude was 18.9 V/m, and after exposure of 2h, the amplitude was 23.46 V/m, with some exceptions owing to the interference of waves in the tissue. The amplitude in the dura tissue was 19.76 V/m at an exposure of 30 min; after 45 min, it declined to 6.203 V/m because of the interference and then increased to 14.78 V/m again with increasing the exposure time. The same behavior was observed in the CSF and brain tissues. CSF had the highest amplitude values after an exposure time of 2h compared to the other layers of the simulated head model. Cerebrospinal fluid is the lubricating fluid for the spinal cord. Carrying high-intensity electrical waves affects the transmission of nerve signals due to its effect on the process of calcium exchange across the cell membrane and the transmission of a signal. Physiological changes in cell membranes and ion channels at cellular levels have been reported [34-36].

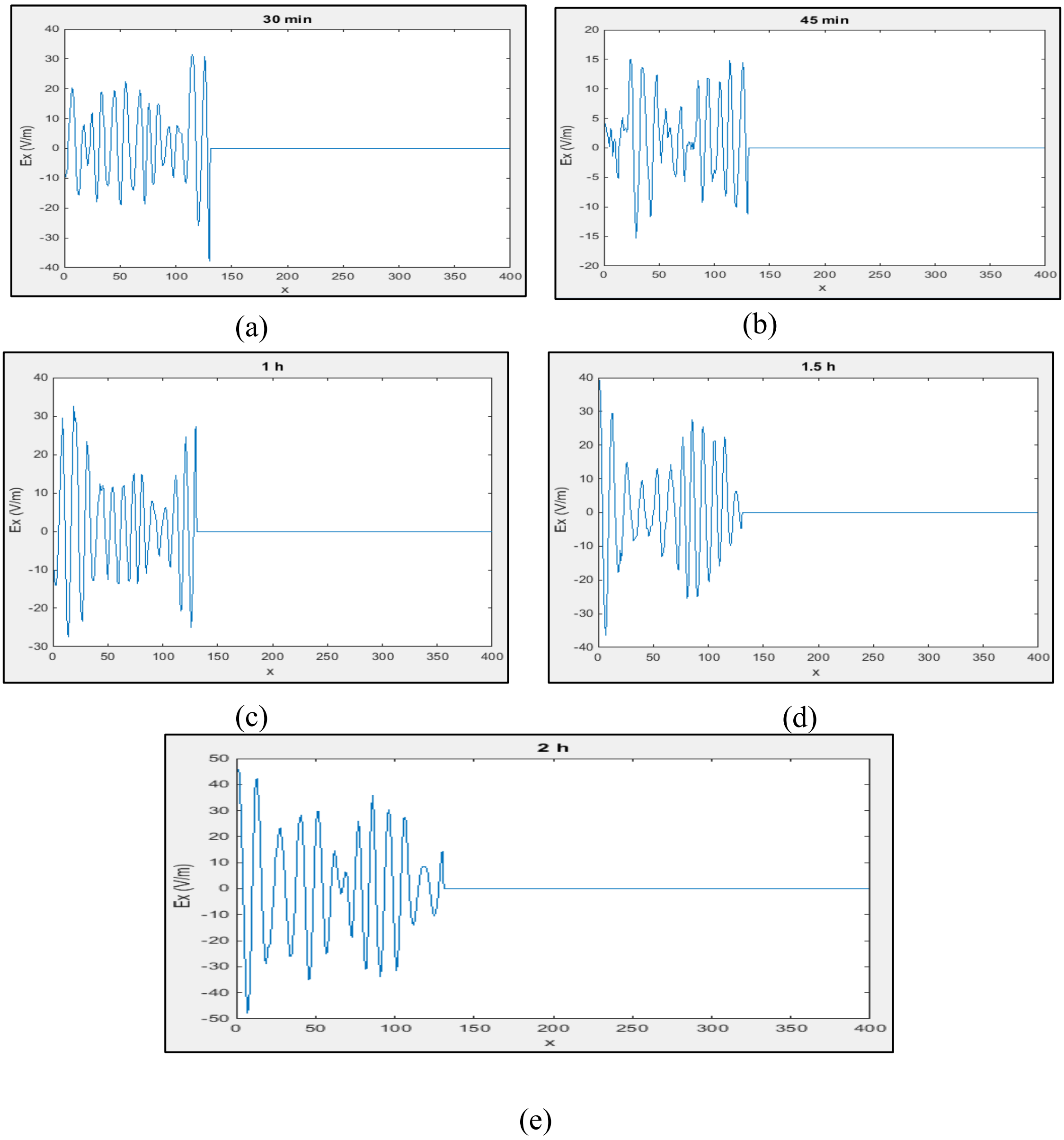

Figure 5: the simulation of the electric field propagation in the head tissue at 1.8 GHz radio wave for exposure times of (a) 30 min, (b) 45 min, (c) 1h, (d) 1.5h and (f) 2h.

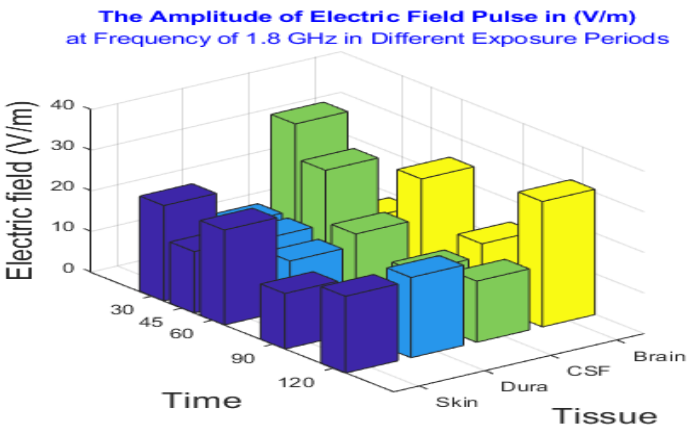

Figure 6 : Electric field pulse amplitude in (V/m) at 1.8 GHz radio wave frequency for different exposure times.

Figure (7) shows the impact of increasing the exposure time of the radio waves at a frequency of 1.8 GHz on the power density of the simulated head model. The power density of the dura, CSF, and brain changed with changes in electric field pulses. The highest power density at a frequency of 1.8 GHz was in the brain tissues for an exposure time of 2 h, which was 1894 W/m^3. It is a huge amount of energy supplied to the brain, which is considered unhealthy for the human brain, knowing that the human brain consumes only 300 W.h per day at rest [37, 38]. Exposure to radio waves, can cause structural changes in the myelin protein, leading to symptoms of electro-hypersensitivity [39, 40]. This exposure significantly damages the myelin sheaths and affects the radiofrequency penetration into the axon [41], leading to biochemical or pathological changes in the spinal cord.

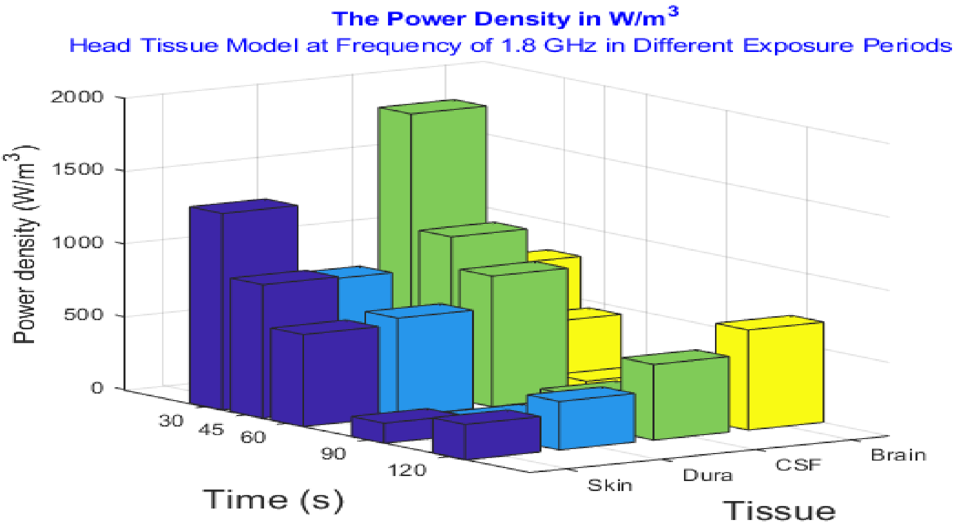

Figure 7: Power density in (W/m^3) at 1.8 GHz radio wave frequency for different exposure times.

Figure (8) shows the simulated SAR values due to exposure to 1.8 GHz frequency radio waves and a separation distance of zero. Generally, an increase in the SAR values with increasing exposure time through the head layers was noticed. The maximum SAR value was in the CSF at an exposure time of 2 h, which was 1.633 W/kg, exceeding the safety the recommended limits set by the Federal Communications Commission (FCC). Many dangers and changes may be caused by exceeding the FCC limit, which are [42]:

1- Genotoxic effects
2- Effects on the blood- brain barrier
3- Effects on learning and memory
4- Effects on neuronal calcium channels
5- Effects on myelin sheath

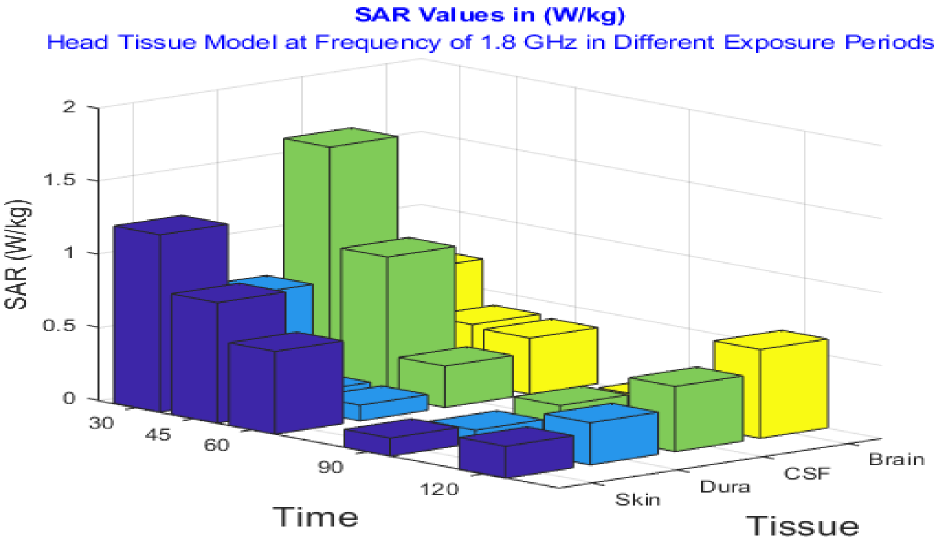

Figure 8 : SAR in (W/kg), at frequency (1. 8 GHz)

The electric field and other variables results agreed with the results of Rashid [1] and Whittow [33]for the first exposure time period (30 s). Their results were based on mathematical concepts, whereas our results were collected using the same mathematical and physical concepts considering the changes at the tissue interfaces, which were not mentioned before.

4- Conclusions:

There were some values which exceeded the safety boundaries values of the SAR established by FCC at 1.6 W/kg. The obtained results indicate a very close relationship between long-term exposure to radio waves and biological damage probability due to increasing SAR values. Many medical studies discuss the damages occurring when the SAR values exceed the safety limits of 1.6 W/kg set by the FCC. These hazards were indicated as genotoxic effects, blood-brain barrier damage and learning and memory disturbance, also the effects of neuronal calcium channels, and Myelin sheet damages. Many physical studies depended on the SAR calculation at short-term exposure without considering the physical interfaces between tissues. From the results of this paper, it was observed that long exposure time contributed to the creation of interference between the emitted and reflected pulses at the interfaces between tissues, which may have resulted from the strengthening or debilitating of the pulse in the tissue.

The results of this study noted that the CSF in the human head model was the most affected tissue. Exposure to 1.8 GHz radio wave at an exposure time of 2h resulted in a high SAR value of 1.633 W/kg.

The obtained results proved that the behavior of the amplitude of the electric field signal, power density, and SAR on the curves are changeable inside the tissues through different exposure times. The curves showed rises and declines in the electric field amplitude, power density, and SAR values of the signal that penetrated the tissue. The signal inside human tissues may have two kinds of interactions. The first is absorption, which is the interaction between the signal and the material of the tissue, resulting in the attenuation of the signal inside the tissue. The second type of interaction is the interference of the transmitted and reflected signals at the tissue interfaces. The exposure times were taken into consideration. The flow of many waves penetrating the tissue has been considered, reaching the inevitability of interference occurrence. The interference may be constructive (a phenomenon that causes high power to be directed on the human tissues), or destructive (causing the weakening of the radio wave power supplied to the tissues). Finally, the authors mentioned a disturbance and electric field fluctuations inside the tissues.

DATA Availability:

No data were used to support this study

Conflict of Interest:

The Authors declare that they have no conflicts of interest regarding the publication of this article.

Authors' Contributions:

Every Author contributed equally to each part of this paper

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