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INVESTIGATION ON THE SPECIFIC ABSORPTION RATE (SAR) IN A 3D HUMAN HEAD MODEL EXPOSED TO ELECTROMAGNETIC RADIATIONS

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ABSTRACT

Exposure human tissue to electromagnetic radiation (EM) from radio wireless frequencies causes many negative health effects. The assessment of the absorbed EM by human tissue depends on the Specific Absorption Rate (SAR) factor. In this paper, a square patch antenna (SPA) is designed to be a source of EM radiation, and optimized to operate at several applicable frequencies, such as GSM 1800, IEEE 802.11 WLAN standard 2.4 GHz and 5.3 GHz bands, and 3.2 GHz WiMAX band. The radiated EM by the SPA antenna is evaluated in a 3D human head model or Specific Anthropomorphic Model (SAM), which consists of two layers, the outer shell (1.5 mm thickness) and filled with tissue simulating liquid (TSL). The investigation involved four aspects, first the distance between the SAM and the EM source has been moved between 0 mm to 50 mm, second for the specific distances (0 mm, 15 mm, 30 mm, and 45 mm) the frequency of EM source has been changed among 1.8 GHz, 2.4 GHz, 3.2 GHz, and 5.3 GHz. Third, the tilt angle (θ) between the SAM and the antenna has been shifted from 0^0 to 90^0. Finally, the antenna encasement (2 mm thickness plastic material) was removed and the procedure in the first step is repeated to investigate the effect of encasement on the SAR reducing. The results reveal that there is an inversely proportional relation between SAR and distance, SAR and tilt angle. Besides, the antenna encasement has a large impact on attenuating SAR value, while the SAR is directly proportional to frequency. All SAR evaluations were performed by CST-2014 Microwave studio simulator which is built on the Finite-Difference-Time-Domain (FDTD) principle. All calculations are achieved over 1 g and 10 g of mass tissue averaging and according to *IEEE/IEC* 62704-1 standards.

KEYWORDS: Head Phantom (SAM); Square patch antenna (SPA); Specific Absorption Rate (SAR).

1. INTRODUCTION

Wireless applications have developed very quickly in recent years. Statistics data show that by the end of 2019 the number of mobile phone users is forecast to reach 4.68 billion, which means that about half of the world's population will be online. However, this large amount of devices radiates a considerable amount of electromagnetic waves, which may have a substantial impact on human body tissue and may lead to health risks, as carcinoma, genetic damage etc., as adduced by the World Health Organization (WHO) (Ali et al., 2018). The SAR is defined as the amount of electromagnetic power absorption by a unit mass of the human tissue (Ghanmi et al., 2013). To ensure the minimum effect of electromagnetic waves exposure to the human body the Institute of Electrical and Electronics Engineers (IEEE) and the International Commission on Non-Ionizing Radiation Protection (ICNIRP) have enacted standards and guidance for the allowable electromagnetic field exposure (ICNIRP, 2013, and IEEEC 95.1, 2005). Therefore, they established the SAR value as 1.6W/kg for 1g of tissue and 2W/kg for 10g of tissue, many countries accepted these limits of SAR to sidestep the health hazard effects.

In the literature, a considerable number of researches addressed the electromagnetic waves exposure to human tissue and their consequences to health effects. Ronald et al. investigated the SAR value for various Asian-Sized heads, they assumed small size hand with the mobile handset in proximity to head, and found that the SAR in the head might increase since there is less SAR in the hand (Ronald et al., 2012). Husni et al. analyzed the effect of the SAR in the human head for various dielectric properties, and for

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exposure frequencies of 900, 1800, and 1900 MHz (Husni et al., 2013). Tateno et al. in 2014 presented a high definition numerical model to compare SARs of the flip phone and tablet; they discovered the SARs of flip phones were higher than those of tablets (Tateno et al., 2014). Ferreira and de Salles in 2015 studied the impact of tablet device on realistic adult and child head models; they used SEMCAD X software for the SAR calculations (Ferreira et al., 2015). In 2018, a new type of microstrip antenna structure for reduction SAR in human brain was proposed by Lovika and Jyoti (Lovika and Jyoti, 2018). In the same year Hamed and Maqsood focused on SAR calculation and tissue temperature response in 28 GHz, 40 GHz, and 60 GHz frequency bands. They detected that the SAR in 60 GHz higher than 28 and 40 GHz, and the rise in temperature in tissues structure had never transcended 0.59 C (Hamed et al., 2018).

In this study, several important parameters affecting the value of SAR have been investigated. This is accomplished on a 3D Specific Anthropomorphic model (SAM), and for operating frequency bands GSM1800, WiFi 2.4 GHz and 5.3 GHz, and WiMAX 3.2 GHz.

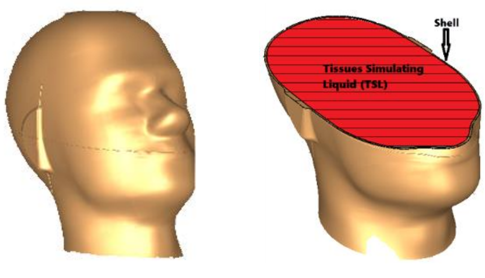
2. MODELS

2.1 Human Head Model

The 3D Standard anthropomorphic model (SAM) is a regular model defined for specific absorption rate (SAR) evaluation in the CST 2014 STUDIO software (Dassault Systèmes, Vélizy-Villacoublay, France) as shown in Figure (1) a. The SAM head model comprises two layers, the outer (shell) which is filled with tissue equivalent materials, or head tissue simulating languid (TSL) fill the shell as shown in Figure (1) b. The dielectric characteristics of the SAM head model are acquired to be homogeneous as the dielectric properties of the tissues in the anatomical head.

The shell thickness is 1.5 mm and with tissue mass density equal to $\rho = 1 g/cm^3$ (Zou et al., 2009), the density of the tissue is the same as water density because there is a large similarity between tissue densities of the human texture and water density.

The outer shell of the SAM head model has a frequency-independent relative dielectric constant (ε_r) value of 3.7. Contrast to TSL that possesses the dielectric properties depends on the operating frequency. The dielectric properties (relative dielectric constant ε_r and electrical conductivity (σ) for both SAM head model layers and at various operating frequencies are simulated and given in Table (1).



(a) (b)

Fig. (1): (a) SAM model and (b) Layers of SAM model

Table (1). Dielectric Properties of the SAM model layers

Frequency (GHz)	Shell		Tissue Simulating Liquid (TSL)	
	ε_r	σ [S/m]	ε_r	σ [S/m]
1.8	3.7	0.00158	40	1.4
2.4	3.7	0.00159	38.7	1.87
3.2	3.7	0.0016	36.87	2.61
5.3	3.7	0.00162	31.5	4.73

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2.2 Antenna Model

Antennas have a crucial role in any wireless system. There are many forms of antennas that are used in communication devices such as horn antennas, wire antennas, and planar antennas, etc.

Square patch antenna (SPA) is mostly considered for recent wireless devices due to its several attractive features such as conformity to host surface, low profile and cost, and simple manufacturing (Kumar et al., 2019).

Initially, the SPA antenna is designed to be a source for radiating the electromagnetic waves that expose to the human tissue as shown in Figure (2). The dimension of the designed antenna is optimized each time to operate at the corresponding resonant frequency as shown in Table (2). The considered resonant operational frequencies are GSM1800 (1.8 GHz) band, IEEE 802.11WLAN standard (2.4 GHz) band, 3.2 GHz WiMAX band, and IEEE 802.11 WLAN standard 5.3 GHz (Ahmed et al., 2018).

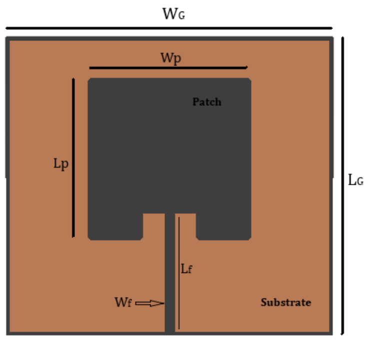

Fig. (2): SPA Antenna

The three prerequisite parameters needed for the design of square patch antenna are resonant frequency (f_r), substrate's relative dielectric constant (ε_r), and the thickness of the substrate (h).

For efficient radiation of SPA its length calculated as in (1) (Kumar et al., 2019).

$$L_p = \frac{c}{2\pi f_r \sqrt{\varepsilon_{reff}}} \quad (1)$$

Where c is the speed of light, and ε_{reff} is the effective relative dielectric constant and is calculated as in (2) [14].

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-1/2} \quad (2)$$

Where ε_r is a relative relative dielectric constant of FR4 substrate and equal to 4.3 with substrate thickness of 1.6 mm.

Also, the width W is selected as in (3).

$$W_p = \frac{c}{2 f_r \sqrt{\frac{\varepsilon_r + 1}{2}}} \quad (3)$$

Table (2): Optimum SPA Antenna Dimensions at corresponding operating frequencies

Parameter (mm)	f_r (1.8 GHz)	f_r (2.4 GHz)	f_r (3.3 GHz)	f_r (5.2 GHz)
L_p	39	29	20.2	12.4
W_p	39	29	26.3	20.5
L_G	60	55	40	33
W_G	60	60	40	29
L_f	18	18	14	19
W_f	0.8	0.8	1	1

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The simulated CST return loss of the designed antenna at various resonant frequencies is given in Figure (3).The antenna is encased with a plastic cover with a thickness of 2 mm and a relative dielectric constant of 2.5, to represent the realistic case in which the antenna is used in communication devices. The antenna is fed with input power value of 0.5 watts in CST simulation.

The antenna's encasement has the main impact in reducing the amount of power absorbed by the SAM, thereby reduces the health effect on the human tissue as will be shown in the section (4.4) of this paper.

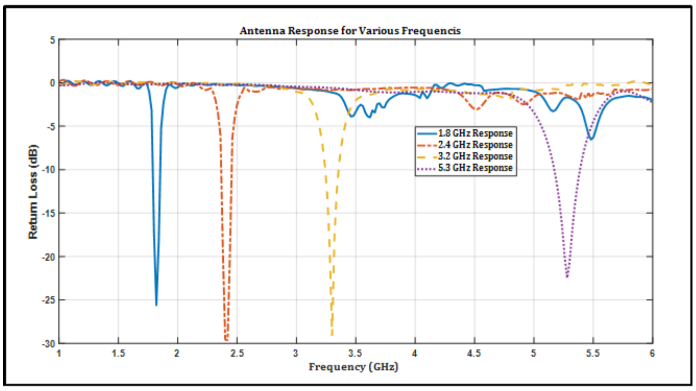

Fig. (3): Simulated CST response of the SPA antenna

3. METHODS AND MATERIAL

3.1 The Specific Absorption Rate Calculation and International Recommendations.

A SAR measures the rates of absorption of non-ionizing RF power by a mass of human biological tissue with mass density (ρ), when exposed to electromagnetic radiation.

Basically, the SAR is averaged either over the whole body or over a cube of mass tissue, either 1g or 10g as in (4) (Arumugam et al., 2009).

$$SAR = \frac{d}{dt}\left(\frac{dw}{dm}\right) = \frac{d}{dt}\left(\frac{dw}{\rho\, dv}\right) \qquad 4$$

Where dw represents absorbed incremental energy, and dm is an incremental mass contained in a volume element dv for a given tissue density.

Additionally, SAR value in (4) might be reformulated in terms of induced electrical field E in (V/m) as in (5) (Arumugam et al., 2009).

$$SAR = \frac{\sigma}{2\rho}|E|^2 = \frac{\omega\varepsilon}{2\rho}|E|^2$$

And

$$E = g(x,y,z)\sum_{n=0}^{\infty} J_n(x,y,z) \qquad 5$$

Where σ is the conductivity of tissue, and the electrical field is approximated using the Bessel function of the first kind with n=0, 1, 2,….., ∞.

To get information about electromagnetic fields that penetrate the texture of the tissue, it is required to define the incoming electromagnetic waves, after reflection at the boundaries conditions, that is further decreased due to energy dissipation .The value of the electromagnetic fields is decreased exponentially along penetrated distance from the boundary conditions as in (6) (Greenebaum et al., 2019).

$$g(z) = Ae^{-\frac{z}{\delta}} \quad and\ \delta = \frac{1}{\omega\left[\frac{\mu\varepsilon}{2}\left(\sqrt{1+p^2}-1\right)\right]^{1/2}} \qquad 6$$

Where, p is the ratio of the conduction current to displacement current in a given media and is the tissue's depth at which the electromagnetic wave decreases by 1/e ≈ 0.368

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of its value at the boundaries. There are studies which confirm that at higher frequencies the effect of the tissue becomes more obvious for humans and vertebrates.

The recommended safety standards ratified by the ICNIRP and IEEE for determining exposure of the electromagnetic radiations were the SAR value of 1.6 W/ Kg regarding to 1 g of human tissues, and 2 W/kg for 10 g of human biological tissue. These threshold of SAR were admitted in several countries to prevent health effects in human tissue in the range of frequencies of (3KHz - 300 GHz) (ICNIRP, 2013, and IEEEC 95.1, 2005).

3.2 Methods

The entire work presented in this research is based on simulation results from Computer Simulated Technology (CST) Microwave studio 2014. This simulator uses the Finite-Difference Time-Domain (FDTD) method for doing all simulations and SAR calculations. The FDTD techniques quantify SAR by partitioning the tissue cells into smaller ones with appropriate meshing properties (Lee et al., 2011).

In this study, the mesh properties have been set up from mesh global properties by setting cells per wavelength of 8; lower mesh limit of 10, mesh line ratio limit of 10, and the total mesh cells in hexahedral mesh type of 10,307,506 cells. The *IEEE/IEC* 62704-1 averaging method standard was regarded SAR evaluation.

4. RESULTS

This investigation involves study variation of several factors on SAR value, such as the distance between the head phantom (SAM) and mobile handset (Antenna), the operating frequency of the radiation source, the tilt angle between the mobile handset and phantom cheek, and the effect of the antenna encasement as well. All these parameters will be discussed in detail in the next sections.

4.1 Effect of Antenna Location Variation on SAR value

In this section, the effect of variation distance between the head's phantom and the antenna has been investigated. The antenna has been placed at first horizontally, parallel, and touching the phantom's cheek as shown in Figure (4). The antenna and phantom are aligned with this form to represent the actual case in which people use the mobile handset.

Thereafter, the antenna was gradually moved away from the SAM with distances of 5 mm up to 50 mm, and the SAR value has been measured at frequency 1.8 GHz, and for both averaging standard 1 g and 10 g, as shown in Figure (5) a. The process is repeated for other frequencies 2.4 GHz, 3.2 GHz, and 5.3 GHz and the result is shown in Figures (5) b, c, and d respectively

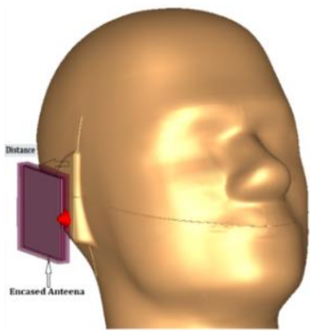

Fig. (4): Alignment of the antenna with SAM

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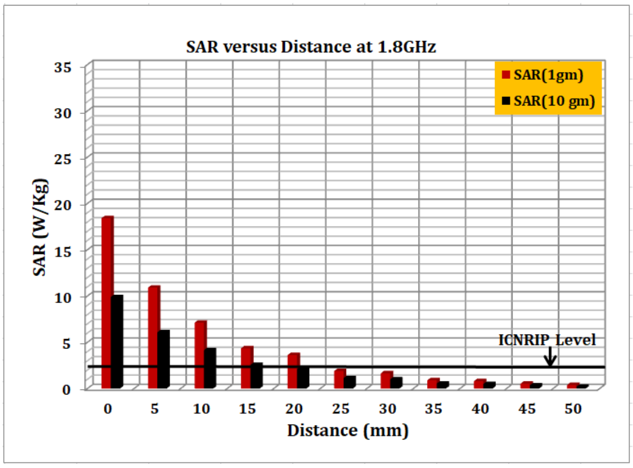
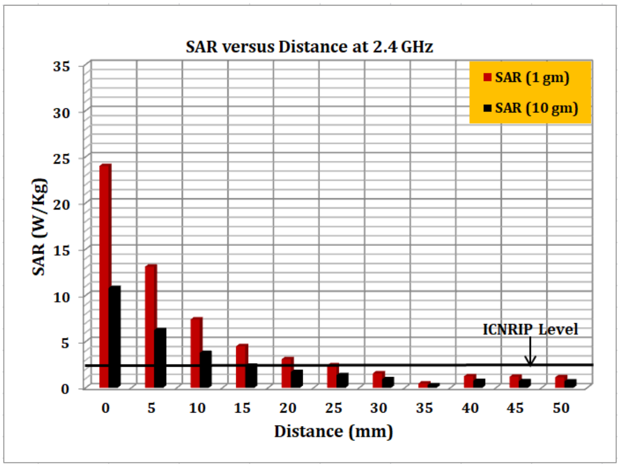


(a)



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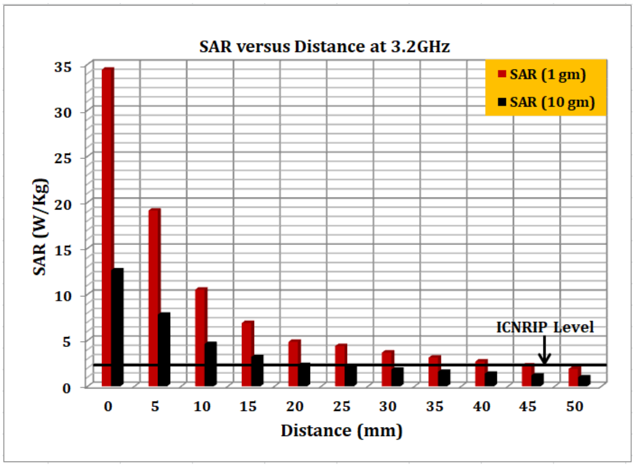
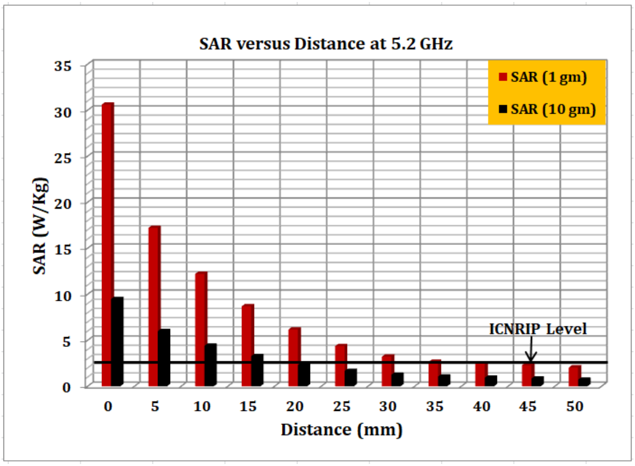


(c)



(d)

Fig. (5): SAR values versus different distances between the antenna and head model (SAM) referenced to ICNIRP level and at: (a) 1.8 GHz, (b) 2.4 GHz, (c) 3.2 GHz, and (d) 5.2 GHz.

4.2 Effect of Frequency Variation for Exposed EM Radiation on SAR value

The influence of frequency variation of the EM source on the SAR value is considered in this section. Here, the distance between the antenna and the SAM is fixed at 0 mm, and then the frequency of EM source is switched between 1.8 GHz, 2.4 GHz, 3.2 GHz, and 5.3 GHz. The value of the 1 g SAR and 10 g SAR has been measured at each frequency, the process has recurred for another farther distances (15 mm, 30 mm, and 45 mm), and the results are presented in Figure (6) a and b respectively.

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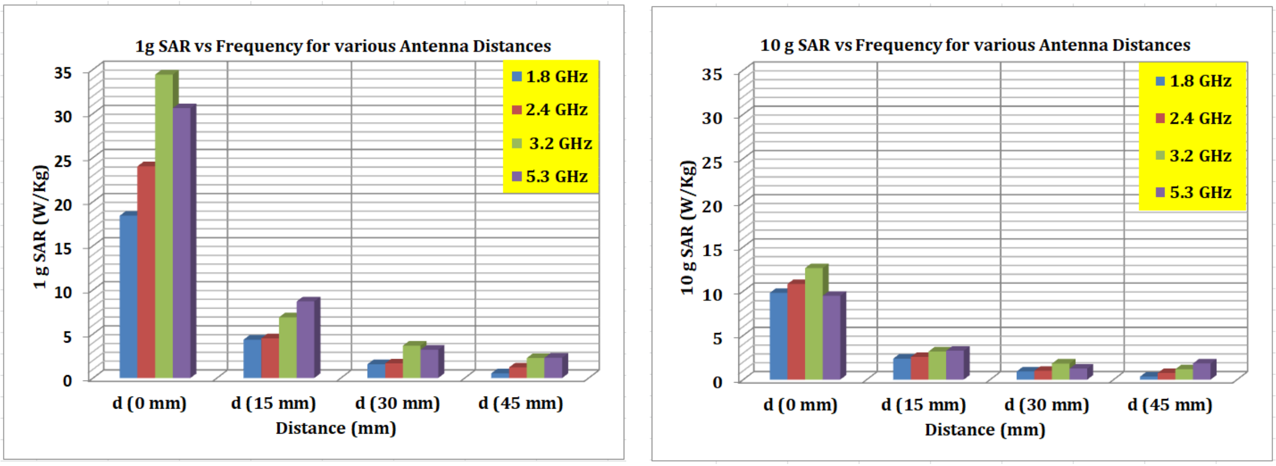

(a) (b)

Fig.(6): SAR values for various frequencies, and at different distances between the antenna and head model; (a) 1g averaging standard, (b) 10g averaging standard.

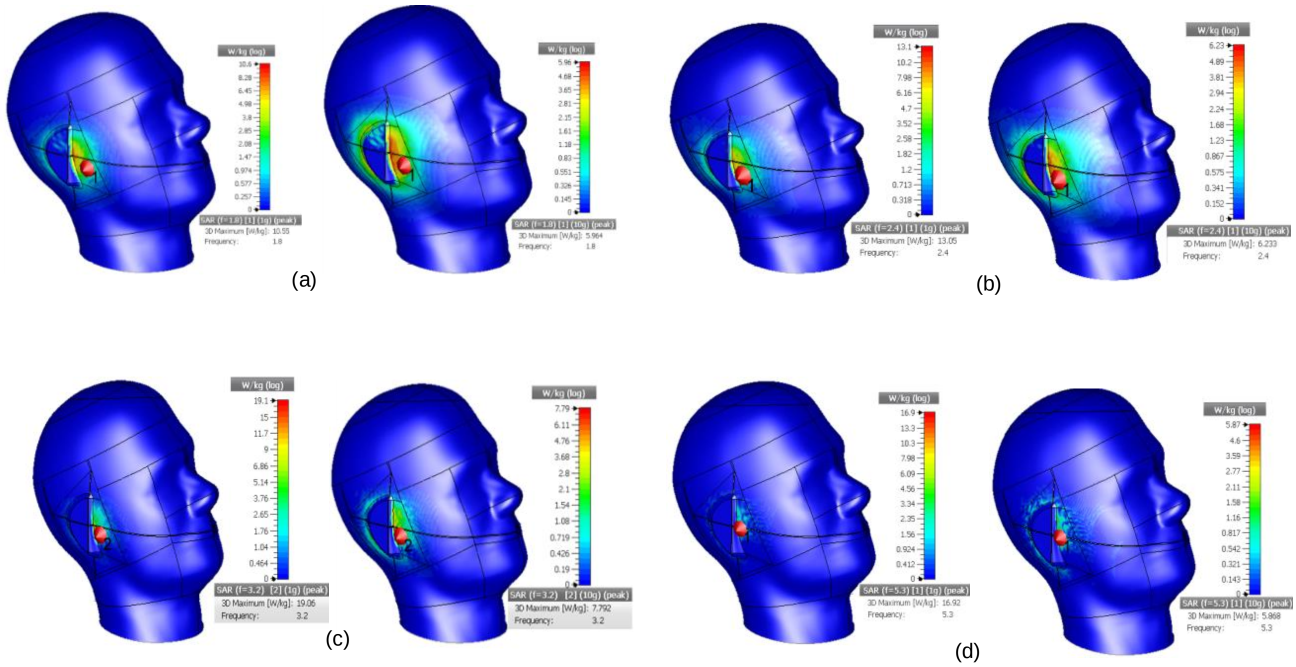

Fig.(7): 3D SAR distribution over human head phantom at (a) 1.8GHz, (b) 2.4 GHz, (c) 3.2 GHz, and (d) 5.3GHz; for 1g SAR left column, and 10g SAR right column.

The 3D SAR distribution for various EM source frequencies and at 5 mm distance between SAM and antenna is shown in Figure (7). The red color points out the highest EM radiation deposited in the SAM region, while the blue color region indicates the SAM region with lower absorbed radiation from the antenna.

4.3 Effect of tilted the Mobile Handset on SAR Value

The effect of the mobile handset (antenna) tilting on SAR is also studied. The antenna is situated at 5 mm far from the SAM, and then it tilted by an angle $\boldsymbol{\theta}$ as in Figure (8) a. However, the mobile handset in a tilted position is to emulate that many people tilt their during phone dialing. Hence, the tilt angle $\boldsymbol{\theta}$ is shifted from 0^0 to 90^0 with step 15^0, and corresponding 1g and 10 g SAR is measured and for all frequencies as in Figure (9).

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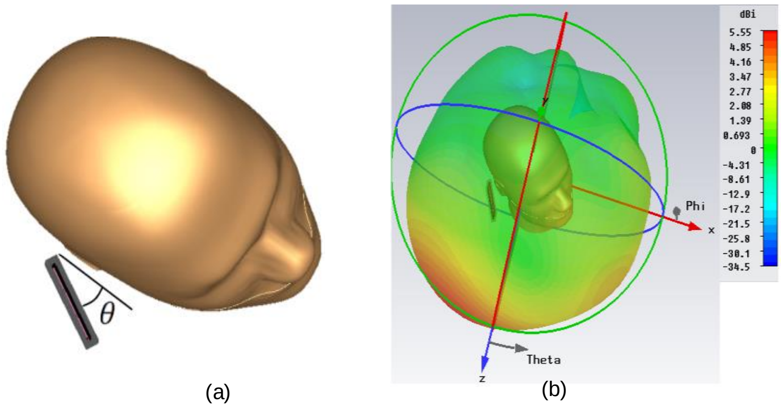
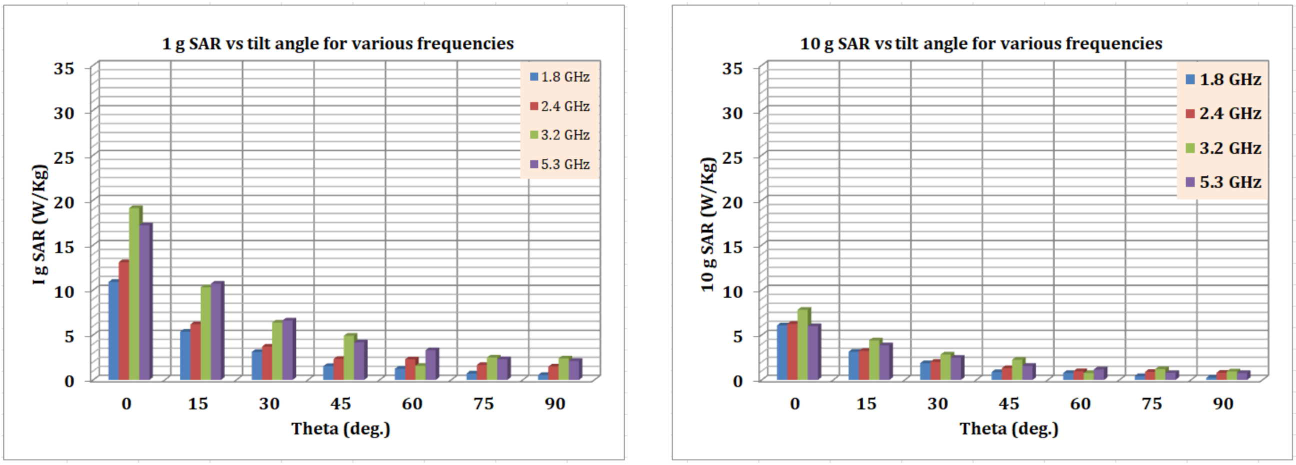


(a) (b)

Fig. (8): (a) tilted antenna with respect to head phantom, (b) 3D radiation pattern with head phantom.



(a) (b)

Fig. (9): SAR values versus tilt angle θ and for different frequencies; (a) 1g averaging standard, (b) 10g averaging standard

4.4 Effect of the Antenna Encasement on SAR Value.

One of the SAR effect diminution methods in the human head model is encasing the antenna with shielding material. The impact of encasement can be estimated in terms of the percentage SAR reducing as in (9 and 10) (Abdulrazzaq et al., 2013).

$$SRF_{10g}(\%) = \frac{SAR_{10g} - SAR_{en10g}}{SAR_{10g}} \times 100\% \qquad 9$$

$$SRF_{1g}(\%) = \frac{SAR_{1g} - SAR_{en1g}}{SAR_{1g}} \times 100\% \qquad 10$$

Where, SRF_{10g} and SRF_{1g} are SAR reduction factor for l0g and 1g averaging standard, respectively. SAR_{10g}, SAR_{en10g}, SAR_{1g} and SAR_{en1g} are 10 g SAR and 1 g SAR averaging standard without and with antenna encasement respectively.

In this paper, the antenna is encased with 2 mm thick plastic material and whose relative dielectric constant of 2.5. Then, to study the impact of the encasement, the procedure in section (4.1) is repeated for the antenna without encasement, and the results are shown in Figures (10).

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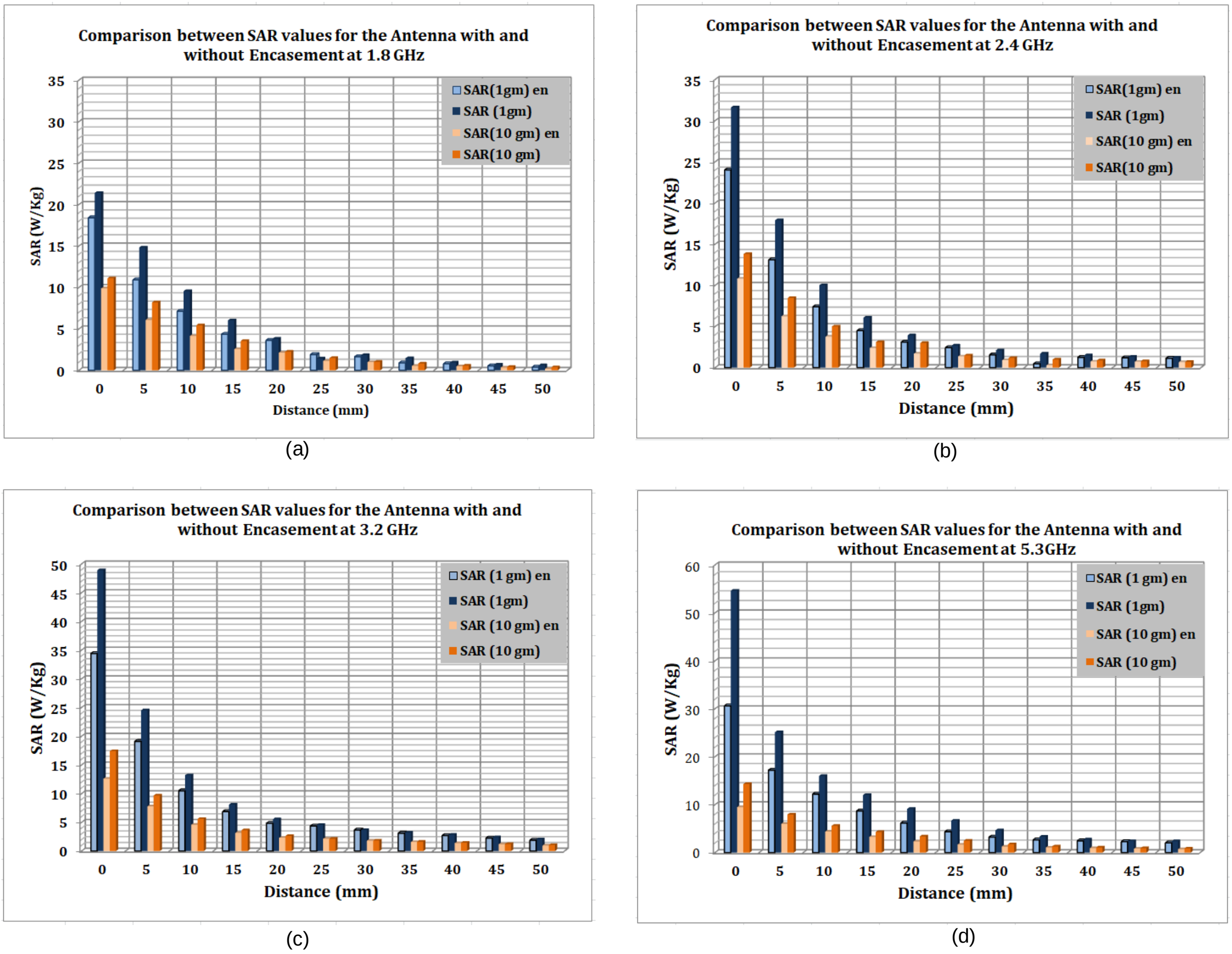

Fig. (10) Comparison between SAR values for the antenna with and without encasement versus different distances between the antenna and head model for: (a) 1.8GHz, (b) 2.4 GHz, (c) 3.2GHz, and (d) 5.2 GHz

5. DISCUSSION

This paper investigates the interaction of the cellular handset's electromagnetic radiation (EM) with the human head, due to the absorption of this EM radiation by the human head tissue.

Figure (5) shows that the SAR value declines gradually by extending the distance between SAM and the antenna for both averaging standard, where the value of SAR is 18.4 W/kg for 1 g and 9.8 W/kg for 10 g at distance of 0 mm, and these values are stood at 0.38 W/kg and 0.18 W/kg respectively at distance of 50 mm.

Figure (5) a, also reveals that up to a distance of 25 mm the value of SAR is still more than the recommended value for 1 g and 15 mm for 10 g. While for Figures (5) b, c, and d the distance in which the values of SARs are still more than recommended values are 25 mm, 50 mm, and 50 mm for 1 g respectively, and 15 mm, 20 mm, and 20 mm for 10 g respectively.

In fact, these distances change occasionally, because they depend on several parameters, including the value of the reference power which has been chosen in this research as 0.5 watts, in addition to the antenna's gain, etc. Accordingly, these distances may vary with these parameters. Furthermore, Figures (5) also tells that the SAR values rise with frequency as illustrated in section 4.2.

Figure (6) a, explains how the 1 g SAR grows with rising frequency. For instance, the value of SAR is 18.4 W/kg at the frequency of 1.8 GHz, while for 2.4 GHz 3.2 GHz, and 5.3GHz the corresponding values are 24 W/kg, 34.4 W/kg, and 30.6 W/kg respectively at the same distance (0 mm).

It is also obvious from Figure (6) that there is increase of 10 g SAR with frequency, except in some cases at 5.3 GHz, where the SAR at 3.2

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GHz is higher than at 5.3 GHz, this actually might be attributed to low antenna performance at 5.3 GHz, and this can be noted by referring to Figure 3 where the antenna return loss (matching) is not as good as at other frequencies, but overall there is rising in SAR for both measuring standards 1 g and 10 g versus frequency.

The direct proportionality between the frequency and SAR is principally associated with the conductivity of head tissue (σ), going back to equation (5) it is seen that the value of SAR is directly proportional to the conductivity of head tissue (σ) and the conductivity (σ) in turn is a function of the frequency as illustrated in Table (1). However, the SAR value in the small volume of mass tissue is more than in the large volume of tissue, wherein for all obtained results the 1g tissue was higher SAR than 10g tissue, this is because the power is well distributed over 1g of mass tissue than 10g (Husni et al., 2013).

Figure (9) shows that any expanding in the tilt angle causes a drop in the SAR value. This is due to the reduction in the incident EM power on the head model (SAM) because the antenna directivity is shifted outward the SAM, considering the antenna has broadside radiation pattern properties as in Figure (8) b.

Comparing the results of Figures (10) and Figure (5), it is apparent that there is a reduction in SAR for the case of the antenna encasement. Using the equation (9) and (10) and based on data of Figure (10), the SAR reduction factor is in the range of (14% − 38%) for 1g and of (11% − 50%) for 10g at frequency 1.8 GHz, Also, for other resonant frequencies 2.4 GHz, 3.2 GHz, and 5.3 GHz are in the ranges of (8.4%−24%),(9.1% − 29.6%), and (15% − 43.9%) for 1g and (7% − 21.7%), (7.8% − 27.5%), and (17.5% − 33.7%) for 10 g respectively.

The results obtained from this research were verified by some of the other papers, but for different operating parameters and cases (Ali et al., 2018), (Zou et al., 2009), (Abdulrazzaq et al., 2013), and (Turgut et al., 2008). The (Ali et al., 2018) proved that the SAR value increases with frequency and for two types of antenna transmitter (SPA and dipole antenna).

The (Turgut et al., 2008) also confirmed that the SAR value increase with frequency, where SAR was measured in Gustav bimodal SAM at 900 MHz and 1800 MHz frequencies. The SAR lab results were 0.175W/kg and 1.748W/kg for 900 MHz and 1800 MHz respectively. The (Zou et al., 2009) established an electromagnetic model of the human head and mobile phone to calculate the electrical field strength and SAR inside the human head. He found that by an increasing space among antenna and mobile phone the calculated SAR in head decreases. The (Abdulrazzaq et al., 2013) confirmed that the SAR in human tissue decreases with EM source distance at 900 MHz and 1800 MHz frequencies, moreover, it is showed that shielding the PIFA antenna with ferrite or aluminum material reduces the effect of SAR about 53% to 65% as compared with an unshielded case.

6. CONCLUSION

Electromagnetic radiation (EM) hazard has become a significant concern in most countries of the world, due to a warning of the World Health Organization about this issue. In this study, several effective parameters influencing SAR were investigated. Several important points may be concluded from this work. It is obvious that with a larger distance between the mobile handset and the human body, the EM has less impact on the human body because the value of the SAR drops with increase the distance. But it is not possible to determine the exact distance at where the SAR value is less than the recommended safety standards ratified by the IEEE and the ICNIRP, because other factors are influencing the SAR value, such as transmitted power, antenna performance, etc. The second point, the relation between operating frequency and SAR is directly proportional, where any increase in the frequency of mobile handset will increase the conductivity of the body tissue, which in turn raises the value of the SAR in the human body. Thirdly, the tilt angle between the mobile handset and the head model also has a large effect. Thus, tilting the mobile phone in the outward direction of the head (increasing the tilt angle), reduces the effect of the exposed EM (But only if the antenna is directional). Finally, antenna's encasement has an important impact in attenuating the radiation toward the tissue, hence reduces the risk of the radiation to the human body.

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