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Current Density and SAR Analysis of Biological Tissues due to Radiant Electromagnetic Waves from Base Station Antennas

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Abstract: *The environment around human contains numerous sources of non ionizing radiation, which include, but not limited to: power lines, power stations, TV and radio repeaters, cable and, RF cellular communications and satellite communications. Due to these sources, there exist a degree of interaction between the electromagnetic fields they generate and biological human tissue. For health purpose, the probe of how electromagnetic energy induces humans or how much electromagnetic energy is absorbed by the biological human tissues should be provided with answer quantitatively as much as possible. Two basic ways in which electromagnetic energy induces and impacts the biological tissue are through thermal effects and stimulant action. Whereas thermal effects occurs as a result of Joule heating, stimulant action is caused by excitation of the biological neurons and muscles owing to the induced current. Where stimulant action is measured in terms of current density J (A/m2), thermal effects is measured by specific absorption rate, SAR (W/kg). The work presents a simplified analytical modelling of the interaction between biological human tissues and radiant electromagnetic fields due to base station antennas. In terms of intensity of induced current density and SAR, the computed results obtained by means of the parametised analytical models are quantitatively presented and discussed.*

Keywords: *Directional Antennas; Radiant Electromagnetic Fields; Biological Tissues; Specific Absorption Rate' Induced Current Density.*

1. INTRODUCTION

The environment around human contains numerous sources of non ionizing radiation, which include, but not limited to: power lines, power stations, TV and radio repeaters, cable and satellite communications. Due to these sources, there exist a degree of interaction between the electromagnetic fields energy they generate and biological human tissue. Human tissues can absorb electromagnetic fields and induce conduction and displacement currents. This interaction between biological human tissues and radiated electromagnetic fields is influenced by a lot of factors in addition field frequency like dielectric properties, configured exposure source, field strength, age factor, time intensity factor, field location factor, geometry and size of the tissue, exposure environment, orientation and field polarization [1].The impact of these radiated fields can be detrimental to human tissues, especially at proximity, if the electromagnetic energy exceeds certain threshold value as recommended by some recognized international standard bodies like World Health Organization (WHO) and ICNRIP. Of late, it has been disclosed by WHO that the radiation from mobile phone potentially result to brain cancer [2-5].The International Agency of Research Cancer (IARC) has categorized electromagnetic fields into Group 2B that is carcinogenic to human. The need to also monitor the intensity electromagnetic radiations from mobile phone base station antennas has also been hinted by WHO [6].

To investigate the intensity and impacts of radiated electromagnetic energy on human tissues, the values of some essential field evaluation parameters, such as magnetic field strength, electric field strength, current density and specific absorption rates must be determined and compared with the afore mentioned internationally recognized permissible values. These field values can be assessed by means of numerical methods, analytical calculations, or by utilizing suitable measurement tools.

In spite of the fact that many electromagnetic radiation phenomena have been investigated as contained in literature [1-5, 7-23], however, interactions that exist between radiant electromagnetic fields and human organic matter, are still yet to be expressively clarified.

In terms of intensity of induced current density and specific absorption rate (SAR), the work presents a simplified analytical modelling of the interaction between biological humantissues and radiant electromagnetic fields due to base station antennas. The considered antenna radiation frequencies are 900, 2100, 2300, 2400 and 2500MHz.

2. RESEARCH METHODOLOGY

2.1. Electric Field Strength

Electromagnetic waves are waves with electric and magnetic field components, which created by oscillating charges, possess the same frequency by way of the oscillation and propagate at the speed of light. In telecommunication systems, radio frequency signals are transmitted in electromagnetic waves form. The electromagnetic waves carries energy and transfers them to objects or bodies placed in their propagation paths. The rate of flow of energy in propagating electromagnetic waves can be defined by a vector, S_p, termed the Pointing vector, and it is given by:

$$S_p = \frac{\vec{E} X \vec{B}}{\mu_0} \tag{1}$$

For plane electromagnetic waves wherein $\vec{E} X \vec{B} = EB$, equation (1) becomes:

$$S_p = \frac{EB}{\mu_0} \tag{2}$$

For the reason that $B = \frac{E}{c_0}$, then equation (2) yields:

$$S_p = \frac{E^2}{\mu_0 c} \tag{3}$$

Next, we introduce the intensity of electromagnetic waves, I_e and it is defined as the time average of S_p; that is:

$$I_e = \langle S_p \rangle = \frac{E^2}{2\mu_0 c} \tag{4}$$

Consider a base station with isotropic antenna which radiates energy in all directions in free space. By applying the law of conservation of energy, the constant net power emanating from the antenna can be expressed as:

$$P = \int I_e . dA \tag{5}$$

Where P and I_e indicate the radiated power and the intensity as a function of a position. dA expresses the differential element of the surface area in which the antenna is transmitting.

By integrating over a surface area of uniform intensity, equation (5) becomes:

$$P = |I_e| . A = I_e . 4\pi r^2 \tag{6}$$

Where r= radius of the sphere and $A = 4\pi r^2$

Solving for I_e in equation (6) gives:

$$Ie = \frac{P}{4\pi r^2} \tag{7}$$

Specifically, for a sector antenna which radiates directionally, equation (7) can be rewritten as:

$$Ie = \frac{PG(\phi, \theta)}{4\pi r^2} \tag{8}$$

Where $G(\phi, \theta$ defines the radiation pattern of the antenna.

So, from equations (4) and (8), we have:

$$Ie = \frac{E^2}{2\mu_0 c} = \frac{PG(\phi,\theta)}{4\pi r^2} \tag{9}$$

Equation (9) also implies that:

$$E = \sqrt{\frac{2\mu_0 cPG(\phi,\theta)}{4\pi r^2}} \tag{10}$$

For $\mu_0 = 4\pi \times 10^{-7} H/m, \varepsilon_0 = 8.85 \times 10^{-12} F/m,$ and

$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} = 3 \times 10^8 m/s^2$, equation (10) after simplification becomes:

$$E = 5.45\frac{\sqrt{PG(\phi,\theta)}}{r} \tag{11}$$

2.2. Induced Current Density and Specific Absorption Rate

The probe of how electromagnetic energy induces humans or how much electromagnetic energy is absorbed by the biological humans tissues should be provided with answer quantitatively as much as possible. Two basic ways in which electromagnetic energy induces and impacts the biological tissue are through thermal effects and stimulant action. Whereas thermal effects occurs as a result of Joule heating, stimulant action is caused by excitation of the biological neurons and muscles owing to the induced current. While stimulant action is measured in terms of current density J (A/m^2) and thermal effects is measured by specific absorption rate, SAR (W/kg).

The SAR can be determined as:

$$SAR = \frac{\sigma E^2}{\rho} \tag{12}$$

The expression in equation can also be rewritten as:

$$E = \sqrt{\frac{\rho SAR}{\sigma}} \tag{13}$$

The current density, J in tissue SAR and electric field strength by:

$$J = (\sigma\rho SAR)^{0.5} = \sigma E \tag{14}$$

σ and ρ indicates the electrical conductivity and the density of the biological tissue in (S/m) and (kg/m3) respectively.

Table 1 lists the recognized standard J and SAR values or requirements as prescribed by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) is listed in Table 1.

Table1. *Dielectric Properties of the Tissues at different Frequency [21- 23]*

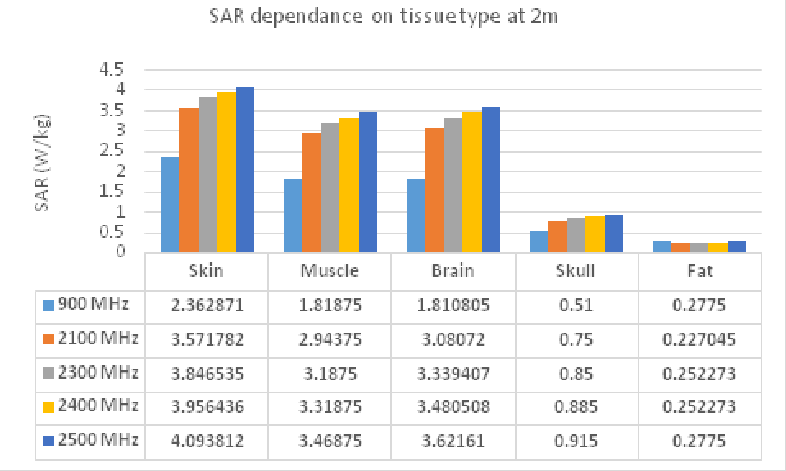
	900MHz		**2100MHz**		**2300 MHz**		**2400 MHz**		**2500MHz**		**Mass Density**
	ε_r	$\sigma(S/m)$	ε_r	$\sigma(S/m)$	ε_r	$\sigma(S/m)$	ε_r	$\sigma(S/m)$	ε_r	$\sigma(S/m)$	$\rho(kg/m^3)$
CSF	68.6	2.41	66.76	3.15	66.47	3.32	66.32	3.41	66.17	3.50	1030
DURA	44.4	0.96	42.49	1.47	42.23	1.58	42.10	1.64	11.29	0.42	1030
Brain	45.80	0.77	43.05	1.31	42.75	1.42	42.61	1.48	42.47	1.54	1030
Muscle	55.90	0.97	54.04	1.57	53.77	1.70	53.64	1.77	53.51	1.85	1480
Skin	43.88	0.86	38.43	1.31	38.18	1.40	38.06	1.44	37.95	1.49	1010
Skull	20.80	0.34	15.28	0.51	15.10	0.56	15.01	0.59	14.92	0.61	1850
Fat	11.30	0.11	5.32	0.09	5.30	0.10	5.28	0.10	5.27	0.11	920

3. RESULTS AND DISCUSSION

3.1. SAR

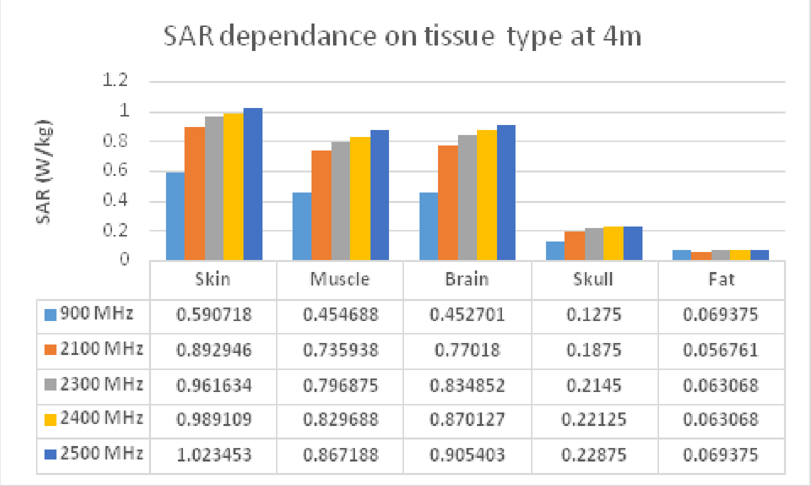
The SAR values dependence on tissue type are plotted in Figs. 1 to 3 at 2, 4 and 6m calculation distances, respectively. The tissues are listed in the slithering order of their computed SAR values.

The three highest SAR values in figure 1 to 3 are obtained for the skin, muscle and brain tissues, owing to their closeness to the body surface. The plots imply that the SAR values of the biological organs closer to the body surface are higher than ones away from the surface. Generally, it is expected that the closer a tissue is to the transmitting antenna, the more expose the tissue is to the antenna's radiated electromagnetic energy and the higher the SAR values. This also implies that the penetration depth of electromagnetic energy into the tissues decreases with increasing distance from base station antennas locations.



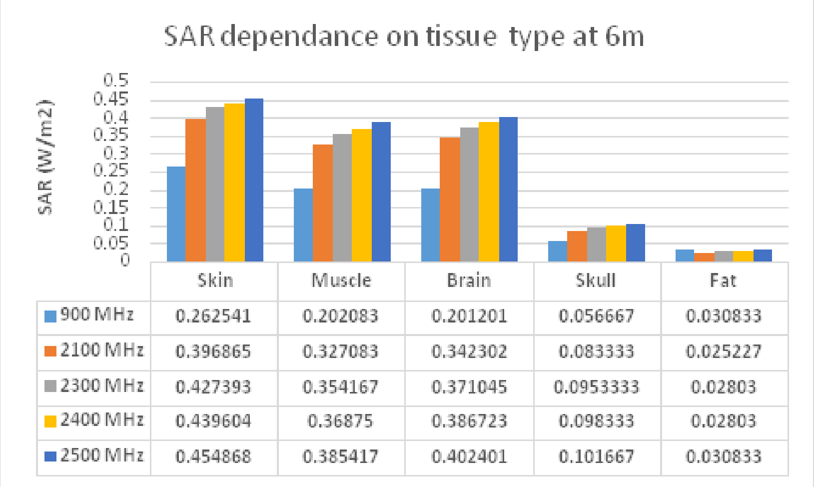
	Skin	Muscle	Brain	Skull	Fat
■ 900 MHz	2.362871	1.81875	1.810805	0.51	0.2775
■ 2100 MHz	3.571782	2.94375	3.08072	0.75	0.227045
■ 2300 MHz	3.846535	3.1875	3.339407	0.85	0.252273
■ 2400 MHz	3.956436	3.31875	3.480508	0.885	0.252273
■ 2500 MHz	4.093812	3.46875	3.62161	0.915	0.2775

Figure1. *SAR dependence on biological tissue type at 2m calculation distance*



	Skin	Muscle	Brain	Skull	Fat
■ 900 MHz	0.590718	0.454688	0.452701	0.1275	0.069375
■ 2100 MHz	0.892946	0.735938	0.77018	0.1875	0.056761
■ 2300 MHz	0.961634	0.796875	0.834852	0.2145	0.063068
■ 2400 MHz	0.989109	0.829688	0.870127	0.22125	0.063068
■ 2500 MHz	1.023453	0.867188	0.905403	0.22875	0.069375

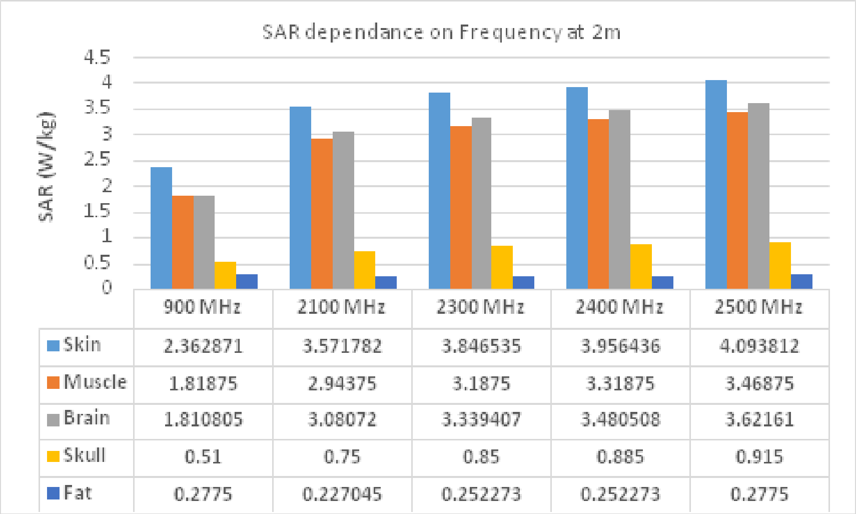
Figure2. *SAR dependence on biological tissue type at 4m calculation distance*



	Skin	Muscle	Brain	Skull	Fat
■ 900 MHz	0.262541	0.202083	0.201201	0.056667	0.030833
■ 2100 MHz	0.396865	0.327083	0.342302	0.083333	0.025227
■ 2300 MHz	0.427393	0.354167	0.371045	0.0953333	0.02803
■ 2400 MHz	0.439604	0.36875	0.386723	0.098333	0.02803
■ 2500 MHz	0.454868	0.385417	0.402401	0.101667	0.030833

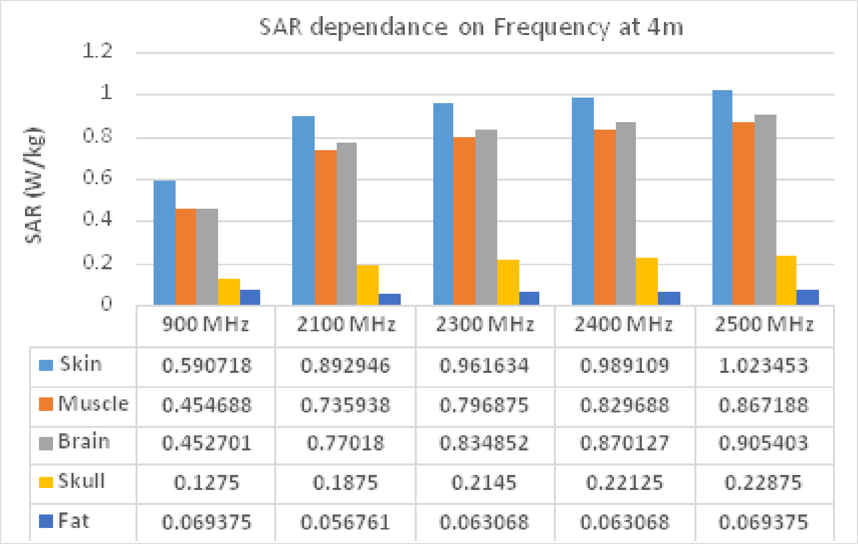
Figure3. *SAR dependence on biological tissue type at 6m calculation distance*

The base station operating frequencies dependence of the SAR values of biological human tissue are plotted in Figs. 4 to 6 at 2, 4, and 6m calculation distances. Accordingly, the largest SAR value is attained at 2500MHz and the least at value at 900MHz. This is because of dominant relative permittivity at higher frequency, thus leading to increase in the SAR values.



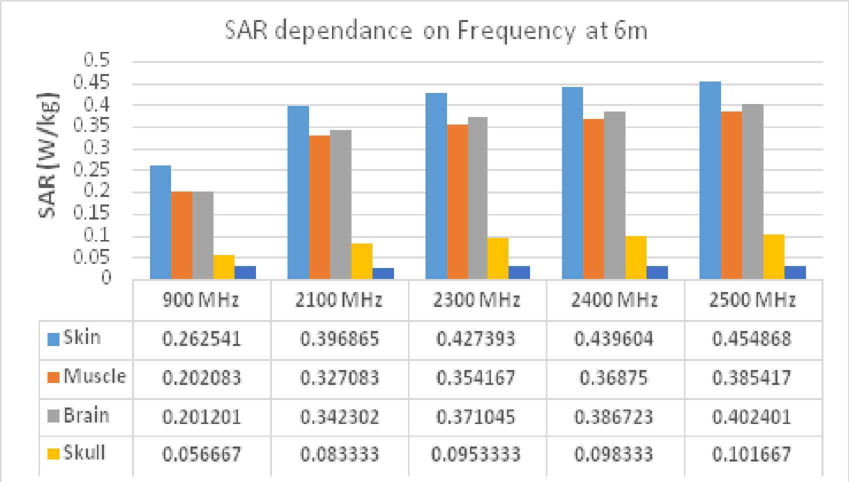
	900 MHz	2100 MHz	2300 MHz	2400 MHz	2500 MHz
Skin	2.362871	3.571782	3.846535	3.956436	4.093812
Muscle	1.81875	2.94375	3.1875	3.31875	3.46875
Brain	1.810805	3.08072	3.339407	3.480508	3.62161
Skull	0.51	0.75	0.85	0.885	0.915
Fat	0.2775	0.227045	0.252273	0.252273	0.2775

Figure4. *SAR dependence on Antenna Frequency at 2m calculation distance*



	900 MHz	2100 MHz	2300 MHz	2400 MHz	2500 MHz
Skin	0.590718	0.892946	0.961634	0.989109	1.023453
Muscle	0.454688	0.735938	0.796875	0.829688	0.867188
Brain	0.452701	0.77018	0.834852	0.870127	0.905403
Skull	0.1275	0.1875	0.2145	0.22125	0.22875
Fat	0.069375	0.056761	0.063068	0.063068	0.069375

Figure5. *SAR dependence on Antenna Frequency at 4m calculation distance*

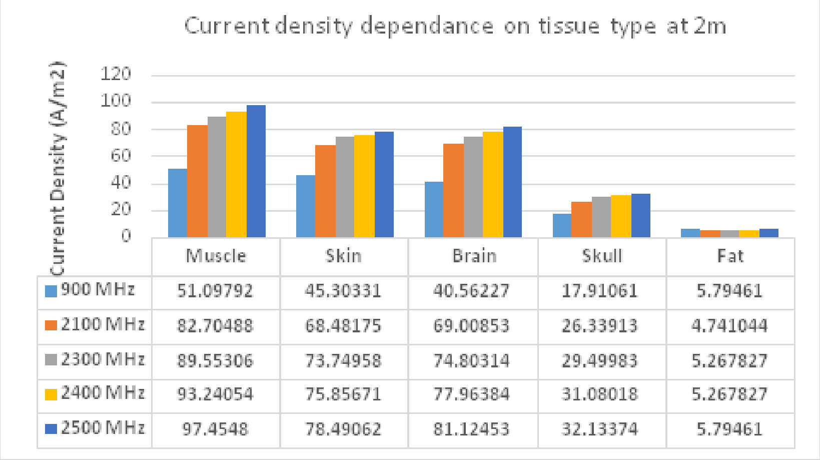


	900 MHz	2100 MHz	2300 MHz	2400 MHz	2500 MHz
Skin	0.262541	0.396865	0.427393	0.439604	0.454868
Muscle	0.202083	0.327083	0.354167	0.36875	0.385417
Brain	0.201201	0.342302	0.371045	0.386723	0.402401
Skull	0.056667	0.083333	0.0953333	0.098333	0.101667

Figure6. *SAR dependence on Antenna Frequency at 6m calculation distance*

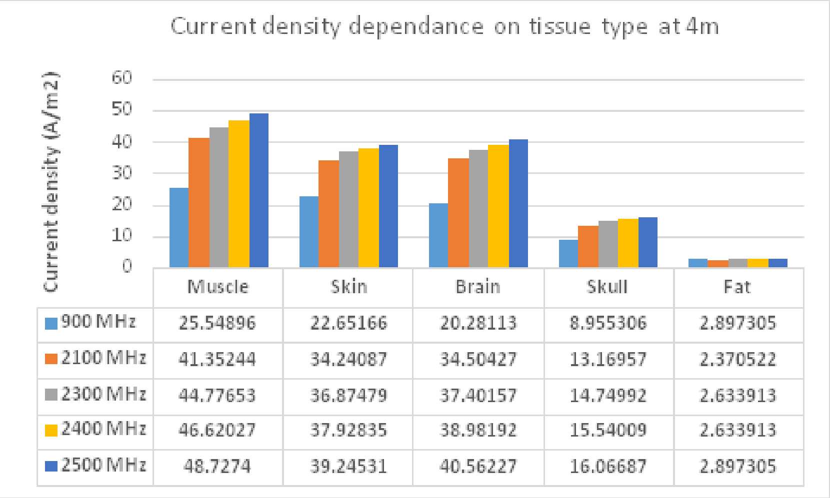
3.2. Induced Current Density

The current density values dependence on tissue type and base station operating frequencies are plotted in Figs. 7 to 12 at 2, 4 and 6m calculation distances, respectively. The three highest current density values in figure 7 to 9 are obtained for the muscle, skin and brain tissues, owing to their higher water contents and dielectric properties. The plots imply that the amount current density induces into the biological tissues ate tied to their water contents and dielectric properties.



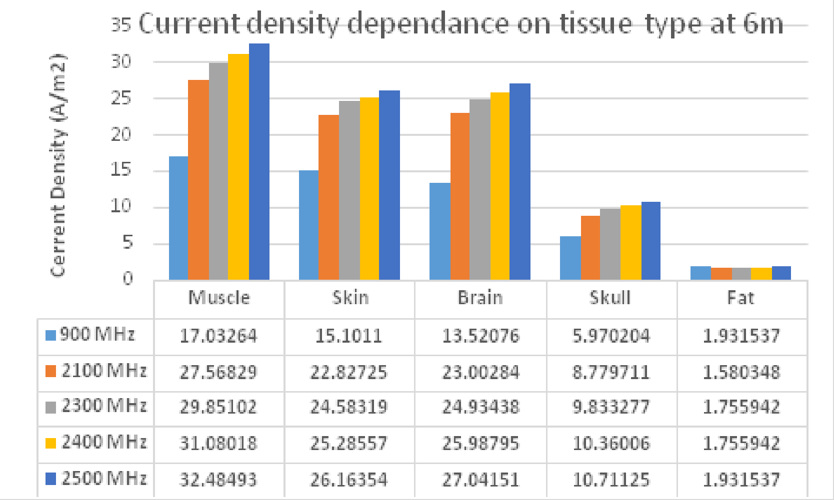
	Muscle	Skin	Brain	Skull	Fat
900 MHz	51.09792	45.30331	40.56227	17.91061	5.79461
2100 MHz	82.70488	68.48175	69.00853	26.33913	4.741044
2300 MHz	89.55306	73.74958	74.80314	29.49983	5.267827
2400 MHz	93.24054	75.85671	77.96384	31.08018	5.267827
2500 MHz	97.4548	78.49062	81.12453	32.13374	5.79461

Figure7. *Current density dependence on tissue type at 2m calculation distance*



	Muscle	Skin	Brain	Skull	Fat
900 MHz	25.54896	22.65166	20.28113	8.955306	2.897305
2100 MHz	41.35244	34.24087	34.50427	13.16957	2.370522
2300 MHz	44.77653	36.87479	37.40157	14.74992	2.633913
2400 MHz	46.62027	37.92835	38.98192	15.54009	2.633913
2500 MHz	48.7274	39.24531	40.56227	16.06687	2.897305

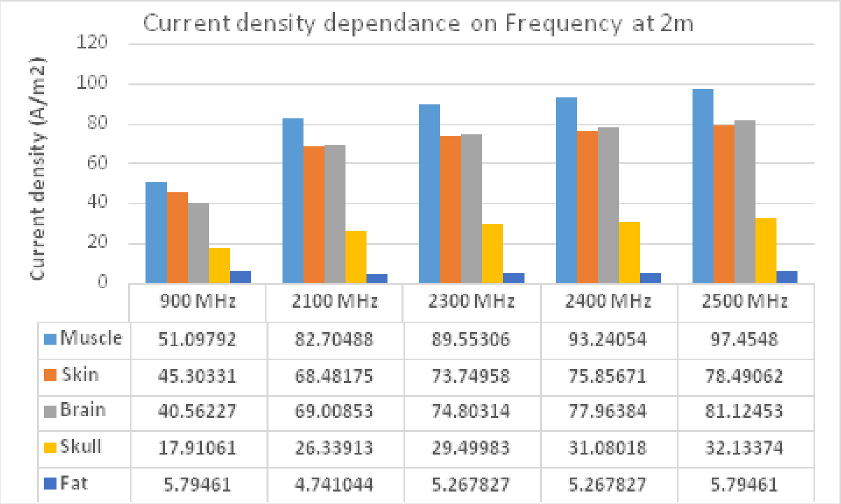
Figure8. *Current density dependence on tissue type at 4m calculation distance*



	Muscle	Skin	Brain	Skull	Fat
900 MHz	17.03264	15.1011	13.52076	5.970204	1.931537
2100 MHz	27.56829	22.82725	23.00284	8.779711	1.580348
2300 MHz	29.85102	24.58319	24.93438	9.833277	1.755942
2400 MHz	31.08018	25.28557	25.98795	10.36006	1.755942
2500 MHz	32.48493	26.16354	27.04151	10.71125	1.931537

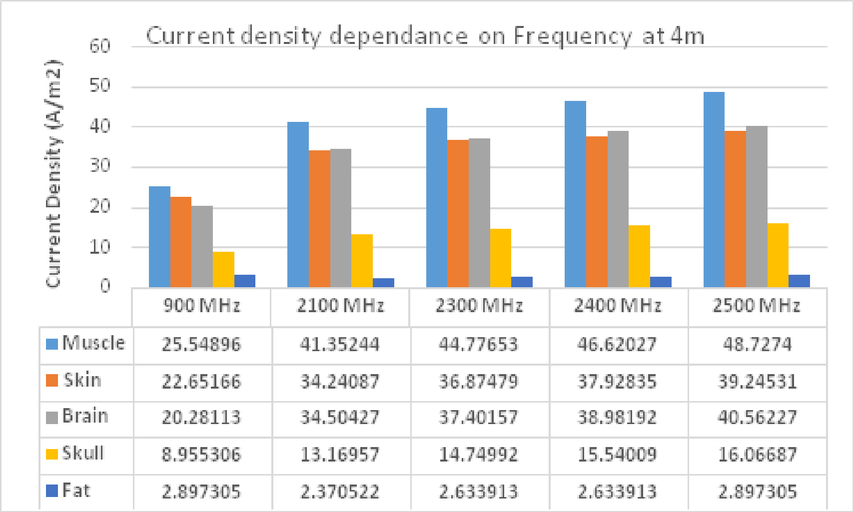
Figure9. *Current density dependence on tissue type at 6m calculation distance*

In terms of the base station operating frequencies, largest current density value is attained at2500MHz for muscle and the least at value at 900MHz for fat. This is because relative permittivity and conductivity of biological tissues increases with frequency, thus leading to increase in the current density values.



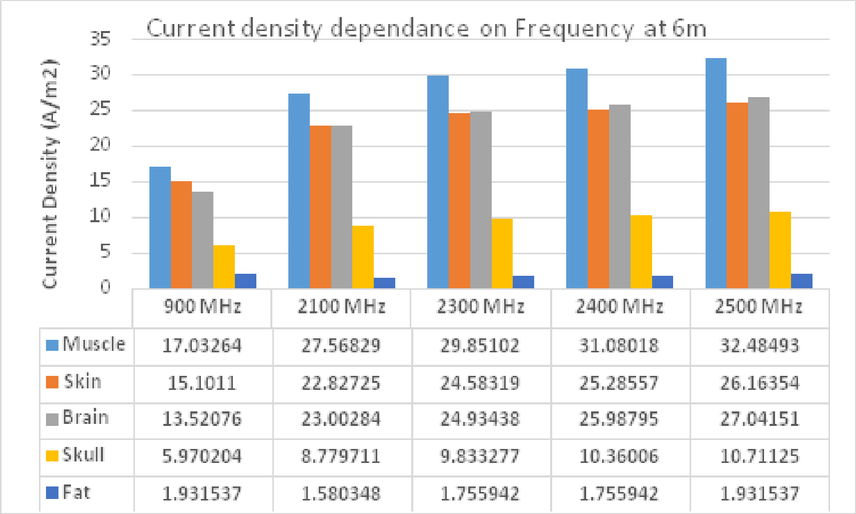
	900 MHz	2100 MHz	2300 MHz	2400 MHz	2500 MHz
Muscle	51.09792	82.70488	89.55306	93.24054	97.4548
Skin	45.30331	68.48175	73.74958	75.85671	78.49062
Brain	40.56227	69.00853	74.80314	77.96384	81.12453
Skull	17.91061	26.33913	29.49983	31.08018	32.13374
Fat	5.79461	4.741044	5.267827	5.267827	5.79461

Figure10. *Current density dependence on Frequency at 2m calculation distance*



	900 MHz	2100 MHz	2300 MHz	2400 MHz	2500 MHz
Muscle	25.54896	41.35244	44.77653	46.62027	48.7274
Skin	22.65166	34.24087	36.87479	37.92835	39.24531
Brain	20.28113	34.50427	37.40157	38.98192	40.56227
Skull	8.955306	13.16957	14.74992	15.54009	16.06687
Fat	2.897305	2.370522	2.633913	2.633913	2.897305

Figure11. *Current density dependence on Frequency at 4m calculation distance*



	900 MHz	2100 MHz	2300 MHz	2400 MHz	2500 MHz
Muscle	17.03264	27.56829	29.85102	31.08018	32.48493
Skin	15.1011	22.82725	24.58319	25.28557	26.16354
Brain	13.52076	23.00284	24.93438	25.98795	27.04151
Skull	5.970204	8.779711	9.833277	10.36006	10.71125
Fat	1.931537	1.580348	1.755942	1.755942	1.931537

Figure12. *Current density dependence on Frequency at 6m calculation distance*

4. CONCLUSION

In telecommunication systems, radio frequency signals are transmitted in electromagnetic waves form. The electromagnetic waves carries energy and transfers them to objects or bodies placed in their propagation paths. For health purpose, the probe of how electromagnetic waves induces humans or how much electromagnetic energy is absorbed by the biological human tissues should be provided with answer quantitatively as much as possible. Two basic ways in which electromagnetic energy induces and impacts the biological tissue through thermal effects and stimulant action. Whereas thermal effects occurs as a result of Joule heating, stimulant action is caused by excitation of the biological neurons and muscles owing to the induced current.

The work presents a simplified analytical modelling of the interaction between biological human tissues and radiant electromagnetic fields due to base station antennas. In terms of induced current density and *SAR* levels, the results obtained by means of the simplified analytical models has been quantitatively computed, presented and discussed. The results reveal that the specific rate of absorption and induced current density are strongly dependent of the radiofrequency, orientation and intensity of the incident electromagnetic fields, tissue type and its constituent dielectric properties (relative permittivity and conductivity).

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