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ASSESSMENT OF RADIOFREQUENCY RADIATION LEVELS OF MOBILE PHONES AND EVALUATION OF SPECIFIC ABSORPTION RATE TO TISSUES OF HUMAN HEAD LAYERS

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Abstract: This study is aimed at accessing and quantifying the dosimetry quantities of radiofrequency radiation of mobile phones used in Delta State, Nigeria. In-situ measurement of electric (E)-field, magnetic (H)-field strengths and power density of 98 mobile phones of different brands and models from different individuals in different towns of Delta State was done in an isolated unit using electrosmog meter model no. 070117199 from LESSEMF, USA. The values obtained were compared with the International Commission on Non-Ionizing Radiation Protection (ICNIRP) recommended safety limits for general public exposure to non-ionizing electromagnetic radiation. The E-field strengths together with available data on dielectric properties and density of various tissues of the head layers were used to evaluate the specific absorption rate (SAR) to six tissue layers of the head. The cerebrospinal fluid (CSF) with conductivity higher than the rest tissues has SAR values higher than the other tissues layer. Apparently, it is observed that the SAR values increase with tissues conductivity and drop with the increment in tissues density. The localized average SAR to the human head due to the contribution of the various tissues for all the phones investigated ranges from 0.001-6.972 W/kg which shows that some phones have localized SAR that are above ICNIRP 2.0 W/kg recommended safe limit which implicate higher penetration of electromagnetic radiation towards the head, thus, more absorption of radiation power by the head tissues which can lead to localized tissue heating.

Keywords: Radiofrequency radiation, specific absorption rate, mobile phones, head tissues

Introduction

Mobile phones have become an integral part of our life; providing services that range from phone calls, Bluetooth connections, internet connections and information sharing via online media. No doubt, the development and use of mobile phones and other telecommunication devices, in general, are associated with relaying information via electromagnetic waves or signals. There is virtually no device that operates on wireless technology that does not make use of electromagnetic field (EMF) radiofrequency (RF) radiations (Ayinmode and Farai, 2013). The intensity of radiofrequency pollution in the environment has increased in the recent years due to new technological improvements in wireless devices and the ease of access to mobile phones. The rise and widespread use of mobile phones and the consequent exposure to electromagnetic RF radiation has continued to generate deep interest in the radiation science community. The possible side-effects of RF radiation on living organisms has caused some measures of concern and at same time stimulated wide and often controversial debates about the potential cancerogenic effects triggered by excessive exposure to RF fields (Danese *et al.*, 2017).

Radiofrequencies are part of the spectrum of Ultra High Frequencies (UHFs), which designates a range of electromagnetic waves with frequencies ranging from 300 MHz to 3 GHz. In particular, those used by the global system for mobile communication (GSM) starts from 900 MHz band (Danese *et al.*, 2017). In different parts of the world, mobile phone networks utilize different frequency bands and different forms of RF signal modulations that enable phones to carry information. In Europe, for example, mobile phones work on 900 and 1800 MHz bands (Mustafa, 2017). Based on their photon energy, which is less than 1.2 MeV (Danese *et al.*, 2017), RFs are classified as non-ionizing radiation since they are virtually unable to generate atomic ionization. A particularly important issue, however, is that non-ionizing radiations have the ability to penetrate through semi-solid substances to a distance proportional to its power density and may be absorbed by biological systems, leading to possible dissociation of molecules and dissipation of energy in the form of heat (that is thermal effect). At communication frequency, human body behaves as a dielectric and EM radiation generated by mobile phone base stations are able to penetrate through substances like living tissues and meat (Ojuh and Isabona, 2015). It is a widespread opinion that mobile phones cause heating of the human body tissues and organs, especially the human head. Some of the possible negative health effects from RF fields presented in scientific reviews have been related to an increase in body temperature from exposure at very high field intensity (WHO, 2006). The consequences of excessive heating in the body vary from temporary disturbances in cell functions to permanent destruction of tissues (Bennet *et al.*, 2017). There is also a concern about the effect of cumulative RF radiation resulting from continuous exposure. This has led to serious debates that long term EM radiation exposure may lead to some diseases like cancer and leukemia (Felix *et al.*, 2017). Symptoms like sleep disorders, headaches, irritability, dizziness, appetite loss, nervousness, fatigue, depression, discomfort, concentration difficulties and many more have also been linked to excess exposure to RF field (Mild *et al.*, 1998; Hutter *et al.*, 2006; Pllana *et al.*, 2007; Chakraborty and Singh, 2013; Felix *et al.*, 2017). The World health organization (WHO) International Agency for Research on Cancer (IARC) has classified RF-EMFs as possibly carcinogenic to humans, based on an increased risk for glioma, a malignant type of brain cancer, associated with wireless phone use (WHO, 2011).

The basic dosimetric quantities for characterizing RF radiation energy in a given medium are the power density, S (W/m^2), electric field strength, E (V/m), magnetic field strength, H (A/m), and the specific absorption rate, SAR (W/Kg). These quantities are mostly assessed in air and may be used to directly estimate the exposure to RF energy in a body (Ayinmode and Farai, 2013). The interaction of electromagnetic field radiation with biological systems is characterized by the electromagnetic properties of tissue media, more specifically, the permittivity and permeability. Generally, assessment of EM RF radiation from mobile phones and base stations is based on the evaluation of specific absorption rate (SAR) which is an indication of the amount of electromagnetic energy absorbed by biological tissues. Specifically, SAR is defined as the power absorbed per unit mass of tissue, usually averaged either over the whole body or over a small sample volume, typically 1 g or 10 g of tissue (Zhang and Alden, 2011). The International Commission on Non-Ionizing Radiation Protection (ICNIRP, 1998) and the Institute of Electrical and Electronics Engineers (IEEE, 2005) have established safety guidelines and standard for limiting electromagnetic fields exposure. These guidelines and standard define basic restrictions which specify SAR limits not to be exceeded. These guidelines have been adopted by most countries as the basic limits on SAR to prevent adverse health effects related to whole-body heat stress and excessive localized tissue heating for frequencies between 3 kHz and 300 GHz (Zhang and Alden, 2011).

With the current state of mobile phone deployment with new technologies and the ease of access to them, the general public is exposed to radiofrequency radiation from mobile phones and their base masts. This suggests the need for an assessment of the FR characterization of different phone brands and evaluation of SAR to different tissues of the body that will provide the public useful information about the possible health consequences. This study is therefore aimed at accessing and quantifying the E-filed, H-field and the power density of commonly used mobile phones from different individuals within Delta State, Nigeria and also to evaluate the SAR to different tissues of the head.

Materials and Methods

Theoretical framework

A time-varying electric field induced magnetic field and vice versa. This mutual relationship between electric and magnetic fields results in the phenomenon of wave propagation. The foremost outcome of Maxwell's equation was the prediction of the existence of electromagnetic waves (EMW) and Maxwell proved that an electromagnetic disturbance that originated from one charged body would travel out as an electromagnetic wave with velocity of light in free space (Arun-Murthy, 2008). Maxwell's equations for a time-varying EM field are;

$$\nabla \times E = -\mu \frac{\partial H}{\partial t} \qquad \text{(1a)}$$

$$\nabla \cdot E = \frac{\rho}{\varepsilon} \qquad \text{(1b)}$$

$$\nabla \times H = J + \varepsilon \frac{\partial E}{\partial t} \qquad \text{(1c)}$$

$$\nabla \cdot H = 0 \qquad \text{(1d)}$$

Where E and H are electric and magnetic field strengths, respectively, J $(= \sigma E)$ is the current density, ρ is charge density, σ is conductivity, ε and μ are permittivity and permeability, respectively. The manipulations of these equations give the EM wave equation.

The E-field and H-field strengths are vector quantities expressed in Volt per meter (V/m) and Ampere per meter (A/m), respectively. Both fields are mathematically interdependent (Isabona *et al.*, 2016), implying that either the magnitude of the E-field or H-field has to be measured. As knowing the E-field for instance, one can determine the H-field and vice versa. The power density, S of an electromagnetic wave is related to the E-field and H-field vectors by using the Poynting vector;

$$S = E \times H \qquad (2)$$

The magnitude of the average power density or power flow per unit area is then given as

$$S = \frac{E^2}{\eta} = \eta H^2 \qquad (3)$$

Where η is the characteristic wave impedance, which for free space, is defined as

$$\eta = \sqrt{\frac{\mu_o}{\varepsilon_o}} = 120\pi = 377\Omega \qquad (4)$$

Thus (3) becomes

$$S = \frac{E^2}{120\pi} = 377H^2 \qquad (5)$$

Exposure to time-varying EMF results in internal body currents and energy absorption in tissues that depend on the coupling mechanisms and the frequency involved (Panagopoulos *et al.*, 2013). The time derivative of the incremental energy, *dW* absorbed by an incremental mass, *dm* of tissue contained in a volume element, *dV* of a given density ρ is defined as the specific absorption rate of an EMF (IEEE, 2005), that is;

$$SAR = \frac{d}{dt}\left(\frac{dP}{dm}\right) = \frac{d}{dt}\left(\frac{dP}{\rho dV}\right) \qquad (6)$$

Where $dm = \rho dV$ (ρ in kg/m^3). The S.I. unit of SAR is Watt per kilogram (W/kg).

The SAR can be related to the electric field at a point by (IEEE, 2005);

$$SAR = \frac{\sigma E^2}{\rho} \qquad (7)$$

Where σ is conductivity of the tissue (S/m), ρ is mass density of the tissue (kg/m^3) and E is rms electric field strength in tissue (V/m). The conductivity varies for different tissues and different field frequencies (Panagopoulos *et al.*, 2013). Equation 7 shows that SAR is proportional to the square of the internal electric field strength. According to ICNIRP (1998), values of SAR depend on the following factors: (1) the incident field parameters, i.e., the frequency, intensity, polarization, and source–object configuration (near or far-field); (2) the characteristics of the exposed body, i.e., its size and internal and external geometry, and the dielectric properties of the various tissues; and (3) ground effects and reflector effects of other objects in the field near the exposed body.

For an homogeneous medium (neglecting the local density variations) with specific heat c, in J/kg.K, (neglecting also the local variations in the specific heat) and by use of a form of the calorimetry law (Panagopoulos *et al.*, 2013);

$$\frac{dQ}{dt} = mc\frac{dT}{dt} \qquad (8)$$

SAR is related to the specific heat, *c* (Panagopoulos *et al.*, 2013) as;

$$SAR = c\frac{dT}{dt} \qquad (9)$$

Where $\frac{dQ}{dt}$ is the wave power, transformed into an incremental amount of heat dQ, within the tissue of mass *m*, producing an incremental temperature increase dT during the incremental time interval dt .

For a measurable time interval, Δt and a corresponding measurable temperature increase, ΔT Equ (9) can be written as:

$$SAR = c\frac{\Delta T}{\Delta t} \qquad (10)$$

Measurement of E, H-fields, power density S and SAR evaluation

Electromagnetic RF dosimetric information is very important to protect humans from probable electromagnetic field health hazards. Most studies on EMF RF assessment and SAR calculations involve numerical modeling, like the Finite Difference Time Domain (FDTD) which simulates the spatial distribution of the radiation energy within an object having dimensions similar to that of the human body and subsequent computation of SAR. This method of assessment is based on users' defined parameters. For on the spot and accurate assessment, field measurement is usually preferred. This involves the use of electromagnetic RF survey meters or detectors which directly measure the field quantities from the source at different point of interest.

In this study therefore, the E, H fields and power density, S of 98 mobile phones of different models and brands from different individuals within Delta State, Nigeria were measured using electrosmog meter model no. 070117199 from LESSEMF, USA. The measurement was done in an isolated unit to avoid direct interference from other RF sources. For each measurement, the background RF field measurement was done and this was subsequently subtracted. The measured values were compared with international stipulated standard for limiting electromagnetic fields exposure. To precisely quantify the rate of RF radiation absorption to different tissues of the head from the phones at defined frequency of 1800 MHz, the specific absorption rates (SAR) were calculated using the measured E-field strength, dielectric property (relative permittivity, ε and electrical conductivity, σ) and density, ρ of the head tissues using Equ. (7). The head tissues of interest are the *skin, fat, bone (Skull) dura mater, brain and cerebrospinal fluid (CSF).* The dielectric properties and density of the tissues were extracted from (Sabbah *et al.*, 2011) and are presented in Tables 1 and 2, respectively.

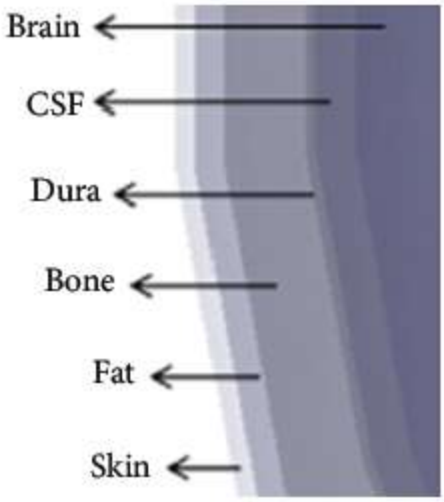
One-way analysis of variance (ANOVA) and correlation coefficient of the data were done to assess the level of significance and influence of the E-field, H-field and power density on the SAR. Results of testing were considered significant at $p \leq 0.05$. All statistical analysis of data was performed using IBM SPSS 25.0 (SPSS Inc., Chicago, IL, USA) software.

Table 1: Conductivity and relative permittivity of the layers of the human head

Tissue	Conductivity (S/m)		Relative permittivity	
	900MHz	1800MHz	900MHz	1800MHz
Skin	0.87	1.18	41.4	38.9
Fat	0.051	0.078	5.46	5.34
Bone (skull)	0.14	0.28	12.45	11.8
Dura	0.96	1.32	44.4	42.9
CSF	2.41	2.92	68.7	67.2
Brain	0.77	1.15	45.8	43.5

Table 2: Tissues density of layers of the human head

Tissues	Skin	Fat	Bone (skull)	Dura	Brain	CSF
Density (kg/m^3)	1100	920	1850	1050	1030	1060



Source: Khodabakhshi and Cheldavi (2010)

Fig. 1: The perspective of Six-layer human head model

Results and Discussion

E-field, H-field and power density, S values

The results of the measured E-field, H-field and power density, S values for the different mobile cell phones investigated and their corresponding SAR to different tissues of the human head layers are presented in Tables 3 to 7 according to phone brands. Table 8 shows ICNIRP recommended safe limits for E-field, H-field strengths, power density, *S* and whole body and localized SAR at 900 MHz, 1800 MHz and 2100 MHz frequencies. In all the 98 mobile phones studied, the E-field ranges from 0.98 – 80.61 V/m, the H-field values range from 2.59 – 138.20 mA/m and the power densities range from 0.01 – 70.90 W/m^2. Samsung GT-88530, Tecno T21 and Samsung S4 have the maximum E-field, H-field and power density, respectively with values of 80.61 V/m, 138.20 mA/m and 70.90 W/m^2, respectively. Minimum E-field 0.98 V/m and H-field 2.59 mA/m were found in Itel 1452 while minimum power density of 0.01 W/m^2 was observed in Itel 1452, Itel 5120, Nokia Asha 302, Nokia Lumia X2. The power densities of Nokia 302 and Lumia 520 were below detection limits (BDL). Statistically, the measured E-field, H-field strengths and power density of Blackberry phones, Samsung phones, Nokia phones, Itel phones, HTC phones, Infinix phones and I Phones were all significant at $p \leq 0.05$. For Tecno phones, the power density shows no significance at $p \leq 0.05$. The observed differences in the measured cell phone RF radiation parameters are attributed to factors such as phone model, antenna strength and frequency range. Other factors that have been identified in literature (Vrijheid *et al.*, 2009; Olorunfemi *et al.*, 2016) are phone casing, brand of phone, signal reception condition, age of phone, battery level, etc. The standard error at 95% confidence, for all the phone models, range from 0.14 – 1.86 for the E-fields, 1.49 – 8.36 for H-fields and 0.16 – 6.84 for power density. The variation between the E-field, H-field and the power density in the investigated phones might be due to the observed errors as no definite pattern or relationship between the variables could be established.

Table 3: E-field, H-field, power density values of blackberry phone models and SAR to different tissues of the head

Blackberry (BB) phone model	E-field V/m	H-field mA/m	S W/m^2	SAR to tissues of the head layers W/kg						Average SAR to human head W/kg
				Skin	Fat	Bone (skull)	Dura	CSF	Brain	
BB 9700	6.30	18.00	0.10	0.043	0.003	0.006	0.050	0.109	0.044	0.043
BB 9930	7.50	19.00	0.30	0.060	0.005	0.009	0.071	0.155	0.063	0.061
BB 8520	9.80	22.00	0.20	0.103	0.008	0.015	0.121	0.265	0.107	0.103
BB bold 5	5.30	24.00	0.30	0.030	0.002	0.004	0.035	0.077	0.031	0.030
BB Q10	9.40	19.20	0.40	0.095	0.007	0.013	0.111	0.243	0.099	0.095
BB 310	10.30	17.80	0.30	0.114	0.009	0.016	0.133	0.292	0.118	0.114
BB 9900	9.10	20.00	0.30	0.089	0.007	0.013	0.104	0.228	0.092	0.089
BB Q5	10.90	20.00	0.30	0.127	0.010	0.018	0.149	0.327	0.133	0.127
BB torch 1	8.70	21.20	0.20	0.081	0.006	0.011	0.095	0.209	0.085	0.081
BB torch 2	9.40	20.80	0.30	0.095	0.007	0.013	0.111	0.243	0.099	0.095
BB curve 2	8.30	21.60	0.40	0.074	0.006	0.010	0.087	0.190	0.077	0.074
BB curve 3	7.60	22.80	0.20	0.062	0.005	0.009	0.073	0.159	0.064	0.062
BB curve 4	6.50	23.10	0.30	0.045	0.004	0.006	0.053	0.116	0.047	0.045
BB bold 6	9.30	24.70	0.30	0.093	0.007	0.013	0.109	0.238	0.097	0.093
BB bold 2	5.60	18.00	1.70	0.034	0.003	0.005	0.039	0.086	0.035	0.034
BB bold 1	4.50	18.30	0.50	0.022	0.002	0.003	0.025	0.056	0.023	0.022

Table 4: E-field, H-field, Power density values of Tecno phone models and SAR to different tissues of the head

Tecno phone model	E-field V/m	H-field mA/m	S W/m^2	SAR to tissues of the head layers W/kg						Average SAR to human head W/kg
				Skin	Fat	Bone (skull)	Dura	CSF	Brain	
Tecno phantom	2.00	3.70	2.80	0.004	0.000	0.001	0.005	0.011	0.004	0.004
Tecno D7	22.31	59.18	1.32	0.534	0.042	0.075	0.626	1.371	0.556	0.534
Tecno M3	15.27	40.50	0.62	0.250	0.020	0.035	0.293	0.642	0.260	0.250
Tecno D5	21.23	56.31	1.20	0.483	0.038	0.068	0.567	1.242	0.503	0.484
Tecno H5	20.92	55.49	1.16	0.469	0.037	0.066	0.550	1.206	0.489	0.470
Tecno T605	23.95	63.54	1.52	0.615	0.049	0.087	0.721	1.580	0.640	0.615
Tecno T630	13.08	34.69	0.45	0.184	0.015	0.026	0.215	0.471	0.191	0.184
Tecno L3	45.45	120.50	5.48	2.216	0.175	0.313	2.597	5.690	2.306	2.216
Tecno M6	22.84	59.00	1.31	0.560	0.044	0.079	0.656	1.437	0.582	0.560
Tecno T1506	12.71	33.72	0.43	0.173	0.014	0.024	0.203	0.445	0.180	0.173
Tecno H7	30.43	80.71	2.46	0.993	0.079	0.140	1.164	2.551	1.034	0.994
Tecno T430	48.00	127.30	6.11	2.472	0.195	0.349	2.896	6.347	2.572	2.472
Tecno S3	50.61	134.20	6.80	2.748	0.217	0.388	3.220	7.056	2.860	2.748
Tecno T21	52.10	138.20	7.20	2.912	0.230	0.411	3.412	7.477	3.031	2.912
Tecno G9	14.80	39.26	0.58	0.235	0.019	0.033	0.275	0.603	0.245	0.235
Tecno T35	12.04	31.96	0.39	0.156	0.012	0.022	0.182	0.399	0.162	0.156
TecnoT431	6.70	17.77	0.12	0.048	0.004	0.007	0.056	0.124	0.050	0.048
Tecno P5 plus	31.22	82.83	2.59	1.046	0.083	0.148	1.225	2.685	1.088	1.046
Tecno P5	30.12	79.91	2.41	0.973	0.077	0.137	1.140	2.499	1.013	0.973

Table 5: E-field, H-field, Power density values of Samsung phone models and SAR to different tissues of the head

Samsung phone model	E-field V/m	H-field mA/m	S W/m^2	SAR to tissues of the head layers W/kg						Average SAR to human head W/kg
				Skin	Fat	Bone (skull)	Dura	CSF	Brain	
Note 4	28.76	76.31	2.20	0.887	0.070	0.125	1.040	2.279	0.906	0.885
Note 2	28.15	76.00	2.18	0.850	0.067	0.120	0.996	2.183	0.885	0.850
Note 3	31.00	82.23	2.55	1.031	0.081	0.145	1.208	2.647	1.073	1.031
Tab 1	22.84	59.00	1.31	0.560	0.044	0.079	0.656	1.437	0.582	0.560
Tab 3	23.95	63.54	1.52	0.615	0.049	0.087	0.721	1.580	0.640	0.615
Tab 2	21.23	56.31	1.20	0.483	0.038	0.068	0.567	1.242	0.503	0.484
Galaxy grand	12.89	34.20	0.44	0.178	0.014	0.025	0.209	0.458	0.186	0.178
Galaxy S3	28.76	76.31	2.20	0.887	0.070	0.125	1.040	2.279	0.924	0.888
Galaxy S2	28.62	75.91	2.17	0.879	0.069	0.124	1.030	2.256	0.915	0.879
Duos-mini	16.07	42.64	0.69	0.277	0.022	0.039	0.325	0.711	0.288	0.277
Y Duos	44.09	116.90	5.16	2.085	0.165	0.294	2.444	5.355	2.170	2.086
GT-88530	80.61	21.38	0.17	6.971	0.551	0.983	8.169	17.900	7.255	6.972
S4	5.40	18.00	70.90	0.031	0.002	0.004	0.037	0.080	0.033	0.031
S3	3.20	20.00	69.80	0.011	0.001	0.002	0.013	0.028	0.011	0.011
Duos	4.60	21.60	62.10	0.023	0.002	0.003	0.027	0.058	0.024	0.023
55	8.20	18.30	2.10	0.072	0.006	0.010	0.085	0.185	0.075	0.072
54 Mini	6.20	18.10	0.30	0.041	0.003	0.006	0.048	0.106	0.043	0.041
53 Mini	5.40	19.20	2.30	0.031	0.002	0.004	0.037	0.080	0.032	0.031

Table 6: E-field, H-field, Power density values of Nokia phone models and SAR to different tissues of the head

Nokia phone model	E-field V/m	H-field mA/m	S W/m^2	SAR to tissues of the head layers W/kg						Average SAR to human head W/kg
				Skin	Fat	Bone (skull)	Dura	CSF	Brain	
Nokia 302	8.30	28.00	BDL	0.074	0.006	0.010	0.087	0.190	0.076	0.074
Express music	16.00	22.50	0.70	0.275	0.022	0.039	0.322	0.705	0.286	0.275
Nokia 3110	9.20	23.00	0.30	0.091	0.007	0.013	0.106	0.233	0.094	0.091
Nokia 3250	8.70	21.30	0.20	0.081	0.006	0.011	0.095	0.209	0.085	0.081
Nokia 1700	6.50	21.90	0.90	0.045	0.004	0.006	0.053	0.116	0.047	0.045
Lumia 520	6.30	29.20	BDL	0.043	0.003	0.006	0.050	0.109	0.044	0.043
Lumia 720	9.80	28.60	1.80	0.103	0.008	0.015	0.121	0.265	0.107	0.103
Nokia 1200	7.10	17.40	0.80	0.054	0.004	0.008	0.063	0.139	0.056	0.054
Nokia 104	44.12	117.00	5.17	2.088	0.165	0.295	2.447	5.362	2.173	2.088
Nokia 112	7.11	18.87	4.10	0.054	0.004	0.008	0.064	0.139	0.056	0.054
Nokia 107	12.47	33.10	0.41	0.167	0.013	0.024	0.195	0.428	0.174	0.167
Nokia N97	22.22	58.94	1.31	0.530	0.042	0.075	0.621	1.360	0.551	0.530
Nokia X2	39.73	105.30	4.19	1.693	0.134	0.239	1.984	4.348	1.762	1.693
Nokia C3	45.16	49.70	5.14	2.188	0.173	0.309	2.564	5.618	2.277	2.188
Nokia Asha 200	19.63	52.08	1.02	0.413	0.033	0.058	0.484	1.061	0.430	0.413
Nokia 2700	50.26	133.30	6.70	2.710	0.214	0.382	3.176	6.959	2.820	2.710
Nokia 3120	15.79	41.90	0.66	0.267	0.021	0.038	0.313	0.687	0.278	0.267
Nokia Asha 302	1.10	2.93	0.01	0.001	0.000	0.000	0.002	0.003	0.001	0.001
Nokia N8	11.12	29.49	0.33	0.133	0.010	0.019	0.155	0.341	0.138	0.133
Lumia 1020	9.18	24.35	0.22	0.090	0.007	0.013	0.106	0.232	0.094	0.090
Lumia X2	2.05	5.44	0.01	0.005	0.000	0.001	0.005	0.012	0.005	0.005
Lumia XL-RM	21.51	57.66	1.23	0.496	0.039	0.070	0.582	1.275	0.517	0.497
Nokia 6500c	48.00	127.30	6.11	2.472	0.195	0.349	2.896	6.347	2.572	2.472
Nokia N70	11.12	29.49	0.33	0.133	0.010	0.019	0.155	0.341	0.138	0.133
Nokia 5300	10.43	27.68	0.29	0.117	0.009	0.016	0.137	0.300	0.121	0.117

BDL: below detection limit

Table 7: E-field, H-field, Power density values of other phone models and SAR to different tissues of the head

Itel, HTC, Infinix & Apple phone model	E-field V/m	H-field mA/m	S W/m^2	SAR to tissues of the head layers W/kg						Average SAR to human head W/kg
				Skin	Fat	Bone (skull)	Dura	CSF	Brain	
Itel 2060	33.65	89.25	3.00	1.215	0.096	0.171	1.423	3.119	1.264	1.215
Itel 2050	12.67	33.62	0.43	0.172	0.014	0.024	0.202	0.442	0.179	0.172
Itel 20	20.16	53.47	1.08	0.436	0.034	0.062	0.511	1.120	0.454	0.436
Itel 5120	1.78	4.71	0.01	0.003	0.000	0.000	0.004	0.009	0.004	0.003
Itel 1457	30.66	81.53	2.49	1.008	0.080	0.142	1.182	2.590	1.050	1.009
Itel 1452	0.98	2.59	0.01	0.001	0.000	0.000	0.001	0.003	0.001	0.001
Itel 2090	33.77	89.60	3.03	1.223	0.097	0.173	1.434	3.142	1.273	1.224
HTC 1	8.20	19.90	2.00	0.072	0.006	0.010	0.085	0.185	0.075	0.072
HTC 2	7.30	21.40	2.20	0.057	0.005	0.008	0.067	0.147	0.058	0.057
HTC 4G	28.78	79.34	2.20	0.881	0.070	0.125	1.041	2.282	0.925	0.887
HTC 3G	34.80	92.31	3.21	1.299	0.103	0.183	1.522	3.336	1.352	1.299
HTC OneM8	10.43	27.68	0.29	0.117	0.009	0.016	0.137	0.300	0.121	0.117
Infinix X307	14.74	39.10	0.58	0.233	0.018	0.033	0.273	0.599	0.243	0.233
Infinix X500	4.16	18.90	0.14	0.055	0.004	0.008	0.064	0.141	0.057	0.055
Infinix X551	4.08	10.81	0.04	0.018	0.001	0.003	0.021	0.046	0.019	0.018
I Phone 4	7.30	18.20	0.43	0.057	0.005	0.008	0.067	0.147	0.059	0.057
I Phone 5	6.80	17.10	0.40	0.050	0.004	0.007	0.058	0.127	0.052	0.050
I Phone 45	6.20	16.30	0.52	0.041	3.259	0.006	0.048	0.106	0.043	0.041
I Phone 55	9.10	17.20	0.80	0.089	0.007	0.013	0.104	0.228	0.010	0.089
I Phone 5c	8.80	18.30	0.70	0.083	0.007	0.012	0.097	0.213	0.086	0.083

Table 8: ICNIRP reference levels and recommended limits for general public exposure to time-varying E, H fields, Power density and SAR at different frequency

Frequency (MHz)	E-Field (V/m)	H-Field (A/m)	Power Density (W/m^2)	Whole-body average SAR (W/kg)	Localized SAR (head and trunk) (W/kg)	Localized SAR (limbs) (W/kg)
900	41.25	0.111	4.5	0.08	2.00	4.00
1800	58.34	0.157	9.0	0.08	2.00	4.00
2100	61.00	0.160	10.0	0.08	2.00	4.00

(Adapted from ICNIRP, 1998)

When compared with ICNIRP recommended reference levels for general public exposure to time-varying electric and magnetic fields at 900 MHz and 1800 MHz (ICNIRP 1998), 9 phones (9.2%) have their H-field strengths above 0.111 A/m (= 111.00 mA/m) ICNIRP reference level at 900 MHz while all the 98 phones have the H-field below 0.157 A/m (= 157.00 mA/m) reference level at 1800 MHz. Similarly, the E-fields for 88 phones (89.8%) are below 41.25 V/m reference level at 900 MHz while the remaining 10 phones (10.2%) have theirs above the reference level. At 1800 MHz, only one phone, Samsung GT-88530, which is 1.02 % of the total phones, has its E-field above 58.34 V/m reference level. Since GSM communication starts at 900MHz and 1800 MHz, it can be said the E-field strengths of the phones are within recommended limits. Safe limits of 4.5 W/m^2 and 9.0 W/m^2 for power density have been set by ICNIRP at 900 MHz and 1800 MHz, respectively for the general public. Three of the phones (3.06%) have power densities above the recommended limit at 1800 MHz while 12 phones (12.2%) have power densities above the recommended limit at 900 MHz. The implication of high RF power density in mobile phones is that the radiation has the ability to penetrate through the human skin when placed close to the ear during call mode. This in effect can cause dielectric heating or thermal effect on the tissue of the human skin. The consequences of excessive heating in the body vary from temporary disturbances in cell functions to permanent destruction of tissues (Bennet *et al.*, 2017), brain cancer and DNA damage. Thus the users of these phones are potentially at risk of any immediate health effect of high power density RF radiation.

The interaction of RF radiation and the human body can induce electric currents and electric fields inside human bodies, which can produce side effects to health (Buckus *et al.*, 2016). Since mobile phones are used closed to the body, the probability of induced electric field in body tissues is high. Radiation from mobile phones can alter the protein expression in human skin due to induced electric field (Basandrai and Dhami, 2016). According to the ICNIRP (1998) guidelines and other scientific reports, the E-field exposure levels recorded in this present study, with exception of few, are much below the values at which biological changes start taking place. The large difference between the measured E-field, H-field strengths and power density values of some of the phones to that of ICNIRP at 900 MHz and 1800 MHz is an indication that the users of the phones are free from any immediate health side effects due to RF radiation from the phones. However, there is also the issue of cumulative RF radiation exposure whose effect is not immediate but later. About 75% of the phones investigated are owned by young adults who most frequently use the phones for browsing and chatting at relatively close range to the body and at long hours. Also there is the case of long minutes to hours calls with the phone placed close to the head at the ear side. These prolong and continuous use of mobile phones leads to cumulative exposure and absorbed power over time. While it is difficult to quantify precisely the health implications of RF exposure from phones (Felix *et al.*, 2017), the effects of long term RF radiation exposure have led to series of scientific debates and investigations. On epidemiological studies, some of the effects recognized are fatigue, loss of memory, sleep disruption, headache, depression, impairment of short term memory, etc. Diseases like cancer and leukemia have also been linked to long term RF radiation from phones (Felix *et al.*, 2017). For those phones with E-field, H-field strengths and power density values above ICNIRP recommendation, the risk associated with such phone could be reduced by using hand-free devices, which keep mobile phones away from the head and body during phone calls, exposure can also be reduced by limiting the time of calls. Using the phone in areas of good reception can also decrease the RF exposure as it allows the phone to transmit at reduced power.

Specific absorption rate (SAR) to tissues of human head layers

The specific absorption rate (SAR) is used to quantify the energy absorbed in tissues at radiofrequency spectrum, which is expressed in units of watts per kilogram. It is defined as the ratio of the absorbed power to the absorbing mass (Lak and Oraizi, 2013). At different frequency exposures, SAR values varied. One of the aims of this study is to evaluate RF electromagnetic absorption by tissues of the head layers from mobile phone use. SAR in six tissue layers of the human head was evaluated at 1800 MHz, because it is the standard for the mobile communication systems. The results show that SAR to the head skin ranged from 0.001 – 6.971 W/kg, that to the fat ranged from 0.000 – 0.551 W/kg, to the bone (skull) ranged from 0.000 – 0.983 W/kg, that to the dura mater range from 0.001 – 8.169 W/kg, that to the CSF range from 0.003 – 17.900 W/kg and that to the brain range from 0.001 – 7.255 W/kg. The variation in SAR values to the different tissues layer is attributed to the E-field strength of the phones and the dielectric properties (conductivity and permittivity) of the head tissues. Each part of the human body has different dielectric properties dependent on the frequency exposure (Husni *et al.*, 2013). Increase head conductivity means increase in SAR values which contradicts with permittivity, where increases in permittivity result in drop of SAR values (Husni *et al.*, 2013). The cerebrospinal fluid with conductivity higher than the rest tissues has SAR values higher than the other tissues layer. Similar peak values have also been observed by Sabbah *et al.* (2011). Electromagnetic radiation is absorbed more from handset by human tissues with higher conductivity than tissues with lower conductivities (Husni *et al.*, 2013). Apparently, it is observed that SAR values drop with increment in tissues density. This is true from Equ. (7), where the density is inversely proportional to SAR values.

The term Localized SAR is used to account for the total contribution of the various tissues in a given organ or system. It is the average SAR to a given organ due to individual tissues. ICNIRP (1998) and IEEE (2005) recommended a reference level of 0.08 W/kg for whole-body average SAR, 2.00 W/kg for localized SAR to the human head and trunk and 4.00 W/kg to the limb (Table 8). These safety guidelines are to prevent adverse health effects related to whole-body heat stress and excessive localized tissue heating for frequencies between 3 kHz and 300 GHz (Zhang and Alden, 2011). In the present study, localized average SAR to the human head for all the phones investigated ranged between 0.001 W/kg and 6.972 W/kg with 89.8% (88 phones) having values below 2.00 W/kg ICNIRP recommended reference level while the remaining 10.2% (10 phones) have localized average SAR to the head to be above the safe limit. The phones are Tecno L3 (2.216 W/kg), Tecno T430 (2.472 W/kg), Tecno S3 (2.748 W/kg), Tecno T21 (2.912 W/kg), Samsung Y Duos (2.086 W/kg), Samsung GT-88530 (6.972 W/kg), Nokia 104 (2.088 W/kg), Nokia C3 (2.188 W/kg), Nokia 2700 (2.710 W/kg), Nokia 6500c (2.472 W/kg). Samsung GT-88530 has the highest SAR to the various tissue layers as well as localized SAR to the human head. Statistical Pearson correlation coefficient (R^2) was used to judge the levels of dependence of localized SARs on the E-fields, H-fields and power density. From statistical point of view, R^2 value of ±1 shows strong positive or negative dependence between variables. Correlation coefficient, R^2, values range from 0.015 – 0.779 for all the phones investigated. Apart from Samsung Duos ($R^2 = 0.015$) and Nokia 302 ($R^2 = 0.082$), the localized SARs show a fair dependence on the E-field, H-field and power density. Nokia C3 having localized SAR 2.188 W/kg and GT-88530 with SAR 6.972 W/kg show good dependence (R^2

= 0.779 and $R^2 = 0.728$ respectively). High SAR values above stipulated guidelines from some of the investigated phones implicate higher penetration of electromagnetic radiation towards the head, thus, more radiation power is absorbed by the head tissues during use which can lead to localized tissue heating. Users of these phone models are thus advised to use hand-free devices which keep mobile phones away from the head and body during phone calls, and use of proper phone casing accessories which have the potential of absorbing part of the radiation energy thereby reducing the exposure of the individual to radiation power. One striking feature observed in the SAR values is that the localized SAR values to the head is the same as those to the skin layer for almost all the phones. This might be to the fact that since the skin is the first layer in contact with the RF radiation, it absorbed the radiation energy first from the phone. The next lower layer with low conductivity absorbs parts of the energy from the skin and this pattern is followed down to the last layer. On the average, the total power absorbed by the head is likely the same as that of the skin. It has been confirmed that tissues with lower conductivity have the potential of absorbing the energy of adjacent area of higher conductivity resulting to higher SAR values (Husni *et al.*, 2013).

Conclusion

With the increasing rate of different brands of mobile phone with sophisticated outlook in the markets, the humans' populace and the environment in general are at risk of RF radiation. This study has been able to access and quantify the radio frequency dosimetry quantities of mobile phones used in Delta State. The results have shown irregular variation in E-field, H-field and power density among the investigated phones and no definite pattern or relationship between the variables could be established. The differences in the quantities have been observed to be due to factors such as phone model, antenna strength and frequency range. Other factors are phone casing, brand of phone, signal reception condition, age of phone and battery level. It is observed that some of the phones have E and F-fields, power density and SAR values above recommended safe limits. Users of such phone models are advised to use hand-free devices, which keep mobile phones away from the head and body during phone calls and also employ proper phone casing accessories which have the potential of absorbing part of the radiation energy thereby reducing the exposure of the to radiation power.

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Conflict of Interest

Authors have declared that there is no conflict of interest in this study.

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