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EVALUATION OF TEMPERATURE GRADIENT WITHIN DIFFERENT HEAD TISSUE LAYERS EXPOSED TO RADIOFREQUENCY RADIATION EMITTED BY CELLULAR NETWORK TRANSCEIVER BASE STATION USING PENNES MODEL OF THE BIO-HEAT EQUATION

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Abstract

While the spectrum growth of radiofrequency (RF) emission is likely to experience astronomical increase in the years to come, the imminent query would be whether the current spectrum management process is capable of fulfilling all future requirements. Public interest in the potential health issues relating to cellular or mobile communication transceiver base station antennas (BSA) emphasize on the importance of having an accessible and easy to understand information on electromagnetic (EM) and radiofrequency radiation (RFR) levels in the surrounding environment. In this study, measurements of electric field and magnetic field level were made around selected transceiver base station antennas in selected South-South States Nigeria, with the aid of frequency-selective equipment (CORNET, Electrosmog meter ED78S EMF RF/LF Dual mode model). Pennes Bio-heat equation was employed to compute the temperature gradient in biological materials due to EM exposure, which takes into account the heat exchange mechanisms such as heat conduction, blood flow, EM energy dissipation, and metabolism. Using the local operator's technical parameters, a theoretical simulation/estimation was done for comparative analysis. This perfectly agrees with other models and it also shows how RF radiation affects biological materials/tissues. It proves that the most vulnerable part of the head when exposed to RF radiation is the brain with temperature gradient of 0.087934°C/mm.

Key Words: Bio-Heat, Radiofrequency, Transceiver, Temperature Gradient, Head Tissue etc.

1.0 Introduction

Most of the theoretical analysis on heat transfer in living tissue is based on the Pennes equation, which describes the influence of blood flow on the temperature distribution in the tissue in terms of volumetrically distributed heat sink or sources. Pennes published the basic work on developing a quantitative basis for describing the thermal interaction between tissues and perfuse blood. His work consisted of a series of experiments to measure temperature distribution as a function of radial position in the forearm of nine human subjects. The environment in the experimental suite was kept thermally neutral during experiments. Pennes proposed a model to describe the effects of metabolism and blood perfusion on the energy balance within the tissue. These two effects were incorporated into the standard thermal diffusion equation, which is written in the following form (Myer, 2003);

$$C_p(z)\rho(z)\,\frac{\partial T(z,t)}{\partial t} = \nabla.[K(z)\nabla T(z,t)] + H + Q(z) - B(z)\,[T(z,t) - T_b] \qquad (1)$$

Where T_b is the temperature of the blood, Q is the metabolic heat generation, H is the heat source or sink and B is the term associated with blood perfusion.

The temperature elevation due to handset antennas can be considered as sufficiently small not to activate the thermoregulatory response; including the activation of sweating mechanism. Thus, this response is neglected in our study. Additionally, the blood temperature is assumed to be spatially and timely constant, since the EM power absorption due to antennas (output power of less than 1 W) is much smaller than the metabolic heat generation of an adult (approximately 100 W). Then, Eq. (1) is simplified as

$$Cp(z)\rho(z)\frac{\partial T(z,t)}{\partial t} = K(z)\nabla^2 T(z,t) + H(z) - B(z)[T(z,t) - T_b]. \qquad (2)$$

2.0 Head Model Phantom

The temperature rise due to the radiofrequency (RF) exposure from a portable telephone was obtained from the difference between the temperature *T(z,t)* and *T(z,0)*, where *T(z,0)* is the normal temperature distribution in the unexposed head, i.e. SAR=0 at thermal equilibrium (Ayman, 2010).

The human head model considered is a stratified medium that consists of several layers as shown in Figs. 1.1 and 1.2.

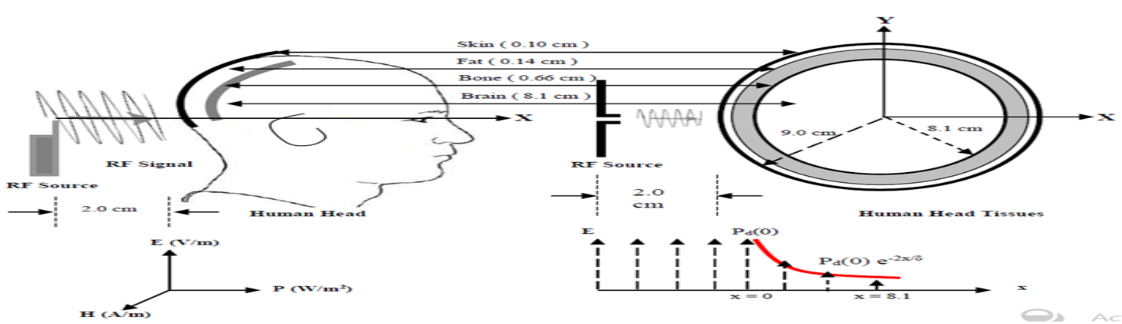


Fig.1.1: RF source – Human Head Model (Adheed, 2012).

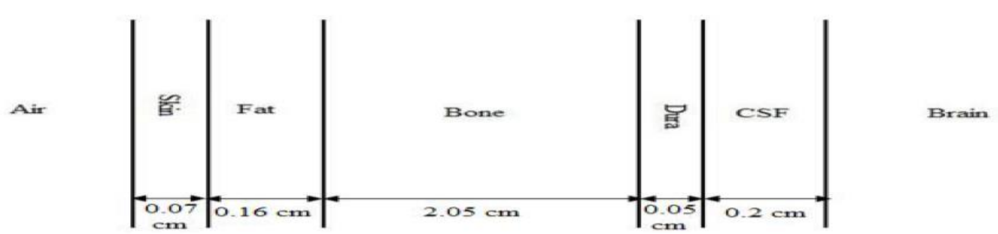


Fig. 1.2: A six-layer human head model (Ayman, 2010).

The thermal parameters are given in Table 1.0, which are the same as in (Ayman, 2010).

Table 1.0: Air and Tissue parameters

						Tissue Thickness	
S/N	**Air/Tissue**	**K (W/k.m)**	**P (kg/m³)**	**B (W/k.m³)**	**Itis, (2016) C(J/ºC.kg)**	**Adheed, 2012 (mm)**	**Ayman, 2010 (mm)**
1	Air	0.024	1.225	0	3513	-	-
2	Skin	0.42	1100	9100	3391	1.0	2.0
3	Fat	0.25	920	1700	2348	1.4	0.16
4	Skull Bone(SB)	0.39	1850	1850	2274	6.6	6.5
5	Dura Matter	0.5	1050	1125	3364	-	0.3
6	Cerebrospinal Fluid(CSF)	0.62	1060	0	4096	-	4.0
7	Brain	0.535	1040	40000	3630	8.1	2.5

(Sabbah and Dib, 2010)

In this study only one dimensional (1D) case of Eq. (2) with constant thermal parameters was particularly studied, which is a good approximation when heat mainly propagates in a direction perpendicular to the skin surface. Thus,

$$C_p(z)\rho(z)\frac{\partial T(z,t)}{\partial t} = K(z)\frac{\partial^2 T(z,t)}{\partial z} + H(z) - B(z)[T(z,t) - T_b] \quad (3)$$

2.1 **Human Thermo-Regulation (HTR)**

In the healthy human body, the thermo-regulatory system will cope with the absorbed heat until it reaches the point at which it cannot maintain the body temperature satisfactorily. Beyond this point, the body may become stressed (Eva et al, 2023). Excessive exposure to RFR can give rise to hyperthermia, sometimes referred to as heat exhaustion, an acute treatable condition which if neglected could have serious effect. Excessive heating can also cause irreversible damage to human tissue if the cell temperature reaches about 43ºC. A rise in body core temperature of about 2.2ºC is often taken as the limit of endurance for clinical trials (Yolanda *et al*., 2008). For RF radiation purposes, a limit of an increase of 1ºC in rectal temperature has often been postulated as a basis for determining a specific absorption rate (SAR) limit for human exposure (Uloma and Olga, 2021). Most western occupational standards are based on a SAR of 4Wkg^{-1} divided by ten to give a further safety margin. Thus the general basis is 0.4Wkg^{-1}. It has already been noted that people with an impaired thermo-regulatory system or with other medical conditions which affect heat regulation may not be so tolerant to the heating permitted by standards which have been set for healthy people. Ambient temperature and relative humidity can make a considerable difference in the ability of the human body to get rid of excess heat. In other way, a specific increase of rectal temperature of 1ºC will require a much higher SAR at low relative humidity than is needed at high humidity. In 1969, Mumford identified this aspect and proposed a comfort index whereby the higher safety level then in use (100Wm^{-2} for all the frequencies covered) was reduced as his temperature–humidity index increased. Current standards generally claim to accommodate environmental factors in the large contingency allowance put into the permitted limits. A particularly interesting paper on the thermo-regulatory mechanisms of the human body is that of Adair, (1987). It notes experimental work done to establish the thermal equivalence of heat generated in the body during physical exercise and passive body heating such as that from high frequency (HF) physiotherapy equipment. It also makes reference to the radical difference between the thermal responses of man and various animals and the consequent difficulty in extrapolating animal exposure data to human beings on this account, quite apart from any resonance differences.

SAR and temperature are related by the following heat equation. An energy balance equation of a body for time interval dt can be express as (www.chem.mtu.edu/2013heatlecture);

$$H = (mc)\left(\frac{dT}{dt}\right) \quad (4)$$

and

$$SAR = C\frac{\Delta T}{\Delta t} = C\left.\frac{dT}{dt}\right|_{\text{at } t=0} \text{(Adheed, 2012)} \quad (5)$$

Where, t is the time in seconds, C is specific heat capacity of tissue (Jkg^{-1}.^{o}C^{-1}), T is the temperature in ^{o}C and m the tissue mass in kg.

SAR is a measure of the electric field, and indirectly the magnetic field at the point under study, and also a measure of the local heating rate *dT*/*dt* (Branko andGjorgi, 2012).

Where, *dT/dt* is the time derivative of temperature in body tissue in K/s or ^{o}C/s.

There is no practical way of measuring the SAR of a human being. In order to make calculations of SAR, either computer modeling or practical experiments with dummy persons using substances which simulate the electric characteristics of human tissues are undertaken. A useful paper by Guy, (1987) on the use of phantoms in experimental work to measure SARs covers dosimetry from very low frequency (VLF) to microwaves. A paper by Stuchly, (1986) illustrates the scanning probe arrangement, using a non-perturbing probe system. Computer modeling attempts to model the human body by sub-dividing it into cells and attributing the relevant characteristics to each cell by analogy with the structure of a human being. There are limitations resulting from the deficiencies of any given model relative to a human body both in respect of the static model and the modeling of the dynamic performance of the complex thermo-regulatory mechanism of the human body. The validation of computer modeling is difficult since it is generally only possible to compare it with some experimental trial such as the phantom method described above, despite the limitations of the method. Another paper by Speigel, (1989) illustrates both a computer simulation and the comparison of the results with a phantom model. Although one can identify the problems these methods pose, it has to be recognized that it has not yet proved possible to devise any other effective measurement method.

3.0. Materials and Methods

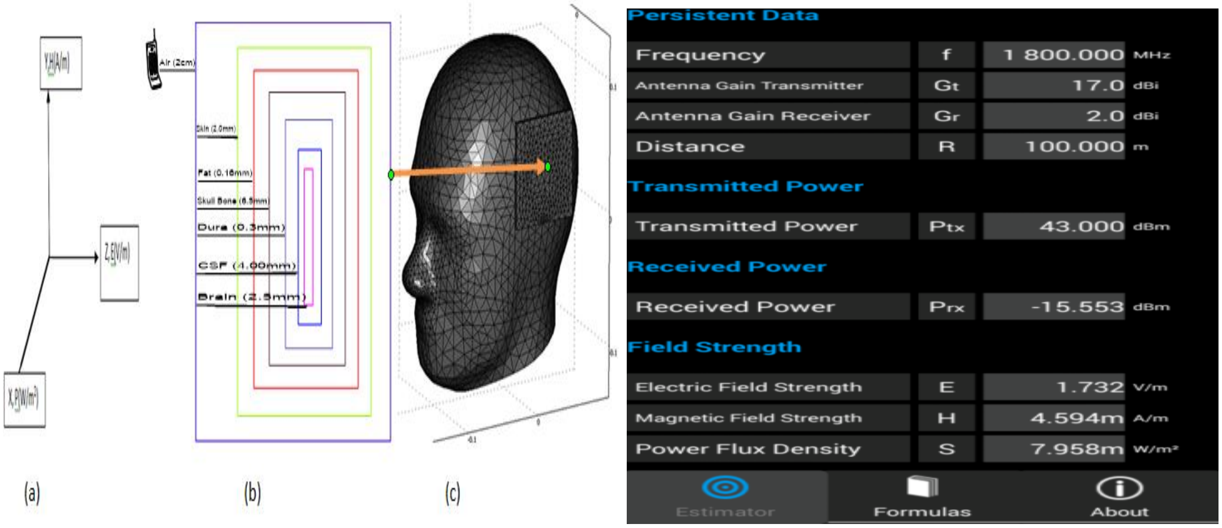
The distance from the foot of the Base Station Antenna (BSA) to point of interest(POI) was measured by means of a tape rule(50 m long).A broadband survey Meter (Cornet Electrosmog Radiofrequency Meter) with the following specifications was used to measure the power density, electric and magnetic field strength around the BSA. Model: ED-78S, Frequency range: 100MHZ -8GHz (Cornet, 2012).

Fig. 3.1: (a) Electrosmog Meter ED-78S

The microcell base stations studied cover the four major network provider base stations in Nigeria. Selection of base station was done base on transmission frequency (1800- 2100 MHz), residential area, office area, open market area and nearness to other radiofrequency antennas (e.g. TV and Radio antennas). Wherever possible, measurements were made in axis that permits measurements in line of sight to the directional antennas or antenna beam. Specifically, for the near field measurement, a transmitting cell phone was placed 2cm from the broad band metre to measure the electric and magnetic field in the near field region. This distance depicts the distance between the cell phone and human head when on call without kits. This was also done for the various distances of 25m, 50m, 75m, and 100m from the foot of the Base Station Antenna (BSA) and at about 1.67 m above sea level i.e height of an average man. The electrosmog meter was used vertically as recommended in the user's manual. This data was recorded for sixty (60) base stations in the study area. In order to investigate the degree of consistency of field measurement with existing models, theoretical estimation/simulation by RF Estimator (model IMA 85) is done using the technical parameters as shown in Table 3.1; the network technical parameters as provided in the estimator's software component of the programme platform is displayed in Fig. 3.2d.

Table 3.1: Antenna parameter from network providers in Nigeria (Isabona, 2012)

Antenna Parameter	1800-2100 MHz	800MHz
Transmitting power(dBm)	43.00	41.-42
Antenna Gain(dBd)	17-18	17 – 18
Antenna Type	Directional	Directional
Antenna hight(m)	45	40
Antenna gain receiver(dBd)	2	-



(d)

Fig. 3.2: (a) Direction of EM wave propagation (b) Section of the head showing the different tissue layers (c) A three-dimensional(3D) finite element mesh of human head model showing different layers (d) Estimator software platform.

In the same near field condition, a typical human head was modeled (Fig. 3.2b) showing the different tissue thickness (parameters are shown in Table 1.2) and direction of propagation of the EM waves.

3.1 Model Formulation

Since the EM emission from the cell towers were observed from a fixed position and does not vary with time, we assume a steady state flow i.e dT/dt = 0

Therefore, Eq. (3) becomes;

$$K(z)\frac{\partial^2 T(z,t)}{\partial z} + H(z) - B(z)[T(z,t) - T_b] = 0 \quad (6)$$

From Fourier's law for heat convection which state that the rate of flow of heat energy per unit area through a surface is proportional to the negative temperature gradient across the surface i.e in1-D (Cannon, 2012).

$$k(z)\frac{dT}{dz} = -h[T(z) - T_a] \quad (7)$$

Ambient temperature (T_a) - Surface temperature T(z) = (infinitesimal temperature difference) T.

Substituting Eq. (4) into Eq. (5) it yields;

$$H = \rho VSAR \quad (8)$$

Where ρ is density of tissue(kg/m^3) and V is the tissue volume(m^3).

Substituting Eq. (8) as heat source and Eq. (7) into Eq. (6) then rearranged using the above assumption of steady state, we arrive at the following equation;

$$\frac{dT}{dz} = \frac{\rho vSAR - B(z)[T_s - T_b]}{h} \quad (9)$$

Where B(z) is the blood perfusion parameter(W/k.m^3), T_s and T_b are the surface and blood temperature respectively, h is the coefficient of heat transfer(Wm^{-2o}C^{-1}) and dT/dz is the temperature gradient (^{o}C/m) which is the rate of temperature changes with a particular homogenous position/location within the human tissue. Eq. (9) is the re-evaluated Pennes Bio-heat equation that was used in this study to evaluate the temperature distribution in human/biological tissue exposed to radiofrequency(RF) radiation from transceiver GSM base stations in the selected South-South States, Nigeria. The convective heat transfer coefficient (h) dueto natural convection and radiation between the various surfaces and air was set to10 W/m^2.^{o}C^{-1}, which is the typical value at room temperature (Zhong-Shan and Jing, 2002). The surface temperature (T_s) and the blood temperature (T_b) were set at 31^{o}C and 37^{o}C, respectively(Coulson and Richard, 2015). Other tissue parameters are shown in Table 1.0.

Analysis using Eq.(9) was compared with a computational work by Emmanuel *et al*., (2013) model using Fourier series solution, Teeropot and Phadungsak, (2012) model using GSM900 MHz and data from estimator software(IMA 85) used in this work.

Also, in terms of physical and electrical parameter of the absorbing object SAR can be calculated by;

$$SAR=\frac{\sigma}{2\rho}|E|^2 \text{(Ushie et al; 2013)} \quad (10)$$

4.0. Results and discussion

Table 4.1: Temperature gradient as calculated using the modeled Pennes Bio-Heat Equation (PBHE), estimated values, Emmanuel *et al*., 2013 Model and Teeropot and Phadungsak, 2012 Model.

Air and Biological Material	TEMPERATURE GRADIENT (^{o}C/mm)						
	OP. 1 Calculated	OP. 2 Calculated	OP. 3 Calculated	OP. 4 Calculated	Estimated	Emmanuel *et al.,* 2013	Teeropot and Phadungsak, 2012
Air	7.78X10^{-6}	1.70X10^{-7}	3.63X10^{-6}	0.00013	7.78X10^{-6}	-	-
Skin	0.01999	0.01998	0.01999	0.02000	0.01999	0.02900	0.07400
Fat	0.00375	0.00374	0.00376	0.00380	0.00375	0.01000	0.05000
Skull Bone(SB)	0.00408	0.00407	0.00409	0.00410	0.00408	0.02500	0.06000
Dura	0.00248	0.00247	0.00249	0.00250	0.00248	0.02000	0.03000
Cerebrospinal Fluid(CSF)	0.0000135	0.00299	6.28X10^{-6}	0.000281	6.67X10^{-6}	0.00500	0.02000
Brain	0.08792	0.08791	0.08793	0.08799	0.08792	0.05000	0.10000

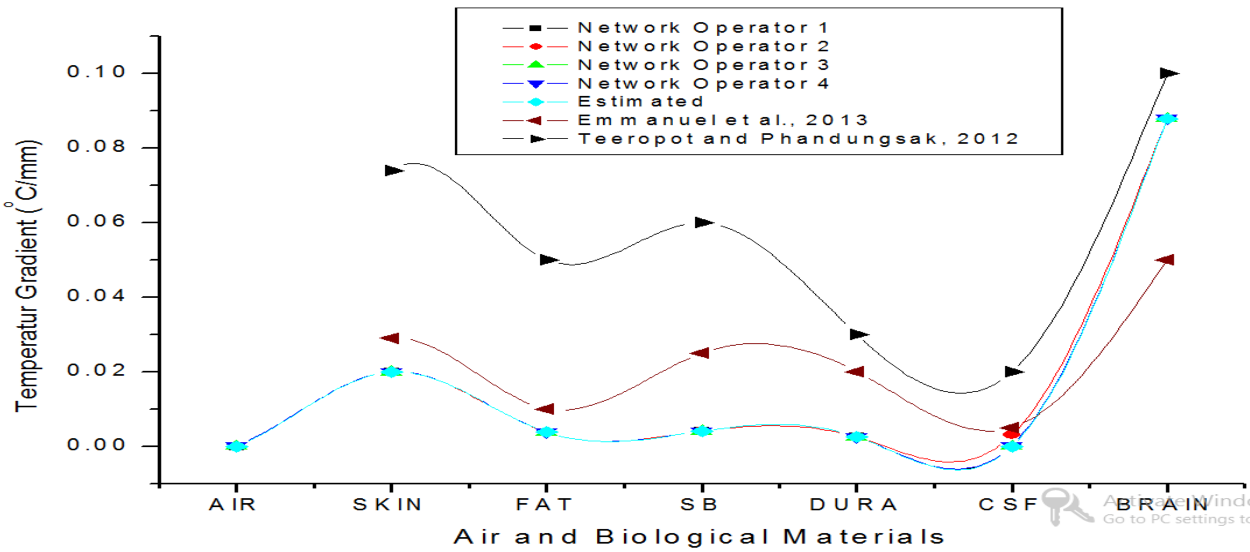


Fig. 4.1: Comparative plot of Temperature gradient against Air and Biological Materials for the modified PBHE (this study), Estimation tools (this study), Emmanuel *et al*., (2013) model and Teeropot and Phadungsak, (2012) model.

The result as presented in Fig. 4.1 indicates that the temperature gradient is maximum in the brain (with high blood perfusion) and least in cerebrospinal fluid (CSF- with zero blood perfusion) in agreement with Table 1.0. This shows that blood perfusion(flow rate)is a contributing factor to temperature distribution in biological materials exposed to RF radiation. It also indicates that the most vulnerable tissue when exposed to RF radiation is the brain; this could be credited to its high blood perfusion (flow rate). Thus the modified (derived) Bio-heat equation accurately explains the exposure to RF radiation in the near field as it shows good correlation with other models.

The little variation in magnitude of exposure for the different models might be due to the fact that;

(i) Emmanuel *et al*., (2013) used the solution of Fourier series equation with 28 $W/m^2.^oC^{-1}$ as heat convective parameter

(ii) Teeropot and Phadungsak, (2012) model used GSM900 frequency band applying the graphical method in finding temperature gradient but

(iii) In this study, the Pennes Bio-heat equation was remodeled, the GSM1800 frequency band was used and the coefficient of heat transfer parameter of 10 $W/m^2.^oC^{-1}$ for radiation heat was adopted (Zhong-Shan and Jing, 2002).

Therefore, temperature distribution using RF radiation as heat source largely depends on tissue parameter, more importantly blood perfusion rate. Health conditions related to blood flow rate will be most affected and should be given proper attention within an RF field.

5.0 Conclusion

The study principally was set out to evaluate the exposure level of people living within

100m from foot of BSA (both in far and near field conditions) in some selected South-South States, Nigeria. This assessment was done using selected sensitive indices like SAR and temperature gradient. Pennes Bio-heat equation was employed to compute the temperature gradient in biological materials due to EM exposure, which takes into account the heat exchange mechanisms such as heat conduction, blood flow, EM energy dissipation, and metabolism. Using the local operator's technical parameters, a theoretical simulation/estimation was done for comparative analysis. This perfectly agrees with other models and it also shows how RF radiation affects biological materials/tissues. It proves that the most vulnerable part of the head when exposed to RF radiation is the brain. It was found that the modified Bio-heat equation can also be used to analyse temperature gradient in an exposed biological material to RF radiation as it shows good agreement with other models.

The derived temperature gradient equation ($\frac{dT}{dz} = \frac{\rho VSAR - B(z)[T_s - T_b]}{h}$) from the Pennes bio-heat equation using RF radiation as heat source has provided another analytical tool for studying RF radiation exposure effect in South-South Nigeria, which can be extended to other areas. This equation can be utilized to predict the evolution of thermal energy and direction within head tissue during thermal therapy. It can also be used in radiotherapy to avoid thermal injury in the head.

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