Physical Science International Journal
7(1): 11-19, 2015, Article no.PSIJ.2015.053
ISSN: 2348-0130

SCIENCEDOMAIN *international*
www.sciencedomain.org

EMF Power Absorption in Bone and Bone Marrow: Mathematical Model

Mona A. El Naggar[1*]

[1]*Department of Engineering Physics and Math, Faculty of Engineering, Cairo University, Cairo, Egypt.*

Author's contribution

The sole author designed, analyzed and interpreted and prepared the manuscript.

Article Information

DOI: 10.9734/PSIJ/2015/17210
Editor(s):
(1) Shi-Hai Dong, Department of Physics, School of Physics and Mathematics, National Polytechnic Institute, Mexico.
(2) Christian Brosseau, Department of Physics, Université de Bretagne Occidentale, France.
Reviewers:
(1) Anonymous, Bulgaria.
(2) Anonymous, Brazil.
Complete Peer review History: http://www.sciencedomain.org/review-history.php?iid=1053&id=33&aid=8988

Original Research Article

Received 3rd March 2015
Accepted 30th March 2015
Published 27th April 2015

ABSTRACT

A deterministic mathematical method is adopted to evaluate the power absorption due to EMF radiation in bone and bone marrow. The specific absorption rate (SAR), in both anatomic structures, is computed according to the present mathematical model, is represented spatially in the bone-marrow-bone layers under study. The effect of exposure to electric field of strengths ranging from 1 V/m to 1 kV/m is investigated for a wide frequency spectrum in each layer of the proposed model. The frequency dependence of the SAR, through these layers, is illustrated for frequencies ranging from 1 kHz to1GHz. The present results are in agreement with international safety standards for applied filed strengths of maximum value; 10 V/m for bone and 100 V/m for bone marrow. Moreover the present model shows that oblique incidence results in higher SAR values than with normal incidence, highly evident for low frequency.

Aim: Evaluation of the EMF power absorption and distribution, in bone and bone marrow, due to EMF radiation.

Study Design: Mathematical analysis followed by computer simulation of the problem.

Place and Duration of Study: Department of Engineering Physics & Math., Faculty of Engineering, Cairo University, between May 2014 and Dec.2015.

Methodology: The author employs a bone-marrow-bone model to investigate the effect of incident EMF. The equations governing the total electric and magnetic field distributions in each layer are deduced, considering its biological electromagnetic properties. The model is simulated by a computer program using Maple V. The computed values of specific absorption rate (SAR) in bone

**Corresponding author: Email: monaelnaggar@eng.cu.edu.eg, monaelnaggar@aucegypt.edu;*

and bone marrow are graphically represented to show spatial distribution in each one. The exposure to electric field of strength ranging from 1V/m to 1kV/m is investigated using the proposed method. The frequency dependence of the SAR through the bone-marrow-bone layers under study is illustrated for a frequency range of 1 kHz-1GHz.

Results: Electromagnetic radiation of 1 MHz-10MHz induce absorbed power within the safety limits for all applied field strengths. The 1 GHz incident radiation induces SAR values higher than permissible ranges for field strengths above 400V/m whereas the same occurs for a low frequency range at 100 V/m. Moreover, the present results are in agreement with international safety standards for applied filed strengths till 10 V/m for bone and till 100 V/m for bone marrow, covering the applied frequencies (1 kHz -1 GHz). Except for exposure to electric field of strength higher than 100 V/m, the SAR acquired by the bone marrow is within the safety levels.

Conclusion: The results obtained are in agreement with international safety standards for filed strengths of maximum value 10 V/m for bone and 100 V/m for bone marrow. Oblique incidence results in higher SAR values than normal incidence, especially for low frequency (1 kHz).

Keywords: Mathematical model; Specific absorption rate; Bone; Bone marrow; EMF radiation; EMF Power absorption; EMF strengths; Frequency dependence; SAR limitations.

1. INTRODUCTION

The recent electromagnetic environment intense existence, accompanying the progressive applications of electromagnetic fields, has indicated a growing threat to the public health. Various electronic devices employing EMF such as, cell phones and their networks, wi-fi routers, microwave transmitters, antennae, etc. impose significant biological effects. Hence, investigation on the EMF radiation interactions with tissues then assessment of their effect on biological systems, have considerably attracted the scientific attention [1-5].

The three main physical quantities for determination of the estimated effect of EMF exposure are: the flowing current per unit length through the body, the energy density the tissues are subjected to and the power absorbed per unit mass of biological tissue. The evaluation of the specific absorption rate (SAR), is the most acknowledged quantity for international standardization [6-11]. The possible EMF exposure hazards are estimated by; experiments, usually performed on animals [12, 13], mathematical approaches employing either sets of definite mathematical equations or stochastic modelling [14-18], or computer simulators, employing either frequency or time domain analysis. The latter is a dependable method for SAR evaluation. In 2008, D. Smith [19] has used SEMCAD X to evaluate directive antennae EMF near field propagation loss through different human body phantom sections. In addition to this, finite difference frequency domain (FDTD) is developed and applied to represent the EMF distribution through a human head phantom [20], where mobile antennae are placed at different distances from the head.

However, the biological EMF effect remains argumentative and a potent source of controversy. There is no sufficient, reliable evidence to confirm or deny whether long-term exposure to these fields has an adverse health effect. Yet renowned scientific communities issue annual reports of safety EMF exposure standards.

The present work adopts a deterministic mathematical model depending on tracing the wave propagation through a multilayer section of bone-bone marrow-bone. Maxwell equations are employed together with the physical and electromagnetic properties of the biological tissues under consideration. A parallel polarized electromagnetic wave is thus assumed to be incident on a homogeneous multilayer section. A mathematical simulation model is thus applied to calculate the root mean square value of the electric and magnetic fields, hence the electromagnetic power density absorbed in each layer. Bone and bone marrow are considered as non-magnetic materials, hence their magnetic permeability is less effective than their permittivity and conductivity are. Skin effect is neglected as it is significant only at VHF ranges. Therefore, the power absorption is studied as a function of both; the frequency (1 kHz-1 GHz) and the electric field strength (1 V/m-1 kV/m). The main goal of the current study is to introduce an approach to the problem of calculation of the average power absorbed by bone and bone marrow, hence compare the produced results to the approved international safety standards.

Computations are performed using Maple-V software. The author constructed a program to compute the total electric and magnetic fields, their root mean squared values, power absorbed and finally SAR in respective layers.

2. MATHEMATICAL METHODOLOGY

In the present work, the problem of electromagnetic wave incidence on a dissipative medium, namely biological tissue is investigated. Firstly, two planar sections of successive bone with marrow in between is assumed to be subjected to incident polarized electromagnetic wave, in the far field. Incident electromagnetic energy is transmitted through bone to bone marrow layer. The reflection on successive interfaces contributes to the overall energy consumed in each layer. Fundamental constants defining the reflected and transmitted fields are the electrical and magnetic parameters of the medium, permittivity, $\varepsilon(f)$, conductivity, $\sigma(f)$, and permeability, $\mu(f)$ for each layer. k(f) is the wavenumber for each layer. The incident polarized electric field is assumed to be propagating in the x-direction, represented by, $E_i(t,x)$ and $H_i(t,x)$ as thus:

$$E_i(x,t) = E_0 \times e^{i(2\pi ft - k_0 x)} \tag{1}$$

$$H_i(x,t) = \sqrt{\mu_1(f)\varepsilon_1(f)} \quad E_0 \times e^{i(2\pi ft - k_0 x + \pi/2)} \tag{2}$$

The posterior bone layer is denoted as layer 1, the bone marrow as layer 2, and the anterior bone layer as 3. Mathematical analysis is adopted to calculate the electric and magnetic field distributions in the three consecutive layers. To avoid complexity and redundancy of equations, the transmitted and reflected horizontal components of electromagnetic field through the marrow are given below:

$$E_{t2}(x,t) = t_{h1}(f) \times E_0 \times e^{-\delta 1(f)\frac{\Delta x1}{2} + i(2\pi ft - k_2 x)} \tag{3}$$

$$E_{r2}(x,t) = t_{h1}(f) r_{h2}(f) \times E_0 e^{-\delta 1(f)\frac{\Delta x1}{2} - \delta 2(f)\frac{\Delta x2}{2} + i(2\pi ft + k_2 x)} \tag{4}$$

$$H_{t2}(x,t) = t_{h1}(f)\sqrt{\mu_2(f)\varepsilon_2(f)} \times E_0 \times e^{-\delta 1(f)\frac{\Delta x1}{2} + i(2\pi ft - k_2 x + \pi/2)} \tag{5}$$

$$H_{r2}(x,t) = t_{h1}(f) r_{h2}(f)\sqrt{\mu_2(f)\varepsilon_2(f)} \times E_0 \times e^{-\delta 1(f)\frac{\Delta x1}{2} - \delta 2(f)\frac{\Delta x2}{2} + i(2\pi ft + k_2 x + \pi/2)} \tag{6}$$

t_{h1}(f), r_{h2}(f), and δ_2(f) are transmission, reflection and absorption coefficients of the medium. Similarly, the vertical components of the field can be determined using the vertical reflection and transmission coefficients, Eq.(8).

$$r_{h2}(f) = \frac{\sqrt{\varepsilon_3}/\sqrt{\varepsilon_2} - \cos\theta_3/\cos\theta_2}{\sqrt{\varepsilon_3}/\sqrt{\varepsilon_2} + \cos\theta_2/\cos\theta_2} \qquad t_{h1}(f) = \frac{2}{\sqrt{\varepsilon_2}/\sqrt{\varepsilon_1} + \cos\theta_2/\cos\theta_1} \tag{7}$$

$$r_{h2}(f) = \frac{1 - \sqrt{\varepsilon_3}\ \cos\theta_3/\sqrt{\varepsilon_2}\cos\theta_2}{1 + \sqrt{\varepsilon_3}\ \cos\theta_3/\sqrt{\varepsilon_2}\cos\theta_2} \qquad t_{v1}(f) = \frac{2}{1 + \sqrt{\varepsilon_2}\cos\theta_2/\sqrt{\varepsilon_2}\cos\theta_1} \tag{8}$$

Considering that the present study aims at the assessment of power absorption, electromagnetic power density vector, $S_{tot}(t,x)$, in a specific layer is represented as:

$$S_{tot}(x,t) = E_{tot}(x,t) \times H_{tot}(x,t) \tag{9}$$

where $E_{tot}(x,t)$ and $H_{tot}(x,t)$ are the total electric and magnetic fields in the respective layer.

The mathematical derivation, introduced in the present work, produces the total electric field, $E_{tot}(x,t)$, in the marrow layer, of thickness Δx_2 as:

$$E_{tot}(x,t) = tp1tp2 e^{-\delta_1 \Delta x_1 2} E0 1 - e^{-\delta_2 \Delta x_2 2} rp2 \cos k1\Delta x1 + 2k2\Delta x2 \sin 2\pi ft - kx - e^{-\delta_2 \Delta x_2 2} rp2 \sin k1\Delta x1 + 2k2\Delta x2 \cos 2\pi ft - kx \qquad (10)$$

Δx_1 and Δx_3 denote the posterior and anterior bone thicknesses respectively. Hence, the root mean square value of $E_{tot}(x,t)$, E_{rms} (x), is deduced from Eq.10 giving:

$$E_{rms}(x,f) = \left\{ \frac{t_{p1}^2 t_{p2}^2 E_o^2}{8\pi} \left(1 - r_{p2}\cos(k_1\Delta x_1 + 2k_2\Delta x_2)\right)^2 + \frac{1}{8\pi} r_p^2 sin^2(k_1\Delta x_1 + 2k_2\Delta x_2) \right\} \{\sin(4\pi f + 2k_2 x) + \sin(2k_2 x) + ½\} \qquad (11)$$

Similar derivations are carried out for the posterior and anterior bone layers. The incident field on a specific layer is that transmitted from the previous one. Reflection and transmission occurs at each interface. Similarly, $H_{rms}(x)$ and $H_{tot}(x,t)$ are deduced, hence $S_{tot}(x,t)$ absorbed in each layer can be calculated.

The specific absorption rate, SAR, being dependent on the electric field root mean squared value, E_{rms}, is averaged over any thickness Δx as:

$$SAR(f) = \frac{1}{\Delta x}\int_0^{\Delta x} \frac{\sigma(f)}{\rho} E_{rms}^2(x,f)\, dx \qquad (12)$$

The frequency dependence of the SAR function is thus complicated, considering the frequency dependence the electromagnetic properties involved.

3. RESULTS

A double layer of bone section, 3 mm thickness each, with a 5mm marrow layer in between, is subjected to incident electromagnetic waves. Horizontally polarized incident fields are assumed to be incident on a unit area of the section. Considerable biological tissues are assumed to be homogeneous. The root mean square of the phas or addition of the transmitted and the reflected electric fields is calculated for each layer as in Eq.11. The mathematical model is applied to illustrate the SAR variation with frequency. In addition to this, the relation between the SAR and the incident electric field strength, E_0, for a wide frequency spectrum is represented. The spatial distribution of the SAR function, through the successive layers, is then calculated and represented as well. The electromagnetic parameters are actually reported data for cortical bone and marrow. The model applied depends greatly on the frequency dependent media parameters reported by references [21-24]. A horizontally polarized plane wave is assumed to be normally incident on a 1mm^2 surface of the bone-marrow-bone layers. The SAR function, due to the horizontally polarized electric field with normal incidence, is calculated. Figs. (1-a,1-b) illustrate the rise of SAR function, in log scale, versus the frequency in log scale as well, for different electric field strengths for both bone and marrow layers. Figs. (2-a,2-b) represent the spatial distribution of the SAR function across the bone- marrow-bone section. These figures show the change of pattern for 1 kHZ and 1 GHz.

The bone thickness, in the range (0.1 mm- 5 mm), does not affect the SAR value. Fig. (3) illustrates the rise of SAR function, in log scale, versus the incident electric field strength, E_0 in V/m, plotted at 1 kHz, 10 MHz and 1 GHz.

For oblique incidence, Figs. (4-a,4-b) illustrate the rise of SAR function, in log scale, versus the frequency in log scale as well, for different electric field strengths for both bone and bone marrow layers. The SAR values are calculated due to horizontally polarized electric field incident at an angle of incidence 30°.

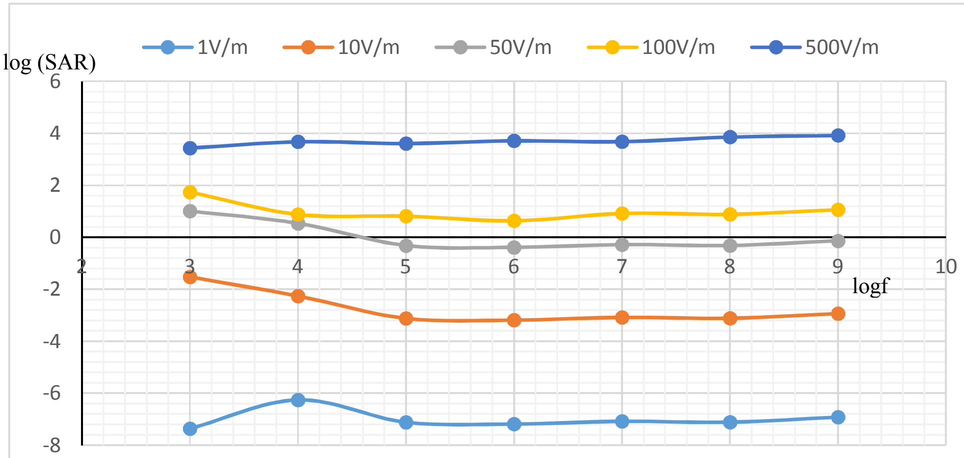

Fig. 1-a. log(SAR) vs log(f) for bone

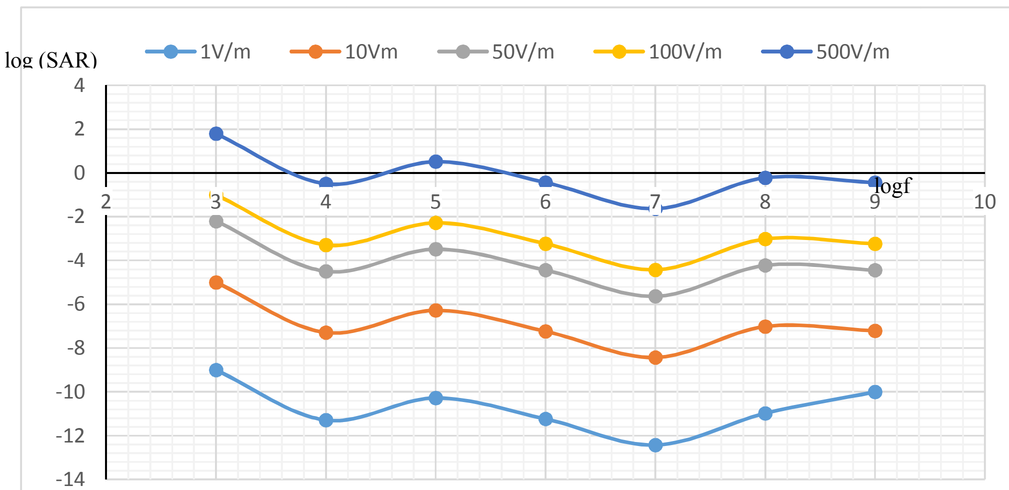

Fig. 1-b. log(SAR) vs log(f) for marrow

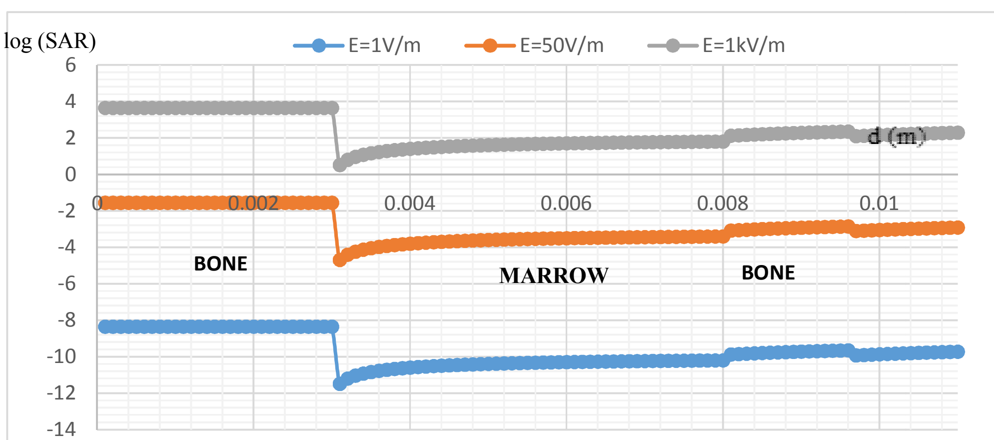

Fig. 2-a. log(SAR) vs depth (m) for bone-marrow-bone layers calculated at 1kHz and different values of vertically polarized electric field strengths

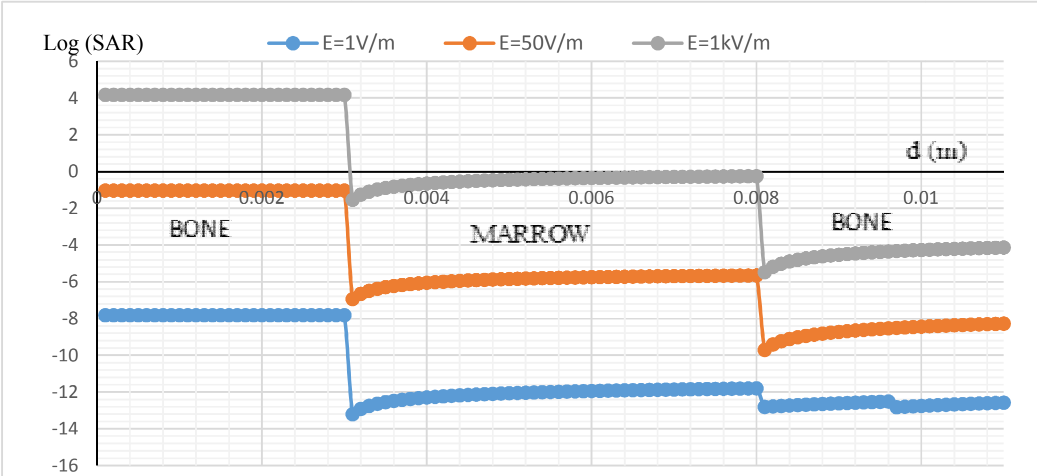

Fig. 2-b. log(SAR) vs depth (m) for bone-marrow-bone layers calculated at 1GHz and different values of vertically polarized electric field strengths

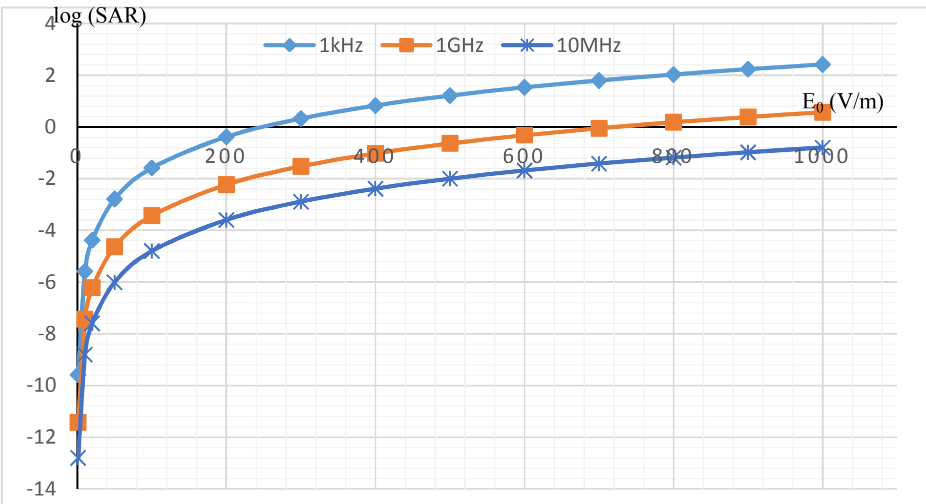

Fig. 3. log(SAR) vs E_0 (V/m) calculated for different frequencies

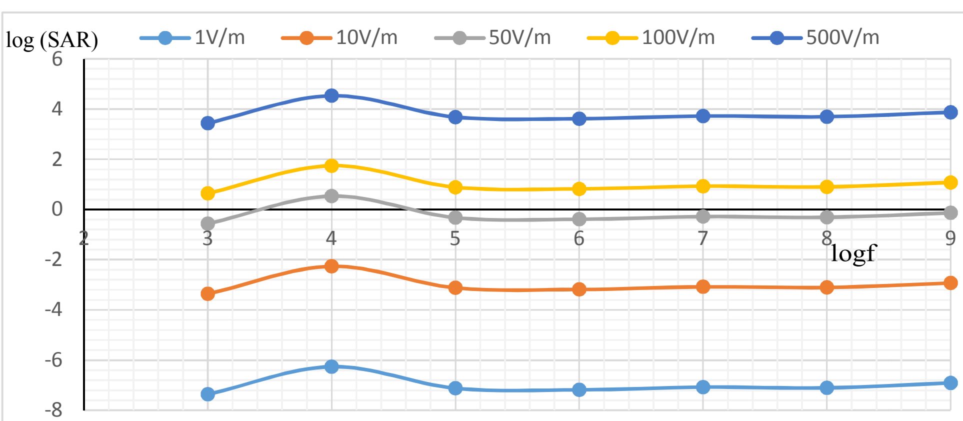

Fig. 4-a. log(SAR) vs log(f) for bone calculated for different values of electric field strenghs with oblique incidence θ=30º

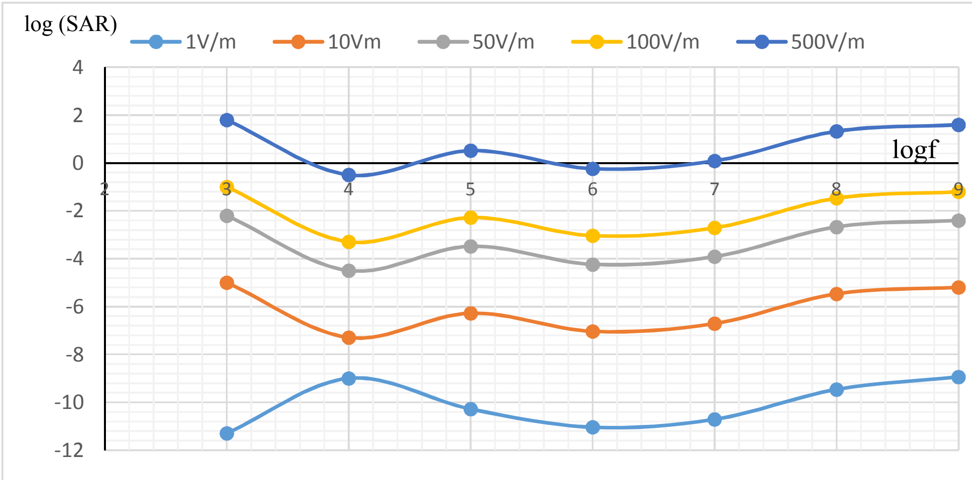

Fig. 4-b. log(SAR) vs log(f) for bone marrow calculated for different values of electric field strengths with oblique incidence θ=30°

4. DISCUSSION AND CONCLUSION

Electromagnetic interactions with biological tissue present a potential source of controversy. This concerns not only the possible effects on health but also the mechanism leading to these effects. It is not well established whether this effect is thermal, caused by high frequency vibrations of the molecules, or non-thermal that could cause serious disturbance on the cell membrane or even the DNA. Zhong et al. [12] reported the harmful effects of low intensity electromagnetic field (0.5 mT, 50 Hz), on bone marrow, increasing cell proliferation and inducing cell differentiation. While, Prisco et al. [13] investigated the effects of GSM-modulated radiofrequency electromagnetic waves on bone marrow.

For mobile phones and their networks, FCC proposes SAR international standards, not exceeding 0.04 W/kg [25]. Harmonization of ICNIRP and IEEE has been established between their standard limits. Their latest reports have restricted the safe SAR limits of the whole-body exposure to 0.4 W/kg and the partial body exposure to 10 W/kg for occupational exposure. For public exposure, SAR limitation for the whole body is 0.08 W/kg and for the partial body is 2 W/kg [9,10,26,27]. European standards limit the maximum public exposure level to 1.6 W/kg [7].

The present work proposes a methodology based on mathematical formulation of EMF penetration through bone. It complements the SAR values resulting from other phantom and mathematical modeling [12-13]. This methodology is suitable for studying other complicated tissues, however the author was interested in obtaining the SAR values absorbed by bone and bone marrow.

According the current results, the electromagnetic radiation of frequency values ranging 1MHz-10 MHz are within the safety limits for all applied field strengths. These data also show that for the 1GHz frequency, SAR values are higher than permissible ranges for field strengths above 400 V/m whereas the same occurs for a low frequency range at 100 V/m. Moreover, the present results are in agreement with international safety standards for applied filed strengths till 10 V/m for bone and till 100 V/m for bone marrow, covering the applied frequencies (1 kHz -1 GHz). Except for exposure to electric field of strength higher than 100 V/m, the SAR acquired by the bone marrow is within the safety levels. Furthermore when oblique incidence is applied the SAR values are higher than with normal incidence case, especially for low frequency (1 kHz).

On the other hand, some limitations of the present method ought to be mentioned; firstly the direction of propagation being taken very specific while in real cases the field is spatially random. Moreover, the present approach is only applicable to far field exposure. This is the common case for public exposure to different sources of radiation. Secondly, not only the reported physical properties of bone and bone marrow are very scarce, but their actual dimensions vary considerably with sex, age and state of health. Despite the fact that at low frequency range, international standardization takes into account the current density instead of SAR, the results presented in this paper extend the SAR calculation to any frequencies. The present work has no previous parallel as most of the researchers did not examine experimentally the absorption of EMF due to the extreme difficulties to perform non -destructive tests *in vivo* or even *in vitro*. Moreover, numerical methods, employed using computer simulators to analyse EMF interaction with human body phantom, are usually investigating fields due to antennae either placed close to or implanted inside it. Hence producing data that could be applicable for directive near field regions.

ACKNOWLEDGEMENT

I hereby acknowledge the help and supervision of Prof. Medhat A. Messiery. He provided valuable assistance in manuscript preparation and its revision.

COMPETING INTERESTS

Author has declared that no competing interests exist.

REFERENCES

1. Behari J. Biological effects and health implication of radiofrequency and microwave. International Conference on Electromagnetic Interference and Compatibility'99. New Delhi, India. 1999; 449-452.
2. Foster R. Thermal and non-thermal mechanisms of interaction of radio-frequency energy with biological systems. IEEE Transactions on Plasma Science. 2000;28(1).
3. Cleary SF, Cao G, Liu L-M. Effects of isothermal 2.45 GHz microwave radiation on the mammalian cell cycle: Comparison with effects of isothermal 27 MHz radiofrequency radiation exposure. Bioelectrochem. Bioeneng. 1996;39:167-173.
4. Stuchly MA. Fundamentals of the Interactions of Radio-frequency and Microwave Energies with Matter. Biological effects and dosimetry of nonionizing radiation. RF and microwave energies; NATO advanced study institutes series, Plenum Press, NY; 1983.
5. Repacholi MH. Low-Level Exposure to radiofrequency electromagnetic fields: Health effects and research needs. Bioelectromagnetics. 1998;(19):1–19.
6. Environmental Health Criteria 137, United Nations World Health Organization, International Radiation Protection Association. Elcetromagnetic Fields (300 Hz - 300 GHz):World Health Organization (WHO). Available:http://www.who.int/peh-emf/project/en/
7. Copies of UK's annual reports on mobile phones. Available:http://www.iegmp.org.uk and Available:http://www.hpa.org.uk/radiation/, Available:www.fcc.gov/oet/rfsafety Available:www.iegmp.org.uk.
8. International Commission on Non -Ionizing Radiation Protection, IARC; 2002. Internet Communication. Available:www.icnirp.org.
9. Chou CK. Technical Committee 95, Conference on: Occupational Exposure to EMFs: paving the way for a future EU initiative; 2009. International Committee on Electromagnetic Safety, IEEE Piscataway, New Jersey, USA.
10. ICNIRP guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz). Health physics. 1998;74(4):494-522.
11. Rosen. Applications of RF / Microwaves in Medicine. IEEE Transactions on Microwave Theory and Techniques. 2002;50(3).
12. Zhong C, Zhang X, Xu Z, He R. Effects of low-intensity electromagnetic fields on the proliferation and differentiation of cultured mouse bone marrow stromal cells. Phys. Ther. 2012,92(9):1208-19. DOI: 10.2522/ptj.20110224. Epub,
13. Prisco MG, Nasta F, Rosado MM, Lovisolo GA, Marino C, Pioli C. Effects of GSM-modulated radiofrequency electromagnetic fields on mouse bone marrow cells. Radiat Res; 2008. DOI: 10.1667/RR1213.1, 170(6):803-10.
14. Gosselin MC, Joseph W, et al. Estimation Formulas for the Specific Absorption Rate in Humans Exposed to Base-Station Antennas. IEEE Transactions on Electromagnetic Compatibility; 2011.
15. Gajšek P, D'Andrea JA, Mason PA, Ziriax JM, Walters TJ, Hurt WD, Meyer FJC,

Jakobus U, Samaras T, Sahalos JN. Mathematical Modeling of EMF Energy Absorption in Biological Systems. Biological Effects of Electromagnetic Fields. 2003;114-41.

16. Findlay Richard. Computational Dosimetry and the EMF Directive A presentation for the Health & Safety; 2006. World Health Organization, 2013EMFComp, ISBN 924.
17. El Naggar MA, El Messiery MA. Evaluation of power absorption in human eye tissue. International Journal of Advanced Research, 2013;1(7). ISSN 2320-5407, 658-665. Available:http:// www.journalijar.com
18. El Naggar MA, El-Messiery MA. A Mathematical Model for Pulsating Flow of Ionic Fluid under an Axial Electric Field: EMF Effect on Blood Flow. Journal of Physical Science and Application, JSAP. 2012;(2). ISSN 4, 61-70.
19. Smith David. Electromagnetic characterization through and around human body by simulation using SEMCAD X. Technical Report summary1: BANESH; 2008.
20. Buleandra Alina, Petrescu Teodor. Comparison of specific absorption rates induced in a model of the human skull. U.P.B. Sci.Bull., series C. 2011;73(1):83-92.
21. Cararra N. An internet resource for the calculation of the dielectric properties of biological tissues in the frequency range of 10 Hz to 100 GHz. Available:http://niremf.ifac.cnr.it/tissprop
22. Gabriel C, Gabriel S. Compilation of the dielectric properties of body tissues at RF and microwave frequencies. The dielectric properties of body tissues. 1996.
23. Gabriel S, Law RW, Gabriel C. The dielectric properties of biological tissues: Measurement in the frequency range 10 Hz to 20 GHz. Physics in medicine and biology. 1996;(41). Issn.11, 2251-2269.
24. Duck FA. Physical properties of tissues: A comprehensive reference book; 1990. Academic press, London.
25. Wireless Devices and Health Concerns - Consumer Information on Wireless Phones, FDA/FCC. Available:http://www.fcc.gov/guides/wireless-devices-and-health-concerns
26. UMEA, IEEE ICES IEEE/ICES TC95/SC4 C95. IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz; 2009. Sweden.
27. ICNIRP Guidelines. Available:http://rfsafetysolutions.com/RF%20Radiation%20Pages /ICNIRP_Guidelines.html

Peer-review history:
The peer review history for this paper can be accessed here:
http://www.sciencedomain.org/review-history.php?iid=1053&id=33&aid=8988