EMF Power Absorption In Bone and Marrow: Mathematical Model

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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 bone and bone marrow is computed and represented graphically to show spatial distribution in each. The mathematical model constructed is applied using the reported frequency dependent electromagnetic properties. The effect of exposure to electric field of strength ranging from 1V/m to 1kV/m is investigated, accordingly, for a wide frequency spectrum. The frequency dependence of the SAR through the bone-marrow-bone layers under study is illustrated for a frequency range of 1kHz-1GHz.

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

Study design: Mathematical analysis then 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 is 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 and bone marrow are graphically represented to show spatial distribution in each. 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 1kHz-1GHz.

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

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

Keywords: Specific absorption rate- Bone-Bone marrow-EMF radiation- Power absorption- Field strengths- Frequency dependence

1. INTRODUCTION

Recently, the intense existence of electromagnetic environment accompanying the progressive applications of electromagnetic fields; have represented a growing threat to the public health. Various electronic devices that employ EMF such as, cellular phones and their networks, microwave transmitters, antennae, etc. impose significant biological effects. Hence, investigating the EMF radiations interaction with tissues and assessing their effect on biological systems have occupied a considerable scientific attention [1-5].

There are three major physical quantities to be determined for evaluating the effect of EMF exposure; namely the flowing current per unit length through the body; the energy density the tissues might be subjected to and the amount of power absorbed per unit mass of biological tissue. The specific absorption rate, SAR, evaluation is the most commonly accepted quantity for international standardization [6-11]. The study of the possible hazards of the EM exposure is either experimentally performed on animals [12, 13] or assessed by mathematical approaches that employ either a defined set of mathematical equations or stochastic modelling [14-18]. Furthermore, using computer simulators, employing either frequency or time domain analysis, is a dependable method for SAR measurements. In 2008, D. Smith [19] has produced an extensive report concerning the EM field propagation loss through different human body phantom sections, using SEMCAD X. Antennae employed are directive and positioned near the body. Finite difference frequency domain, FDTD, is another method that has been employed to represent the EMF distribution through a human head phantom [20]. EMF has been emitted from mobile antenna placed at different distances from the head.

However, the adverse effect of the EM fields remains a potent source of controversy. There is no sufficient, reliable evidence to confirm or deny whether long-term exposure to these fields have an adverse health effect.

Mathematical modelling, adopted in the present work, is deterministic depending on tracing the wave propagation through a multilayer section of bone-marrow-bone. Maxwell equations are employed together with the physical and electromagnetic properties of the biological tissues under consideration, to study their EMF interaction. An electromagnetic wave is thus assumed to be incident on a homogeneous multilayer bone-marrow-bone 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 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 only significant at VHF ranges. Hence, 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 present work is to introduce an approach to the problem of calculating the average power absorbed by bone marrow and hence compare the results to the approved safety standards. Computations are performed using Maple-V software. The program is constructed by the author to compute the total electric and magnetic fields and their root mean squared values 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 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, σ*(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:

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

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

The posterior bone layer is denoted as layer 1, the 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:

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

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

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

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

$t_{h1}(f)$, $r_{h2}(f)$, and $\delta_2(f)$ 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).

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

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

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:

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

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:

$$E_{tot}(x,t) = t_{p1}t_{p2}e^{-\delta 1\frac{\Delta x1}{2}} E_0\Big\{\Big(1 - e^{-\delta 2\frac{\Delta x2}{2}} r_{p2}\cos(k_1\Delta x_1 + 2k_2\Delta x_2)\Big)\sin(2\pi ft - kx) - e^{-\delta 2\frac{\Delta x2}{2}} r_{p2}\sin(k_1\Delta x_1 + 2k_2\Delta x_2)\cos(2\pi ft - kx)\Big\} \quad (10)$$

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:

$$E_{rms}(x,f) = \left\{\frac{t_{p1}^2 t_{p2}^2 E_0^2}{8\pi}\left(1 - r_{p2}\cos(k_1\Delta x_1 + 2k_2\Delta x_2)\right)^2 + \frac{1}{8\pi} r_p^2 \sin^2(k_1\Delta x_1 + 2k_2\Delta x_2)\right\}\{\sin(4\pi f + 2k_2 x) + \sin(2k_2 x) + ½\} \quad (11)$$

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:

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

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

3. RESULTS

A double layer of bone section, 3mm 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 phasor 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 actual 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. Figures (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. Figures (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 1kHZ and 1GHz.

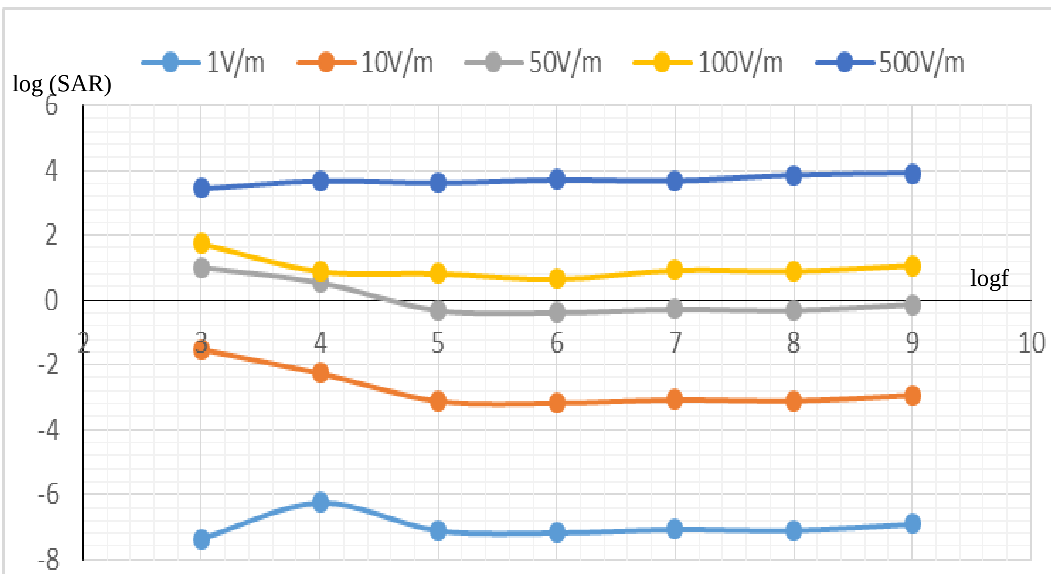

Fig.1-a log(SAR) vs log(f) for bone

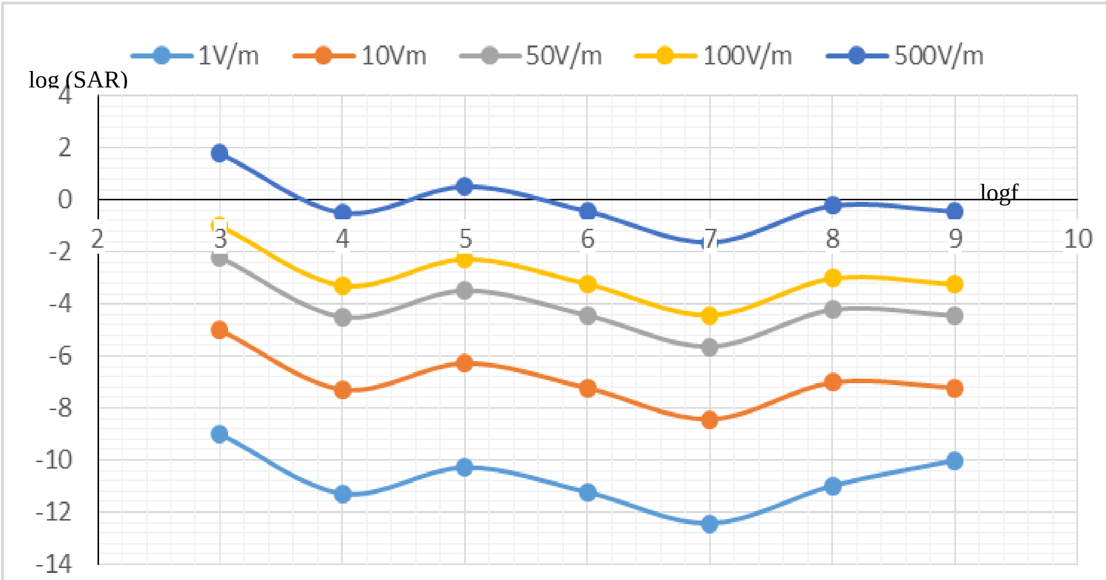

Fig.1-b log(SAR) vs log(f) for marrow

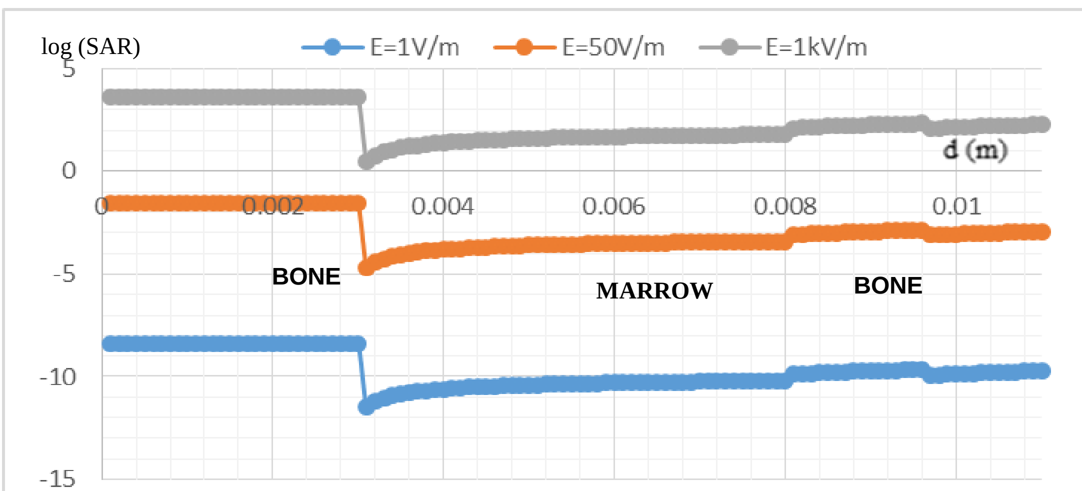

Fig.2-a log(SAR) vs depth (m) for bone-marrow-bone layers calculated at 1kHz and different values of vertically polarized electric field strengths.

The bone thickness, in the range (0.1 mm- 5 mm), does not affect the SAR value. Figure (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.

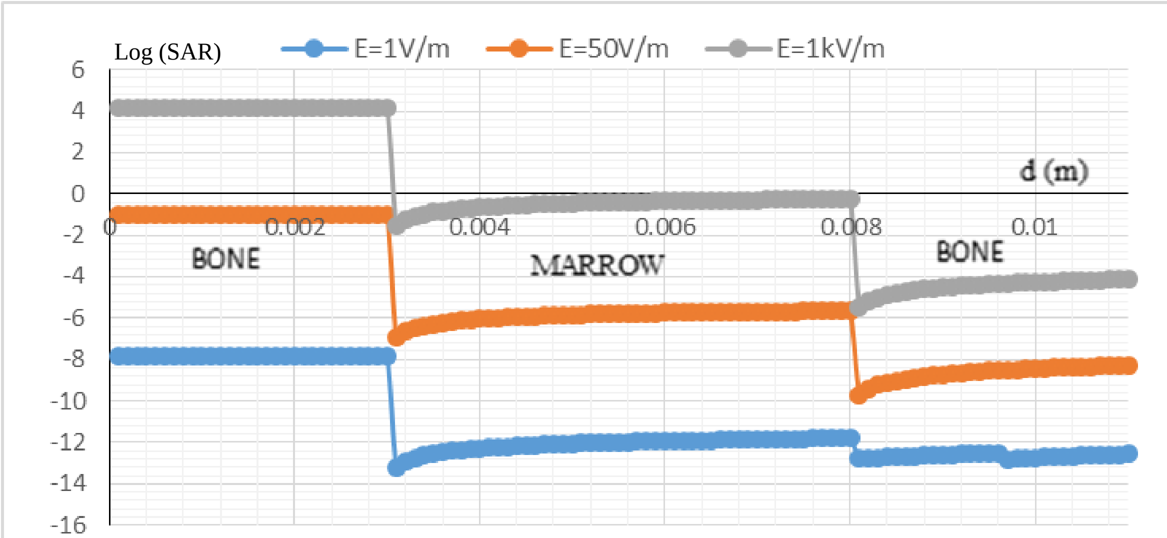

Fig.2-b log(SAR) vs depth (m) for bone-marrow-bone layers calculated at 1GHz and different values of vertically polarized electric field strengths

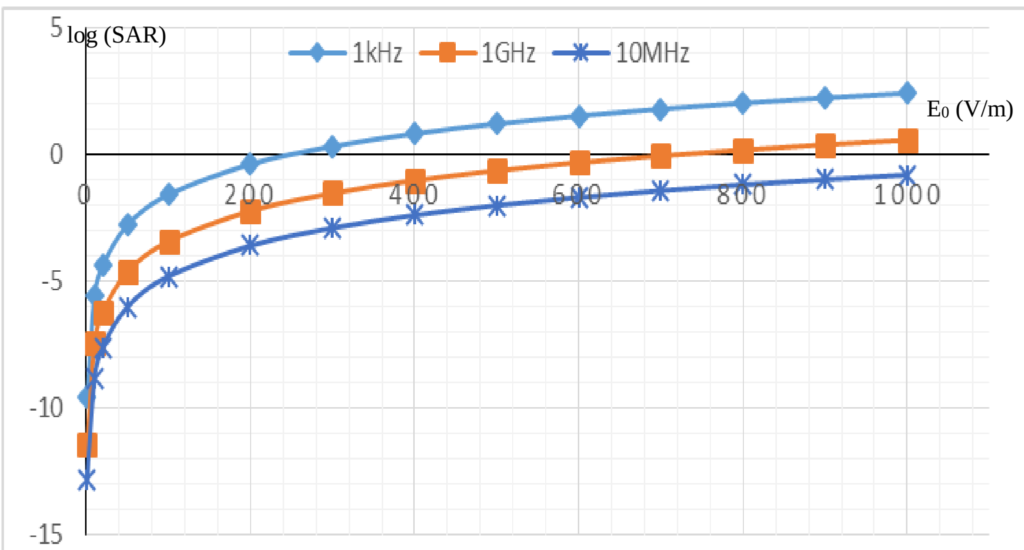

Fig.3 log(SAR) vs E_0 (V/m) calculated for different frequencies

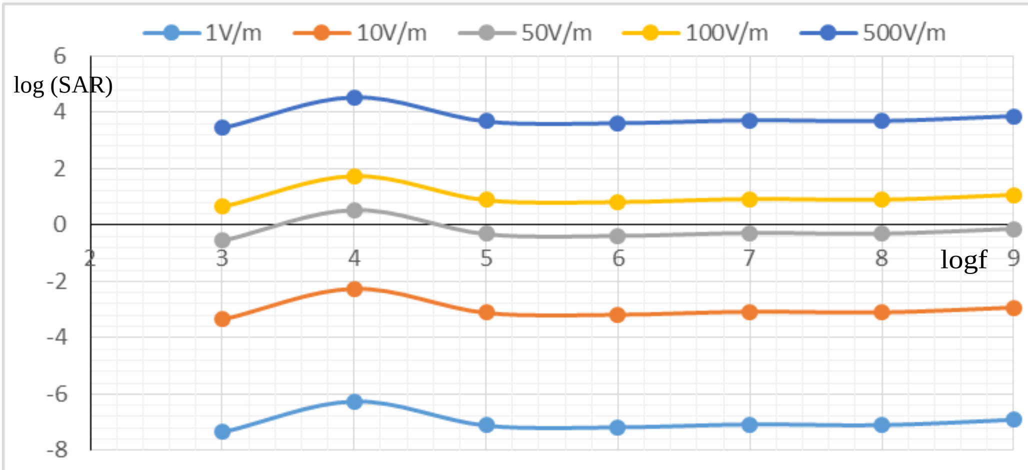

Fig.4-a log(SAR) vs log(f) for bone calculated for different values of electric field strenghs with oblique incidence θ=30º

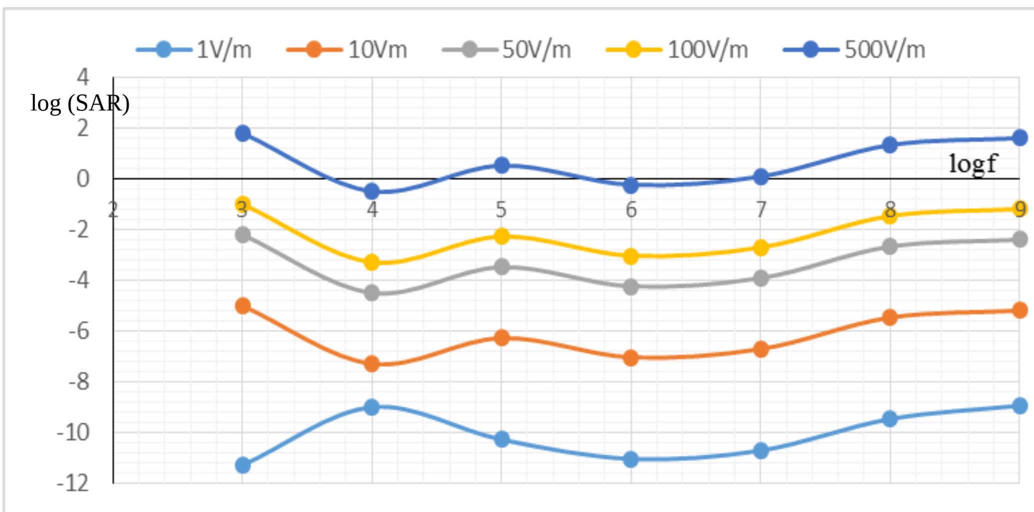

Fig.4-b log(SAR) vs log(f) for bone marrow calculated for different values of electric field strengths with oblique incidence θ=30º

For oblique incidence, figures (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 marrow layers. The SAR values are calculated due to horizontally polarized electric field incident at an angle of incidence 30º.

4. DISCUSSION AND CONCLUSION

Electromagnetic interactions with biological tissue are a potent source of controversy. Not only the possible health effects is the controversial but also the mechanism that leads to these effects is under constant debate. 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.

However, scientific communities periodically issue safety standards concerning EMF exposure. FCC recommend that SAR international standards, for mobile phones and their networks, not to exceed 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 0.4W/kg and the partial body exposure to 10 W/kg for occupational exposure. For public exposure, SAR limit for the whole body is 0.08 W/kg and for the partial body is 2W/kg [9, 10, 26, 27]. European standards limit the maximum public exposure level to 1.6W/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.

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

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 marrow are very scarce, but their actual dimensions differ 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 applicable for directive near field regions.

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