MICROWAVE HEATING PATTERN OF A SIMULATED HUMAN BRAIN

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ABSTRACT

Microwave heating of a simulated human brain is investigated. The human brain model is considered as a semi-sphere with a complex permittivity. The mathematical tool is started with the solution of the field equations in spherical coordinates due to an incident plane wave. The corresponding power absorption inside the model is computed. The temperature distribution (heating pattern) associated with the power absorption is also calculated by solving the diffusion equation. The relevant differential equation together with initial and boundary conditions is solved numerically using a finite-difference technique.

Keywords: Electromagnetic waves, Microwave heating, Biomedical applications of electromagnetic waves hyper thermic, Non invasive techniques.

1. INTRODUCTION

In recent years there has been considerable interest in using electromagnetic waves deposition to get a required heating pattern inside biological tissues. Microwave heating in flat layers of human tissues has been theoretically investigated for plane wave sources by schwan *et al.* [1], and by Guy [2] for aperture sources. Also, microwave heating in model of human limbs exposed to a direct contact aperture source is analyzed by Ho *et al.* [3]. Recently, invasive methods to produce heating pattern in human brain models by using implanted dipoles or arrays are discussed [4]-[6]. In this paper, interest is focused on the heating patterns created inside a human brain model by transmitting a plane wave inside the model. The model is assumed to be a semi-sphere of a radius a and permittivity ε_b. Since the skull thickness is too small w.r.to brain size and the dielectric constant of bone has a low value [7], therefore, the skull effect is ignored in the model considered. In section 2 , the electric field component equations inside the brain model are expressed in terms of the potential functions. The fields formula are obtained in terms of summation of Bessel and Hankel functions with complex arguments. In section 3, the power absorption and the heating patterns for different exposure times are determined. Section 4 is devoted to discussion and conclusion.

2. ELECTROMAGNETIC FIELD PROBLEM

Since the absorbed power in a biological medium is proportional to the magnitude of the electric field inside it , therefore, the field equations will be focused on the electric field only. Let us assume a plane wave polarized in the $\hat{x}$-direction is incident upon the human brain model as shown in Figure (1). It is expressed as

$$\bar{E} = E_o e^{jkz} \hat{x} \tag{1}$$

where $k = \omega\sqrt{\varepsilon_o \mu_o}$, is the wave number in free space. The time factor exp(jωt) is omitted in the formula. The problem of a plane wave scattered by a sphere is treated by Kong [8]. The electric field inside a sphere is expressed in terms of the electric and magnetic potential functions Π_e, Π_m as

$$E_r = \frac{j}{\omega \varepsilon_b}\left[\frac{\partial^2}{\partial r^2}(r\Pi_e) + k_b^2(r\Pi_e)\right] \tag{2}$$

$$E_\theta = \frac{j}{\omega \varepsilon_b}\frac{1}{r}\frac{\partial^2}{\partial r \partial \theta}(r\Pi_e) + \frac{1}{\sin\theta}\frac{\partial}{\partial \phi}\Pi_m \quad (3)$$

$$E_\phi = \frac{j}{\omega \varepsilon_b}\frac{1}{r\sin\theta}\frac{\partial^2}{\partial r \partial \phi}(r\Pi_e) - \frac{\partial}{\partial \theta}\Pi_m \quad (4)$$

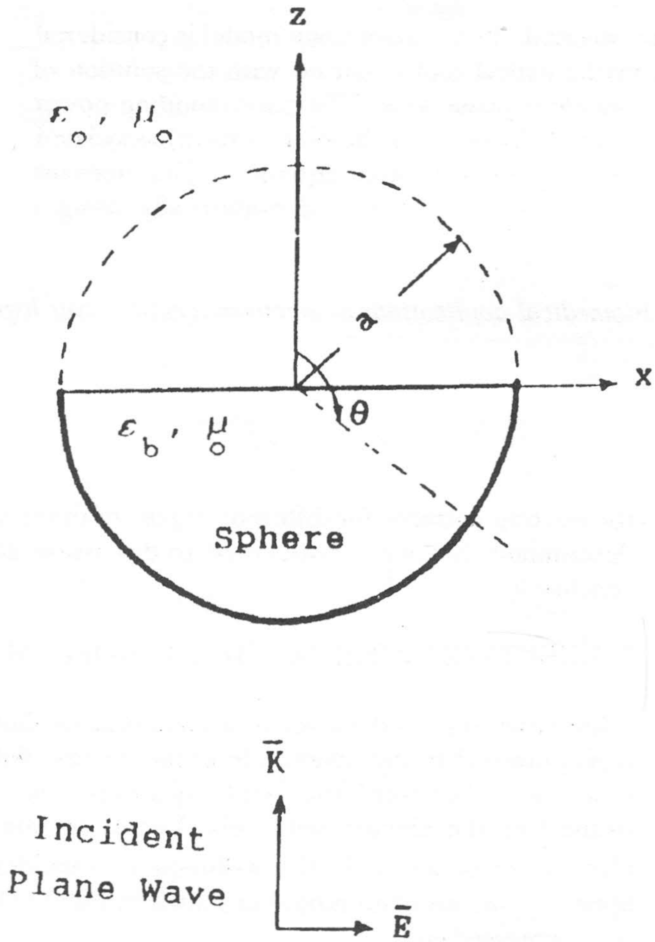

Figure 1. A plane wave incident upon the human brain model.

The case of ϕ- symmetry ($\frac{\partial}{\partial \phi} = 0$), and $\phi = 0$ are considered. The potential functions Π_e , Π_m expressions become as,[8]

$$\Pi_e = -\frac{E_o}{\omega \mu_o r}\sum_{n=1}^{\infty} C_n \hat{J}_n(k_b r) P_n^1(\cos\theta) \quad (5)$$

$$\Pi_m = 0 \quad (6)$$

where $\hat{J}_n(x) = x j_n(x)$ and $j_n(x)$ is the spherical Bessel function and it is related to Bessel function $J_n(x)$ as, [9]

$$j_n(x) = \sqrt{\pi/2x}\, J_{n+1/2}(x) \quad (7)$$

$P_n^1(x)$ is the associated Legendre polynomials of degree 1. C_n is found from matching the boundary conditions and it is given as

$$C_n = \frac{(-j)^{-n}(2n+1)}{n(n+1)} \frac{j\sqrt{\varepsilon_b \mu_o}}{\sqrt{\varepsilon_b \mu_o}\hat{H}_n^{(1)\prime}(ka)\hat{J}_n(k_b a) - \sqrt{\varepsilon_o \mu_o}\hat{H}_n^{(1)}(ka)\hat{J}_n'(k_b a)} \quad (8)$$

where $\hat{H}_n^{(1)}(x) = x h_n^{(1)}(x)$ and $h_n^{(1)}$ is the spherical Hankel function of the first kind and it is related to Hankel function $H_n^{(1)}(x)$ as

$$h_n^{(1)}(x) = \sqrt{\pi/2x}\, H_{n+1/2}^{(1)}(x) \quad (9)$$

In equation (5) the summation starts with $n = 1$ because $P_o^1(\cos\theta) = 0$. Substituting equations (5),(6) in (2),(3) and (4), we get

$$E_r = -jE_o \sum_{n=1}^{\infty} C_n\left(\hat{J}_n''(k_b r) + \hat{J}_n(k_b r)\right) P_n^1(\cos\theta) \quad (10)$$

$$E_\theta = \frac{jE_o}{k_b r}\sin\theta \sum_{n=1}^{\infty} C_n \hat{J}_n'(k_b r) P_n^{1\prime}(\cos\theta) \quad (11)$$

$$E_\phi = 0 \quad (12)$$

where $k_b = \omega\sqrt{\varepsilon_b \mu_o}$.

3. POWER ABSORPTION AND HEATING PATTERNS

The absorbed power density, $W(r,\theta)$, due to the electric fields E_r and E_θ inside the model is written as

$$W(r,\theta) = \frac{1}{2}\sigma(|E_r|^2 + |E_\theta|^2) \qquad (13)$$

where σ is the brain conductivity. $W(r,\theta)$ is calculated at the medical frequencies 0.433, 0.918 and 2.45 GHz and for θ varying from 90° to 180° in order to satisfy the suggested semi-sphere model. The brain conductivity and permittivity values at the operating frequencies are given by Stuchly [10] and they are listed in Table (I). Figures (2) show the relative absorbed power, $w(r,\theta) = W(r,\theta)/E_o^2$, as a function of brain depth at different values for the angle θ. The heating pattern due to absorbed power $W(r,\theta)$ can be obtained by solving the heat diffusion equation. The diffusion equation for the phantom model (the effect of blood flow is neglected) is given by Ho *et al.* [3] as

$$\rho c \frac{\partial T(r,t)}{\partial t} - \mathrm{div}(\gamma \nabla T(r,t)) = W(r,\theta) \qquad (14)$$

Table I. Brain permittivity and Conductivity Constants at the Operating Frequencies.

f (GHz)	ϵ'	ϵ''	σ (S/m)
0.433	35.5	28.0	0.674
0.918	34.4	15.2	0.776
2.450	33.6	9.1	1.240

where $T(r,t)$ is the temperature in °C inside the brain model, ρ is the density of brain in Kg/m^3, c is the specific heat of brain in J/Kg °C, and γ is the thermal conductivity of brain in W/m °C. All the brain physical parameters are given by Van Den Berg *et al.* [11] and they are listed in Table (II). In the range of temperature where hyperthermia is applied, the change of γ, ρ and c with temperature can be ignored. The partial differential equation must be supplement by initial and boundary conditions. Let t=0 be the instant at which the incident plane wave is applied. Therefore, the initial condition is $T(r,0) = T_o$, while the boundary condition is $T(0,t) = T_o$. T_o is the equilibrium temperature of human brain (37°C).

The heat partial differential equation can be solved numerically by the finite difference explicit method. The explicit method is based on dividing the plane (r,t) into thin rectangular plates of thicknesses of Δt and Δr, then converting the differential equation into a difference equation as [12]

$$\frac{T_{i,j+1} - T_{i,j}}{\Delta t} = \frac{\alpha(T_{i+1,j} - 2T_{i,j} + T_{i-1,j})}{\Delta r^2} + \frac{1}{r_i}\frac{\alpha(T_{i+1,j} - T_{i-1,j})}{\Delta r} + W(r_i,\theta_o)/\rho c \qquad (15)$$

Table II. Brain physical parameters.

τ (W/m°C)	σ(Kg/m^3)	c (J/Kg °C)
0.5	10^3	3.5 x 10^3

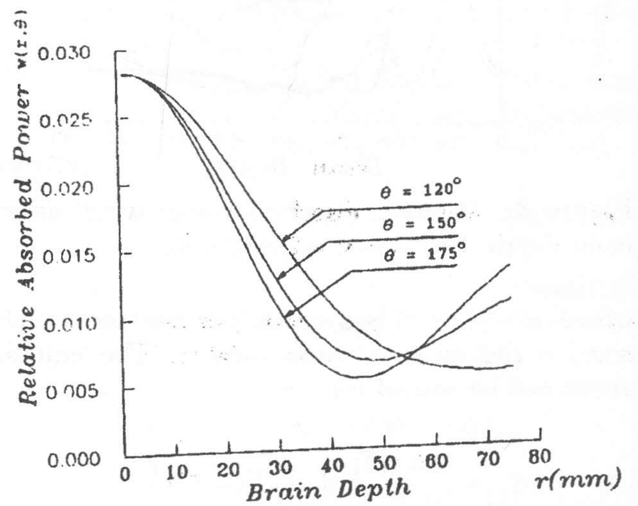

Figure 2a. Relative absorbed power w (r,θ) against brain depth frequency = 0.433 GHz.

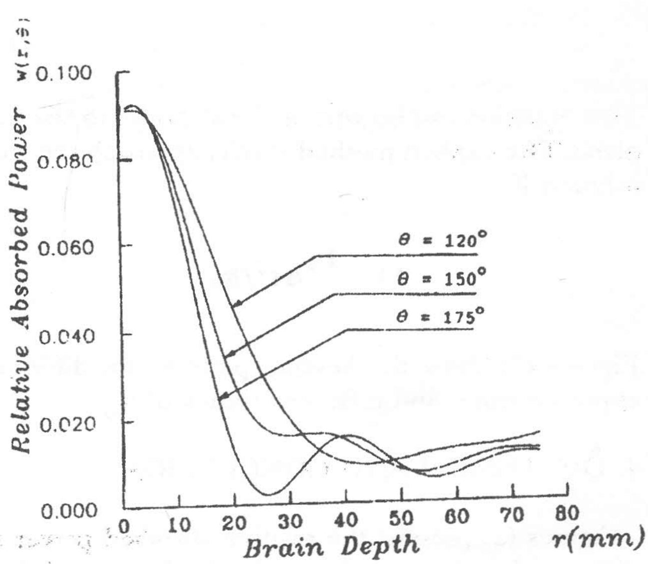

Figure 2b. Relative absorbed power w (r,θ) against brain depth. Frequency = 0.918 GHz.

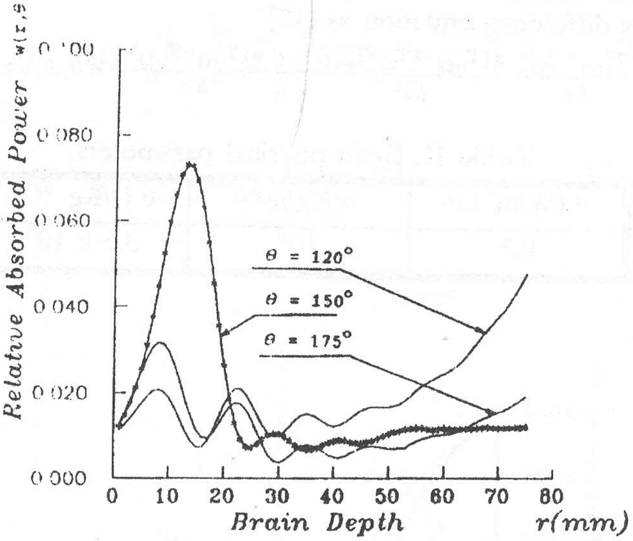

Figure 3c. Relative absorbed power $w(r,\theta)$ against brain depth. Frequency = 2.45 GHz.

where $\alpha = \gamma/\rho c$. i is the index of position variable and j is the index of time variable. The equation above can be solved for

$$T_{i,j+1} = T_{i,j} + \frac{\alpha \Delta t(T_{i+1,j} - 2T_{i,j} + T_{i-1,j})}{\Delta r^2} + \frac{1}{r_i}\frac{\alpha \Delta t(T_{i+1,j} - T_{i-1,j})}{\Delta r} + W(r_i,\theta_o)\frac{\Delta t}{\rho c} \tag{16}$$

This equation can be written for all nodes in the (r,t) plane. The explicit method results approach the true solution if

$$\Delta t \leq \frac{1}{2}(\Delta r^2/\alpha) \tag{17}$$

Figures (3) show the heating patterns for different exposure time and different values of E_o.

4. DISCUSSION AND CONCLUSION

Figures (2) present the relative absorbed power at different locations (r_i, θ_i) inside the brain model. It is observed that the frequencies 0.433 and 0.918 GHz are unsatisfactory as diathermy frequencies because the relative absorbed power $w(r,\theta)$ decreases as the brain depth increases. While for 2.45 GHz, $w(r,\theta)$ increases then decreases as the brain depth increases. Also, it is observed that at θ = 150°, $w(r,\theta)$ increases to a maximum value then decreases within a width of approximately 25 mm. Thus, the frequency 2.45 GHz can be considered as a diathermy frequency for the human brain model. The heating patterns for a phantom brain model are presented in Figures (3). The operating frequency is 2.45 GHz and the suitable angle θ_o =150°. Figure 3-a shows that for E_o= 7.07 x 10^3 V/m the maximum temperature values are 43°C, 45°C, 47°C for exposure time 6 , 8 and 10 seconds. While figure 3-b shows that the temperature peak values 41°C, 45°C, 49°C can be achieved at the same location by E_o = 10^4 V/m but for exposure time 2 ,4 and 6 seconds respectively.

As a result, the required maximum temperature value to treat a tumor can be achieved by selecting suitable values of exposure time and E_o. Furthermore, it is important to specify the plane wave incident direction to ensure that the tumor location be on the direction of the angle θo.

Finally, the noninvasive method discussed in this paper may be applied towards hyperthermia treatment to destroy tumor at certain location inside human brain without surgery operations.

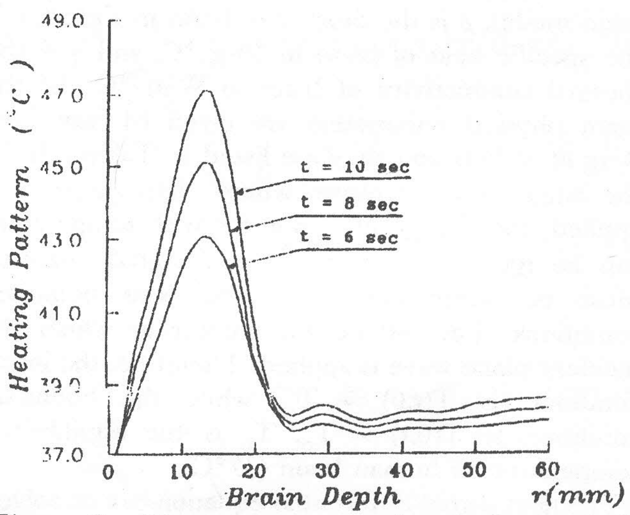

Figure 3a. Heating pattern against brain depth for different exposure time t. Frequency = 2.45 GHz, θ_o = 150°, E_o = 7.07 x 10^3 V.m.

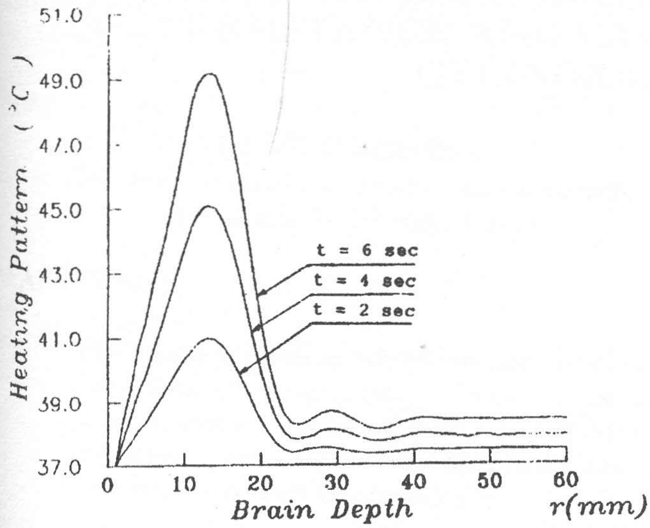

Figure 3b. Heating pattern against brain depth for different exposure time t. Frequency = 2.45 GHz, θ_o=150°, E_o=10^4 V/m.

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