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THERMAL EFFECTS IN HUMAN EXPOSURE TO MICROWAVES

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Abstract
Radiofrequency exposure guidelines and standards for localized human exposures state averaging specific (energy) absorption rate (SAR) over a mass of tissue [11]. Cubic volumes with mass of 1 or 10 g (sides of approximately 1.0 or 2.1 cm, respectively) have been recommended. Averaging volume becomes important for exposures near the radiofrequency (RF) source at high frequencies with low depth penetration. Controversy exists because averaging the volume at 10 g permits higher SAR peak than at 1g. Assuming that temperature has the major effect on biological tissue, we estimate average temperatures over 1 and 10 g in a simplified head geometry, to give quantitative comparation criteria between the two measuring methods

1. INTRODUCTION

The recommendations concerning exposure to RF energy have been based on limiting the exposure to levels that do not significantly increase the body's heat load. For human beings and animals, the principal measure of RF dose rate is the Specific (energy) Absorption Rate (*SAR*) averaged over the whole body. The average *SAR*, as defined by standards (NCPS, 1986; ICNIRP, 1998; IEEE/ANSI, 1999), is the measure that limits permissible RF exposure to specific parts of the body, especially the head and the trunk..

The mobile phone users have the RF emissions focussed in head, which is placed in the proximity of the antenna or other radiating parts of the phone. Sophisticated models have been developed with anatomically accurate tissue structure and dielectric properties (conductivity and permittivity) and RF field radiation patterns specific for mobile phones.

In papers [2] and [3] we demonstrate that the accuracy of anatomical structures is not so relevant for *SAR* estimations, because the electric field (*E*) distribution is mainly superficial. The electric field *E* and *SAR* distributions depend more on the geometrical shape of the body at the electromagnetic field (EMF) impact. Sustaining this idea, the experimental determinations of *SAR* are made on an equivalent phantom (SAM) with an accurate head shape but a homogenous inside structure [10]

In this previous studies and also in [4, 5] we validate a 2D model with equivalent dielectric properties for head.

The present paper continues the study estimating the temperatures in the human head exposed on RF, for different specific mobile phone frequencies and 2D simplified head.

2. THE HEATING PROBLEM

Biological cells are sensitive to temperature. The fundamental basis for acceptance of radio frequency devices is the limitation on temperature rise that can be expected in the exposed tissue. For safety, *SAR* must remain below given limits to avoid tissue damage caused by heating. The local temperature rise is limited by heat conduction, heat convection by blood flow, and perhaps other heat transport mechanisms as well. In this case, the total excessive local temperature rises might occur, even though the total thermal burden to the body is modest. Comparing the time constants from thermal conduction and heat convection by blood flow paper [6] demonstrates that at frequencies above 2-3GHz the thermal response of tissue in conduction dominated.

The temperature of tissues exposed to RF when the depth penetration of energy is little, without taking into account the influence of the heat generated by metabolism, may be described by making use of the Pennes bioheat equation:

$$\rho C \frac{dT}{dt} = \nabla(k\nabla T) + \rho_B w C_B (T - T_B) + SAR\,\rho \tag{1}$$

where T represents the temperature of tissue [K], ρ is the tissue density [kg/m^3], C is the tissue heat capacity [J/kg K], k is the tissue thermal conductivity [W/m K], w is the blood perfusion rate [ml/g/s]. The terms ρ_B, C_B and $\mathbf{T_B}$ are representing the mass density, temperature and heat capacity values for unheated blood (310K).

The second term from the right side of equation *(1)* is used to introduce the remove of tissue heating by the blood perfusion.

The heating source for the domain is the resistive heating due to the electric field penetration. The conductive material is the biological tissue. The general equation for *SAR* is

$$SAR = \frac{\sigma |E|^2}{2\rho} \tag{2}$$

where σ, ρ are the electrical conductivity, mass density, respectively and E is the electrical field strength.

In conclusion, the possibility of temperature determination is based on electrical field evaluation for a biological tissue domain exposed to RF.

3. THE EMF PROBLEM

In the microwave (MW) RF domain the tissue dielectric properties are expressed in terms of complex values.

$$\underline{\varepsilon} = \varepsilon - j\sigma/\omega \qquad\qquad \underline{\sigma} = \sigma + j\omega\varepsilon \tag{3}$$

where ε is the dielectric permittivity, σ is the electric conductivity and $\omega = 2\pi f$ is the angular frequency and f is the frequency. The materials presenting such complex values for dielectric properties are called *lossy materials*. Unlike this, the tissue magnetic properties are unaffected from frequency *(* $\mu_0 = 4\pi 10^{-7}$ *H/m*).

The wave equations applied for lossy materials are described by Maxwell equations for time-harmonic propagation:

$$\nabla\times\left(\frac{1}{\mu_0}\nabla\times\underline{E}\right) - \omega^2\underline{\varepsilon}\,\underline{E} = 0 \qquad\qquad \nabla\times\left(\frac{1}{\underline{\varepsilon}}\nabla\times\underline{H}\right) - \omega^2\mu_0\underline{H} = 0$$

The solution of this equations system, in terms of electric field, determine the heat source of the considered domain (Eq.2).

4. THE COMPUTATIONAL MODEL

The evolution of phenomena permits to construct the heating model for the head. The heating problem is based on knowing *SAR* value in head tissues. This represents the heating source in the domain. So, the EMF problem must be solved before the heat problem.

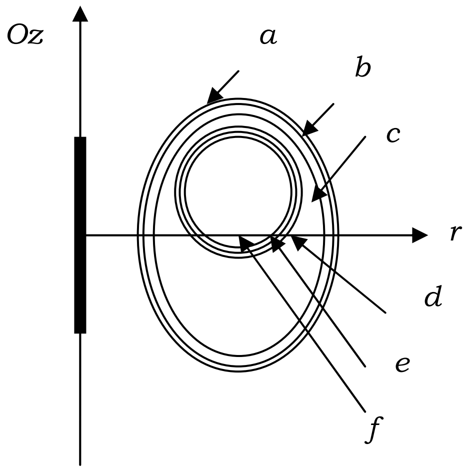


Fig.1 2D axisymmetrical computational domain

The computational domain is based on a 2D axisymmetrical geometry (this choice was validated in [2]) and the numerical computation used is based on Finite Element Method (we used finite element software FEMLAB 3.0 [9]).

The geometry describes a multilayered ellipsoid witch approximate a human head and an EMF source, a dipolar antenna, placed at 0.5cm near the head (on the ear proximity). The geometry dimensions are specified in [4] and [5]. The six tissues involved are skin (*a*), fat (*b*), bone (*c*), dura (*d*), cerebro spinal fluid (CSF) (*e*) and brain (*f*) (Fig.1). The dielectric properties and the mass density values are considered the same as in [5]. The electrical properties are depending on considered frequency. The computation was done for frequencies used in European GSM mobile system (0.9-1.8-2.5)GHz.

The thermal properties of the tissue depend on temperature [7]. We assume that the temperature rise does not exceed a few grades over 310K (the healthy body temperature) (Table1).

The computation was made also for a homogenous structure. For this case the electrical properties used are computed in [5] and the thermal properties considered are recommended from literature [6] (Table1).

Tissue	Skin (a)	Fat (b)	Bone (c)	Dura (d)	CSF (e)	Brain (f)	Blood	Homogenous structure
k [W/m C]	0.293	0.201	0.41	0.564	0.564	0.502		0.6
C [J/kg C]	3662	2973	1256	4182	4182	3664	3894	4000
ρ [kg/m^3]	1100	920	1850	1050	1060	1030	1060	1000

Table 1: Tissues thermal properties

The EMF source is a half-wavelength dipole antenna oriented on Oz axis. Its length is adapted on the emitted wave frequency and its radiated power is maintained at 0.125W in all studied cases.

Computational software module

For the EMF problem the FEMLAB 3.0 software - *Electromagnetics Module* was used, in the *axisymmetric transversal magnetic (TM)* wave application mode, *time-harmonic* submode [9].

For the heat problem the *Heat-Transfer Module* was chosen, in the *Conduction* mode, *steady-state* submode.

Boundary conditions for EMF problem

The computational domain is limited with *low-reflecting boundary conditions* and the boundary on Oz axis satisfies *axial symmetry conditions*. The EMF is introduced through a magnetic field variation boundary condition.

Boundary conditions for heat problem

Because the resistive losses exist only in biological tissues, the heat problem was computed in these subdomains. The boundary conditions fix the outside of the head at the temperature of 310K.

5. RESULTS

The first step of the computation was made without considering the influence of blood perfusion cooling.

Fig.(2) presents temperature distributions for the six-layers head model, at three EMF frequencies (0.9-1.8-2.5 GHz). The maximum values for SAR and temperature are found near the outside surface because the penetration depth is very low at microwave frequencies. At 0.9GHz the maximum values are placed nearby the dura-CSF region and for 2.5GHz they are moved in the bone region.

Tables 2 and 3 present the average values for *SAR* and temperature considering 1 and 10g of tissue (SAR_1 and SAR_{10} - T_1 and T_{10}).

	0.9 GHz	**1.8 GHz**	**2.5 GHz**
SAR_1	1.58	4.18	6.97
SAR_{10}	1.39	3.43	5.46
SAR_{max}	6.89	14.43	14.5

Table2: SAR values without considering blood perfusion cooling

		0.9 GHz	**1.8 GHz**	**2.5 GHz**
T_1	[K]	310.**274**	310.**393**	310.**465**
T_{10}	[K]	310.**245**	310.**306**	310.**356**
T_{max}	[K]	310.**291**	310.**417**	310.**554**

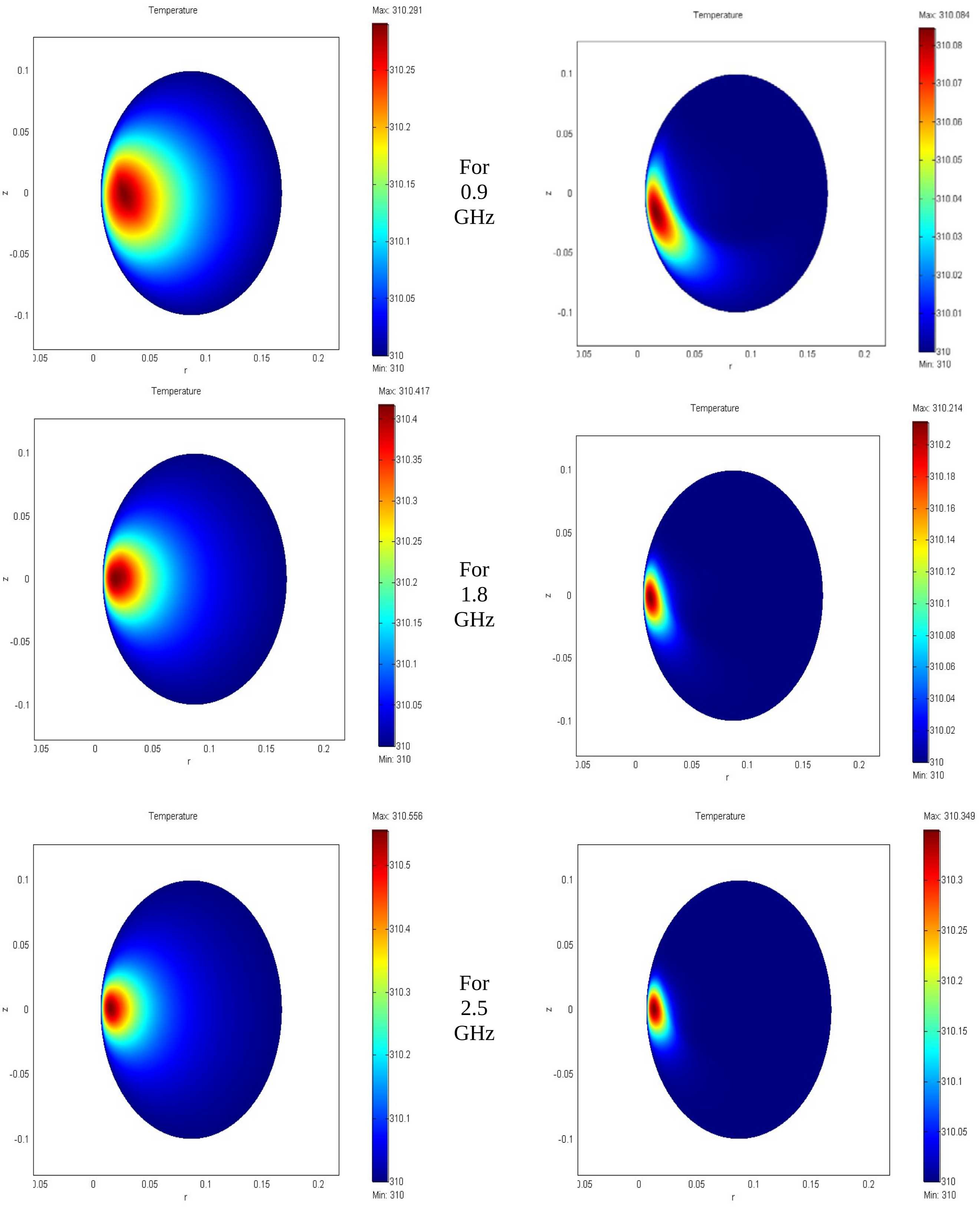
Table3: T values without considering blood perfusion cooling

The temperature increases over the normal temperature (310K), are in the range estimated in [6] and [11]. Average SAR values for higher frequencies (1.8-2.5GHz) overpass the imposed values by standards.

For an accurate problem modeling it is correct to consider also that blood perfusion cools the tissues. In this case, we take into account the $\rho_B w C_B (T - T_B)$ term of Pennes bioheat equation (Eq1). This can be made only for tissues that have blood circulation (skin, dura, CSF, brain). The blood perfusion rate is assumed to have a typical value for biological tissue 0.0066 ml/g/s. The results for this case are presented in Table 4 and they show that the blood cooling diminuates the over-temperatures with 60-80%.

	0.9 GHz	**1.8 GHz**	**2.5 GHz**
T_{max}	310.**084**	310.**214**	310.**244**

Table4: T values considering blood perfusion cooling



For
0.9
GHz

For
1.8
GHz

For
2.5
GHz

without blood perfusion

with blood perfusion

Fig.2 T distribution values on head surface for three different frequencies: 0.9, 1.8, 2.5GHz

6. CONCLUSIONS

The international concern about the possibility of physiological perturbations in human tissues exposed on RF, generate a large number of studies and experimental measurements of average *SAR* and temperatures in tissues. This paper presents the average temperature estimation on 1 and 10g of tissue for the human head exposed on mobile phone emitted EMF. The considered frequencies are typically for the European GSM mobile system (0.9-1.8-2.5)GHz. The computational domain was simplified to a 2D axisymetrical domain with a six-layered head structure.

The heating problem was preceded by the EMF problem, which evaluated the average *SAR* values in the computational domain. Unlike the values of average *SAR* for 0.9GHz, at 1.8 and 2.5GHz these values exceed the standards recommendations.

Many laboratory studies have demonstrated that the board range of tissue damage resulting from either partial-body or whole-body heating, are producing by temperature rises in excess of 1-2C. This threshold for irreversible effects, in even the most sensitive tissues, is greater then 4W/kg under normal environmental conditions [11]. The results that we estimated solving the heat problem are in the spirit of these conclusions.

The average temperatures do not exceed 310.6K (37.6C) neither for average *SAR* values greater than recommended values. The temperatures are even less when we consider the influence of blood perfusion cooling in tissues.

In this terms the paper creates the possibility of a quickly evaluation of an over thermal load of human head due to the emitted mobile phone EMF.

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