EFFECT OF WAVE PROPAGATION AND HEAT TRANSFER IN SKULL-CSF-BRAIN SYSTEM EXPOSED TO ELECTROMAGNETIC WAVE

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Abstract. *The purpose of this work is to analyze the temperature field within human head subjected to electromagnetic waves of very high frequency. The source of electromagnetic wave is a patch antenna. For this, we use a coupled electromagnetic-heat transfer model. The resolution of the coupled problem was done using the finite element method.*

1 INTRODUCTION

In recent decades, intensive use of mobile phones has led some scientists and researchers to study the effects of electromagnetic waves of high frequency on living tissue. Most studies focuses on the variation of the Specific Absorption Rate (SAR), which is considered to be a relevant parameter for quantifying the degree of absorption of the Electromagnetic waves in living tissues. Several models have been proposed. Most these models use the coupling of an electromagnetic model with bioheat model. Thus, one can access to temperature distribution in the different layers of tissues constituting the human head. Our study focuses on electromagnetic-biothermal coupling model applied to the human head, taking into account the presence of Cerebro Spinal Fluid (CSF), because its physical characteristics (either thermal or electromagnetic) are very different compared to the other tissues within head. Indeed, in most previous studies conducted e.g. [1]-[4], the influence of the CSF is not taken into account.

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2 MATHEMATICAL MODEL OF THE HEAD

In this study, we consider a simple model which consists of a patch antenna (Ω_T), a spherical head $(\Omega) = \bigcup_{k=1}^{N} \Omega_k$ formed of N concentric layers and environmental domain (Ω_a) as reported on Figure 1. To avoid wave reflection phenomena on the head boundary, a Perfectly Matched Layer (PML) was added on the outer surface. On the boundary (Γ_∞), we add a scattering boundary condition. We denote $\Omega_0 = \Omega \cup \Omega_T \cup \Omega_a$. The problem is to find the electric field $\mathbf{E}$ in the whole domain and the temperature field T in the head.
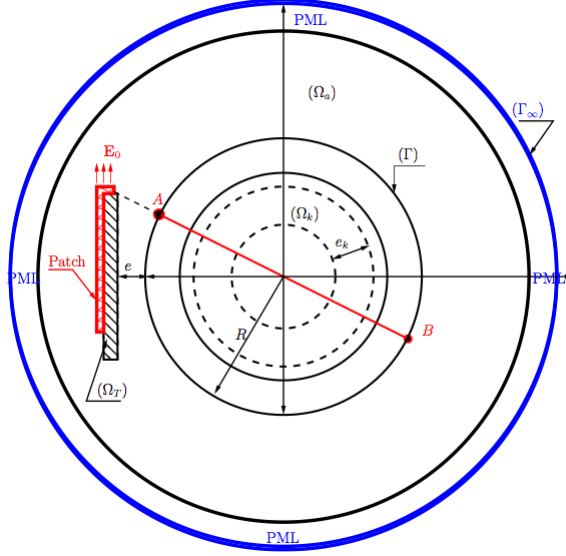

Figure 1: Simplified model of the head and the PML (surrounding the head)

For the harmonic analysis the problem is stated as follows: Given a frequency parameter ω, find the electric and temperature fields $(\mathbf{E}, T)$ solutions of problem with boundary conditions :

$$\begin{cases} \nabla \times \left(\dfrac{1}{\mu_r} \nabla \times \mathbf{E} \right) - k_0^2 \varepsilon_{rc} \mathbf{E} & = & \mathbf{0} & (\Omega_0) \\ \nabla \cdot (-\lambda_c \nabla T) & = & \rho_b C_b \omega_b (T_b - T) + Q_{met} + Q_{ext} & (\Omega) \\ \mathbf{n} \cdot \nabla T & = & \mathbf{0} & (\Gamma) \\ \mathbf{n} \times (\mathbf{E} - \mathbf{E}_a) & = & \mathbf{0} & (\Gamma) \\ \mathbf{E} & = & \mathbf{E}_0 & (\Gamma_0) \\ \varepsilon_{rc} & = & \varepsilon_r - j \dfrac{\sigma}{\omega \varepsilon_0} & (\Omega_i) \\ \mathbf{E} & = & \mathbf{E}_\infty & (\Gamma_\infty) \end{cases} \quad (1)$$

The first equation governs the electromagnetic wave propagation, whereas the second equation one expresses the heat propagation (conservation of energy or bioheat equation). In this system, $\mathbf{E}$ is the electric field intensity (V/m), μ_r is the relative magnetic permeability, ε_r is the

relative dielectric constant, σ is the electric conductivity (S/m), and k_0 is the free space wave number $(1/m)$ of the ekectromagnetic waves. When electromagnetic waves propagate through the human head, the energy of electromagnetic waves is absorbed by the tissues. The amount of energy absorbed is measured by the so-called Specific Absorption Rate (SAR) defined by

$$\text{SAR} = \sum_{\text{k}=1}^{\text{N}} \sigma_{\text{k}} \frac{||\mathbf{E}_{\text{k}}||^2}{\rho_{\text{k}}} \tag{2}$$

where ρ_k and σ_k are the density and the electric conductivity of tissue Ω_k respectively.

In the bioheat equation, λ_c is the thermal conductivity of tissue (W/m K), T is the tissue temperature ($^{\circ}C$), T_b is the temperature of blood ($^{\circ}C$), ρ_b is the density of blood (kg/m^3), C_b is the heat capacity of blood (3960J/kg K), ω_m is the blood perfusion rate (1/s), Q_{met} is the metabolism heat source (W/m^3), and Q_{ext} is the external heat source (electromagnetic heat-source density) (W/m^3). The external heat source term is equal to the resistive heat generated by the electromagnetic field (electromagnetic power absorbed), which is defined as

$$\text{Q}_{\text{ext}} = \frac{1}{2} \sum_{\text{k}=1}^{\text{N}} \sigma_{\text{k}} ||\mathbf{E}_{\text{k}}||^2 \tag{3}$$

2.1 Numerical solution of model

First we proceed to the variational formulation of the local equations in (1). As the problem contains a rotational term, we define new functional spaces involving the curl of a vector field:

$$\mathbf{H}(\mathbf{rot}, \Omega) = \{\mathbf{v} \in L^2(\Omega), \nabla \times \mathbf{v} \in L^2(\Omega)\} \, ; \, \mathbf{H}(div, \Omega) = \{\mathbf{v} \in L^2(\Omega), \, \nabla \cdot \mathbf{v} \in L^2(\Omega)\} \tag{4}$$

We can now introduce spaces of functions tests (analogous to the space of virtual velocities):

$$\mathbf{V} = \{\mathbf{v} \in \mathbf{H}(\mathbf{rot}, \Omega), \, \mathbf{n} \times \mathbf{v} = \mathbf{0} \, (\Gamma)\} \, ; \, \mathbf{W} = \{\mathbf{v} \in \mathbf{H}(div, \Omega), \, \mathbf{n} \cdot \mathbf{v} = \mathbf{0} \, (\Gamma)\} \tag{5}$$

The choice of the second space makes it possible to suitably treat the Gauss's law. First, we multiply the wave equation of electromagnetic field in (1) by a test function $\mathbf{v}$ and used the Green's formula, then the same method is applied for the heat equation with a test function ϕ and we deduce the variational formulation of the boundary value problem (1) :

$$\begin{cases} \int_{\Omega_0} \left(\frac{1}{\mu_r} \nabla \times \mathbf{E}\right) \cdot (\nabla \times \mathbf{v})dx - \int_{\Omega_0} k_0^2 \varepsilon_{rc} \mathbf{E} \cdot \mathbf{v} dx & = & 0 \\ \int_{\Omega} \lambda_c \nabla T \cdot \nabla \phi dx - \int_{\Omega} \rho_b C_b \omega_b (T_b - T)\phi dx & = & \int_{\Omega} [Q_{met} + Q_{ext}]\phi dx \end{cases} \tag{6}$$

for all $(\mathbf{v}, \phi) \in (\mathbf{V} \cap \mathbf{W}, Q)$, with $Q = H^1(\Omega)$. To discretize the variational formulation (6), we use the finite element method adapted to functional spaces which are introduced previously. We denote (A_k) the mesh nodes and consider mesh nodes and therefor introduce the shape

functions $\mathbf{N}_k$ such as $\mathbf{E}(x) = \sum_{k=1}^{N} \mathbf{E}(A_k)\mathbf{N}_k(x)$. Discretization of the variational formulation of the problem (6) leads to the system

$$\left\{ \begin{array}{rcl} (\mathbb{K} - \omega^2\mathbb{M})\,\mathbf{E} & = & \mathbf{0} \\ \mathbb{K}_T\mathbf{T} & = & \mathbf{F}(\omega, \mathbf{E}) \end{array} \right. \tag{7}$$

where $\mathbb{K}$ et $\mathbb{M}$ are called electromagnetic stiffness and electromagnetic mass matrices respectively, whereas $\mathbb{K}_T$ is the heat stiffness matrix.

2.2 Physical properties of tissues

We take the physical properties from literature. Dielectric properties of tissues [6] of the head are given in table 1.

Tissue	900MHz			1800MHz			2450MHz		
	ε_r	σ	ρ	ε_r	σ	ρ	ε_r	σ	ρ
Skin	43.8	0.86	1100	43.85	1.23	1100	42.85	1.59	1100
Fat	11.3	0.11	1100	11.02	0.19	1100	10.82	0.26	1100
Muscle	55.9	0.97	1040	54.44	1.38	1040	53,64	1.77	1040
Skull	20.8	0.34	1850	15.56	0.43	1850	15.01	0.57	1850
Dura	44.4	0.96	1030	42.89	1.32	1030	42.03	1.66	1030
CSF	68.6	2.41	1030	67.2	2.92	1030	66.24	3.45	1030
Brain	45.8	0.77	1030	43.54	1.15	1030	42.61	1.48	1030

Table 1: Values of dielectric properties of tissues depending on the frequency

Thermal properties of tissues [6] of the head are given in table 3.

Tissue	ρ	k	C_p	Q_{met}	ω_b	C_b
Skin	1125	0.42	3600	1620	0.02	3960
Fat	916	0.25	3000	300	4.58×10^{-4}	3960
Muscle	1090	0.49	3421	480	8.69×10^{-3}	3960
Skull	1990	0.37	3100	610	4.36×10^{-4}	3960
Dura	1030	0.436	1300	610	4.36×10^{-4}	3960
CSF	1060	0.62	4096	0	0	3960
Brain	1038	0.535	3650	7100	8.83×10^{-3}	3960

Table 2: Values of thermal properties of tissues depending on the frequency

3   MODAL ANALYSIS IN 2D MODEL

Modal analysis is an important step before making harmonic analysis. Indeed, it helps to have specific information about the resonance frequencies of the system we consider. In this section, we address the electromagnetic modal analysis. This analysis faces some real diffuculties, because of the dielectric properties of biological tissues, which vary with the excitation frequency, as shown in Table 1. The problem consist to find electric field and temperature field $(\omega, \mathbf{E})$ solutions of system :

$$\left(\mathbb{K} - \omega^2 \mathbb{M}\right) \mathbf{E} = \mathbf{0} \tag{8}$$

The Four layers model consists of the following tissues : Skin-Fat-Muscle-Skull-Dura-CSF-Brain. It is analogous to that used in [6]. Using COMSOL software, we obtain the frequecies and modal shapes. The seven layers model consists of the tissues : Skin-Fat-Skull-Brain. It is also analogous to that used in [3]. We observe that the results on modal shapes are very sensitive to the number of layers used in the model. Taking as values of the dielectric constants those corresponding to a frequency $f_0 = 900 MHz$, we report the calculated resonance frequecies associated to the four and seven layers models.

	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}
4 Layers	237.9	420.9	579.7	625.9	728.9	804.6	872.9	971.4	999.6	1013.7
7 Layers	122.9	244.4	354.8	381.9	402.3	504.4	529.1	543.4	633.0	643.5

Table 3: The first 10 resonance frequencies for both models in MHz

4   ELECTROMAGNETIC-BIOHEAT COUPLED MODEL IN 2D

We will now use the model developed in the previous paragraph govenrned by the system of equations (7). The expected results concern the SAR and the temperature field and their variation along the diameter AB of the head.

4.1   Four layers model

For the electric field, we then obtain the following results. We observe that the distribution of SAR on AB is very similar to that obtained in [3].
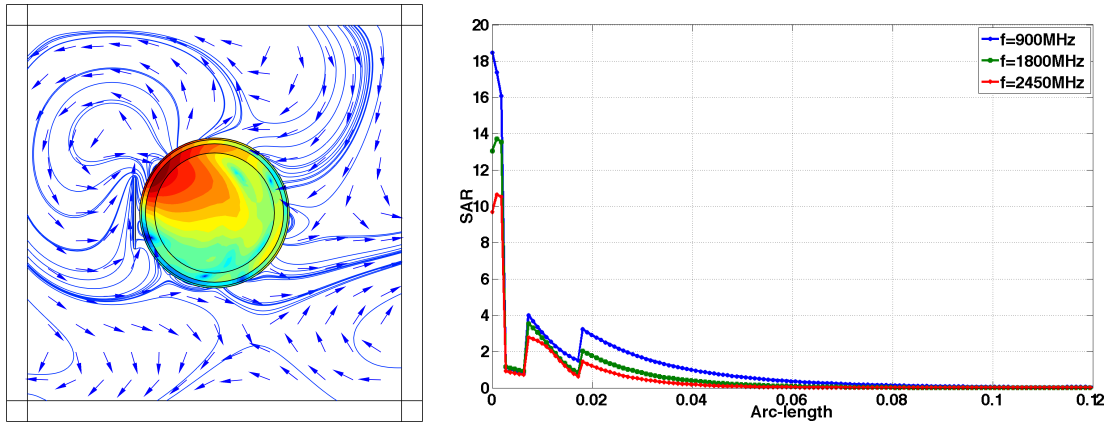
Figure 2: Magnetic fields, SAR distribution in the head for frequencies $f = 900MHz$ and SAR along AB.

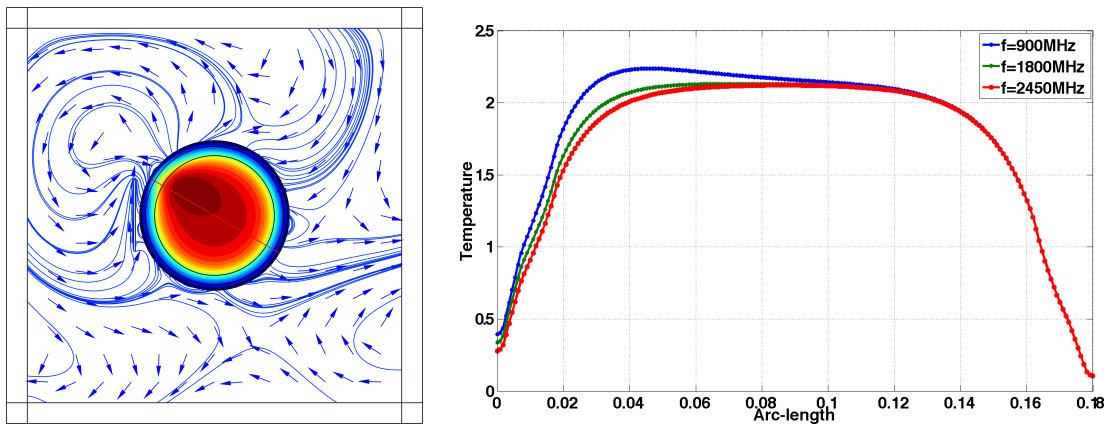For the temperature field, we then obtain the following results. It can be seen that there is

Figure 3: Magnetic fields, T distribution in the head for frequencies $f = 900MHz$ and T along AB.

an increase of the temperature in center of the head. Conversely, the peripheral layers are not affected by this increase of temperature.

4.2   Seven layers model

This is the model proposed in [6] to calculate the distribution of SAR. We added in the framework of the present study, a heat transfer model. For the electric field, we report the results on the figure below. We observe that the distribution of SAR on AB is very similar to that obtained in [6]. However, the accounting for the number of layers may drastically change the results (see partcularly the distribution of SAR along AB).
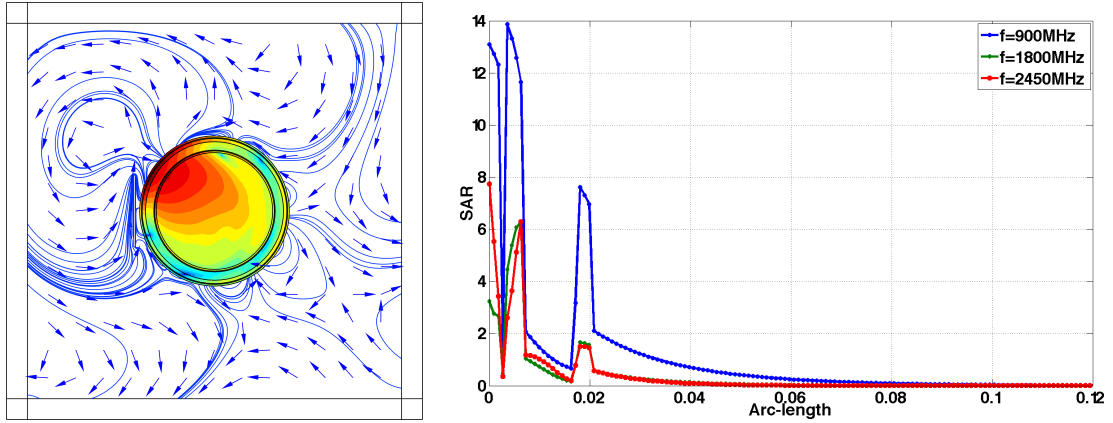
Figure 4: Magnetic fields, SAR distribution in the head for frequencies $f = 900MHz$ and SAR on AB.

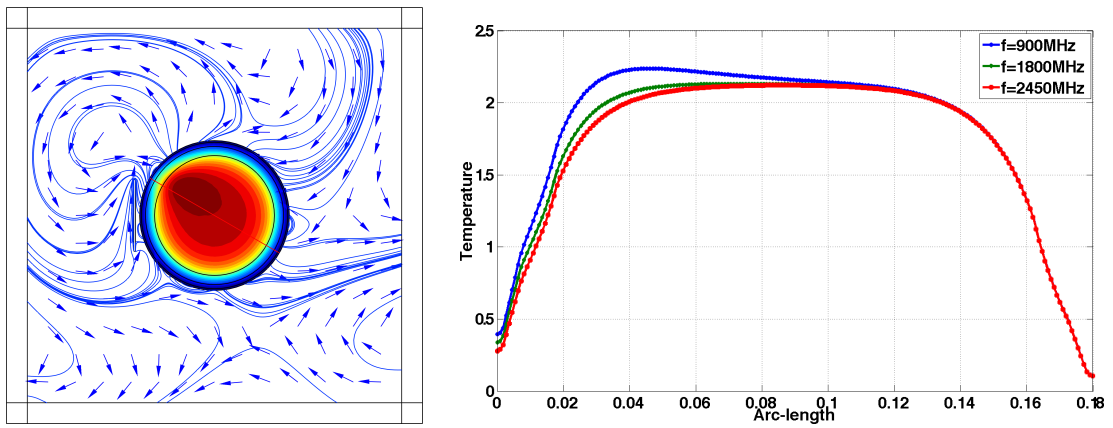For the temperature field, results is reported below for the seven layers model. We observE

Figure 5: Magnetic fields, T distribution in the head for frequencies $f = 900MHz$ and T on AB.

that the shape of the temperature curves along AB is very similar to those obtained with the four-layer model.

5 ELECTROMAGNETIC-BIOHEAT COUPLED MODEL IN 3D

The model is identical to that presented previously in 2D. It is also described by the boundary value problem (1) and by the system (7). Only the domain of the head model is changed (2D to 3D).

5.1 Four layers model

Again, we calculate the electric field and we obtain the below results. For the sake of the simplicity, countour plots are reported on different slices of the spherical head. We observe that
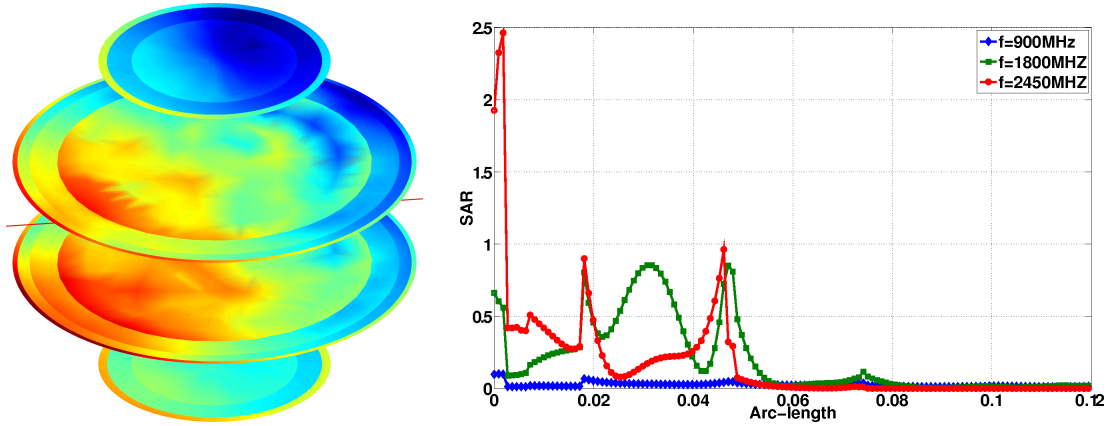
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Figure 6: SAR distribution in the head for frequencies $f = 900MHz$ and SAR on AB.

the distribution of SAR along AB is very similar to that obtained in [3].

The temperature field for the 3D head model is displayed on the figure below, it conforms to the 2D model since high temperature are observed in the central domain of the head.
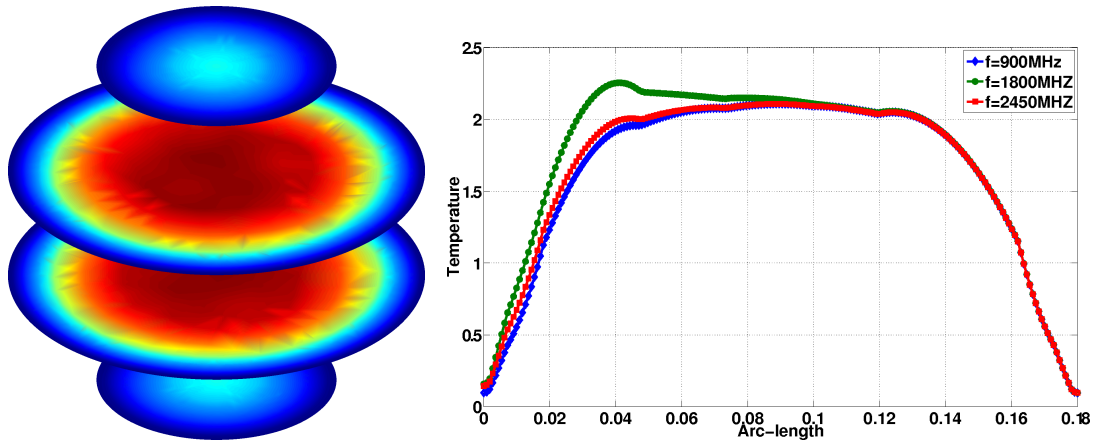

Figure 7: T distribution in the head for frequencies $f = 900MHz$ and T on AB.

It can be seen that there is an increase of the temperature in domain center. The peripheral layers are not affected by this increase of temperature.

5.2 Seven layers model

The distribution of the electric field is reported on the figure below for the 2seven layers 3D model. The distribution of DAS on AB is very similar to that obtained in [6].
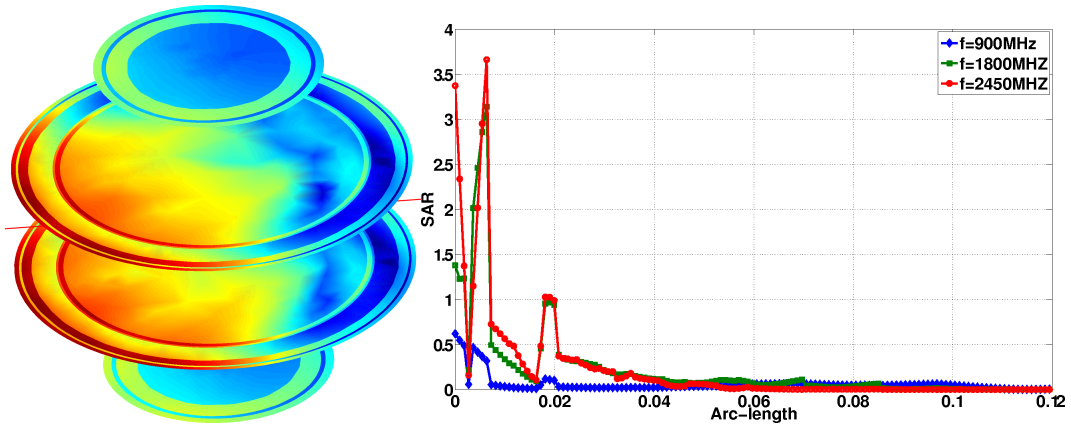
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Figure 8: SAR distribution in the head for frequencies $f = 900MHz$ and SAR along AB.

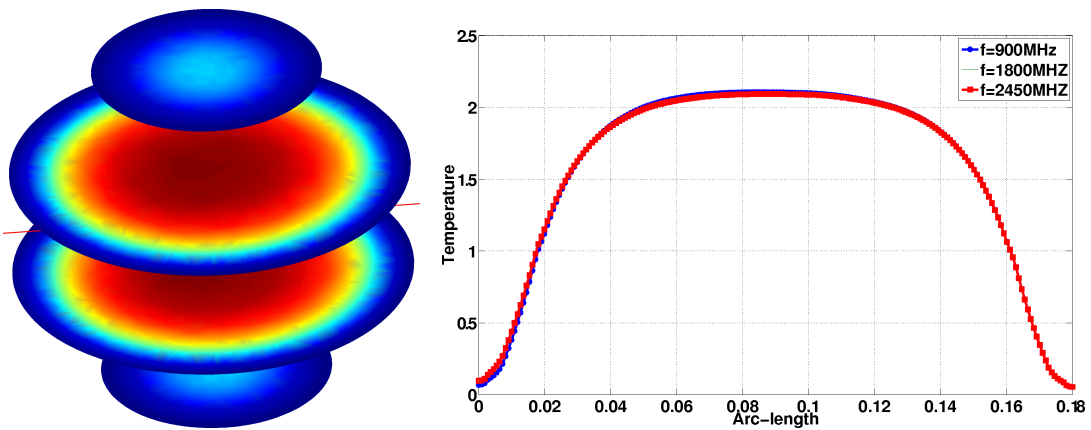As a last illustration, the distribution of temperature within the 3D model is given below.

Figure 9: T distribution in the head for frequencies $f = 900MHz$ and T on AB.

We observe that there is an increase of the temperature in central region of the head. The peripheral layers are not affected by this increase of temperature.

6 CONCLUSIONS

From the results obtained in this study, some preliminary conclusions could be drawn.

- The results are very sensitive to the number of layers used, as well to dielectric and thermal properties of the layers.

- Whatever the power emitted by the antenna, the shape of the response curves are similar. However the intensity of the SAR and the value of the temperature changes with the power emitted by the antenna.

- The presence or not of CSF has a great influence on the frequency response of the system.

These may be considered as preliminary results, some improvements should be undertaken as the accounting for a more realistic geometry of the head, and particularly of the extremely complex shape and the heterogeneity of the brain. However, the results we obtain can be considered as first step, and helpful to define the research direction in the domain of the bioheat due to electromagnetic waves provoked by antenna patch. The coupling of electromagnetic waves and heat production in living tissues remains a great challenge to future studies on the intensive use of cell phone, particularly for children and adolescents, for which brain damage may be irreversible.

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