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Numerical Modeling of the Interface between Source RF and the Human Body

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Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

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ABSTRACT

We want to write a very important part of our research by a presentation with a numerical method, which aims to solve the electromagnetic radiation effects of radio frequency source on the human body. With other words, what are the effects of the use of mobile phone on human tissue, and specifically the human head, with choosing the best interface between the mobile and the latter? Therefore, our problem is the electromagnetic field coupling between the radio frequency power source and the biological tissue (human head). To solve this problem, a system of equations placed and the choice of formulation of finite elements that coupled with the boundary integral formulation that adopts with the system. A call to the numerical modeling gives results which shows the connection between the characteristics of the exterior medium (σ,ε,μ) and the electromagnetic field of the RF source in the interior medium (human head). With this method we can assess the RF energy at each point of the interior medium (human head), basing on the parameters of the exterior medium, we are able to choose the best material of the interface's realization.

Keywords: Numerical method; electromagnetic radiation; interface; radio frequency; biological tissues; finite element formulation.

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1. INTRODUCTION

Electromagnetic fields are a part of our daily life: mobile phone, radio, Wi-Fi ... We focus our work specifically to mobile telephony, including risks lend more to debate. On the one hand, the waves associated with mobile phones are numerous and varied: Wi-Fi, Bluetooth, GSM antennas, UMTS or 3G, power grids ... and have as many potential health risks. Furthermore, the use of mobile phones is growing exponentially. These factors led to ask the question: what are the risks of mobile phones on human health? Many studies regularly published on this subject, and public authorities tend to apply a precautionary approach in the fight against these dangers. Is it really justified? To answer this question it is necessary at first to understand the nature of the waves to mobile telephony, and analyze the studies on the subject, before considering the standards and regulations to limit these effects. Our work had purpose of limited the effects of electromagnetic waves by selecting an interface between an RF source (mobile telephony) and biological tissue (human head), and like that we will escape to the standards and recommendations. A Call to numerical method allows an energy assessment in different parts of our model (human head). This method is to vary the characteristics (σ,ε,μ) of our interface (exterior medium), electromagnetic field values vary from ascending or descending with these, which allows us to quantify the energy dissipated in the interior medium, these characteristics which give minimum absorption of energy in our model with they we had selected the material of our best interface. Our study want confirm which energy dissipated in the human head, vary with the distance between the human head and the electromagnetic source, and with the variation of exterior medium parameters (σ,ε,μ).

2. PHYSICAL MODEL DESCRIPTION

When a wave emitted and spread in any medium, during his path, she encounters obstacles, a portion of this incident wave reflected and the other transmitted. Fig. 1 totally we have a reflected wave,which it was necessary to set up an interface that gives a zero transmitted or absorbed wave, which gives a minimum of the energy absorbed in the biological material (human head). RF fields penetrate into the exposed tissues and produce heating in it and by the huge difficult to quantify, we will develop a numerical method which gives accurate results.

The diffraction problem of an electromagnetic wave against an obstacle of any geometric shape is one of the most important aspects in electromagnetic compatibility. As a part of our work, we want to analyze the coupling of an electromagnetic wave with a human head spherical, this sphere immersed in a time-varying electromagnetic field created by ELM source (mobile phone). The interaction of the incident wave with our structure introduces the birth of a diffracted wave and a transmitted one. This dispersion of the electromagnetic energy in the different environments forming the structure, which depends directly on their characteristics, their geometrical shape, their angle of incidence and the distance d between the source and the structure. To simplify the physical system, we called **Ωi** the inside area of the sphere and **Ωe** the outside area. **Γ** represents the system boundary, with n the normal oriented from inside to outside **Ωe**, the field coming a source which materialized by a coil traversed by a current **Js**, which induces the creation of the electromagnetic field.

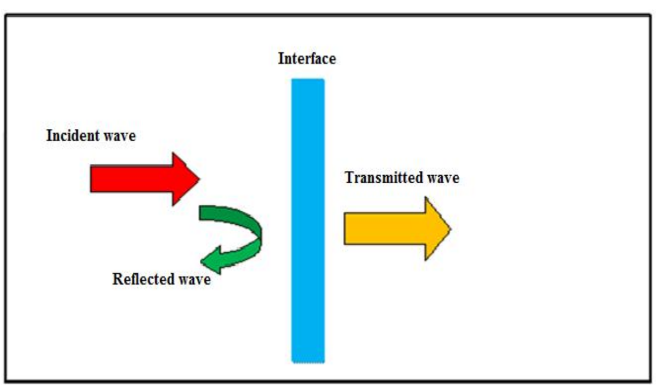

Fig. 1. Decomposition of the incident electromagnetic wave

(E, H). Assuming that source is perfect and does not carry electric charges ρ, Fig. (2). [1]

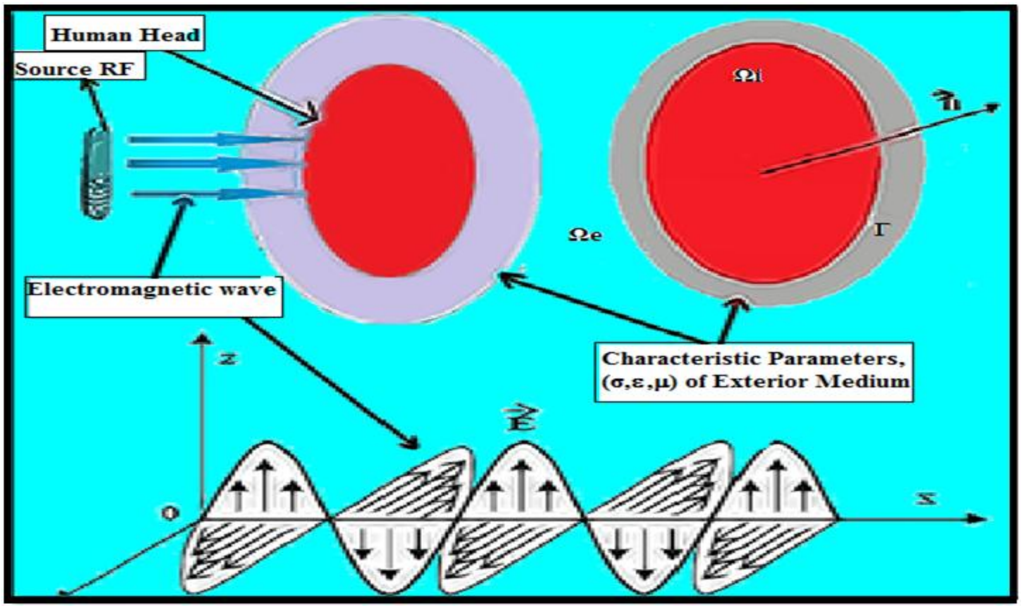

Fig. 2. Physical system

3. THE CONSTITUVE EQUATIONS

Maxwell's equations, valid whatever the problem studied, do not take into account the characteristics of the medium. To determine the problem completely; we must also know the laws and behavior, depending on the physical properties of materials where the fields exist. These laws allow you to model on a macroscopic scale the microscopic electromagnetic phenomena that occur in the treated areas. These constitutive relations given by

$$D(x,t) = \varepsilon \mathrm{E}\,(\mathrm{x},\mathrm{t})$$
$$B(x,t) = \mu\,\mathrm{H}\,(\mathrm{x},\mathrm{t})$$
$$J(x,t) = \sigma\,\mathrm{E}\,(\mathrm{x},\mathrm{t}$$

With:

These equations can be non-linear or anisotropic and in this case (μ, ε, σ) are tensor quantities.

In the general case, the behavior of the medium depends laws conductive medium, Ohm's law verified

$J(x,t) = \sigma\,(\mathrm{x})\,\mathrm{E}(\mathrm{x},\mathrm{t})$ isotropic medium $J_i\,(\mathrm{x},\mathrm{t}) = \sum_{\mathrm{j}=1}\sigma_{ij}\,(\mathrm{x})\,E_j\,(x,t)_i$ $\mathrm{i} = 1{,}3$ anisotropic medium
In the case of a perfect conductor, σ is infinite: the E and H fields are zero.

Insulating medium, σ is zero, so J = 0: there is no current flowing in the middle.

Perfect medium, that has to say, the mediums for which the behavior laws are linear, the following relationships verified:

$D(x,t) = \varepsilon\,(\mathrm{x})\,\mathrm{E}\,(\mathrm{x},\mathrm{t})$ isotropic medium

$D(x,t) = \sum_{j=1}\varepsilon_{ij}(x)E_j(x,t)i = 1{,}3$ anisotropic medium

$B(x,t) = \mu(\mathrm{x})\mathrm{H}(\mathrm{x},\mathrm{t})$ isotropic medium

$B_i(\,x,t) = \sum_{j=1}\mu_{ij}\,(x)H_j(x,t), i = 1{,}3$ anisotropic medium

Therefore, the quantities (μ, ε, σ) they are a tensor

(for anisotropic media) that may depend on the position (for heterogeneous medium) and amplitudes of the fields (for nonlinear mediums).

$$\left(\mathrm{RotE} + \mu\frac{\partial \mathrm{H}}{\partial \mathrm{t}} = 0\right)$$
$$\left(\mathrm{RotH} + \varepsilon\frac{\partial \mathrm{E}}{\partial \mathrm{t}} = J + J_s\right)$$
$$(\mathrm{div}\,(\varepsilon \mathrm{E})\ =\ \rho)$$
$$(\mathrm{div}\,(\mu\,\mathrm{H})\ =\ 0)$$

4. MODEL FORMULATION

Consider the domain **Ω** occupied by the electromagnetic system, which is a sphere of $\mathbf{R}^3$ compact border, denoted **Γ** or ∂Ω; **n** is the unit vector normal to **∂Ω** and outside **Ω** Fig. (2). It assumed in the following, that the domain **Ω** and filled with a homogeneous dielectric material or the permittivity and permeability are two positive real constants. The medium in question is supposed to be perfect. [2]

Let **H** be a test vector field **H∈ rot (Ω),** with the same regularity as the field H and

$(\mathrm{rot\,H} = 0)$, or $[\Omega e\,(\sigma = 0)]$
Using Faraday's law: $(\mathrm{rot\,E} = -\mathrm{i}\omega\mu\,\mathrm{H})$

We integrate R[3], multiplying by the test function, which gives:

$$\int_{R^3}^{0} \mathrm{i}\omega\,\mu\mathrm{HH}'.\,\mathrm{d}\Omega + \int_{R^3}^{0} \mathrm{rotE.\,H}'\mathrm{d}\,\Omega = 0 \qquad (1)$$

To solve the second integral, we apply some mathematical properties this allows for another form of $\int \mathrm{Erot.\,H'd\Omega}$:

$$\int_{R^3}^{0} \acute{\mathrm{H}}.\,\mathrm{rotEd}\Omega + \int_{R^3}^{0} \mathrm{E.\,rot}\acute{\mathrm{H}}\mathrm{d}\Omega = \int_{\Omega}^{0} \mathrm{E.\,rot}\acute{\mathrm{H}}\mathrm{d}\Omega + \int_{\Omega}^{0} \acute{\mathrm{H}}.\,\mathrm{rotEd}\Omega = 0 \qquad (2)$$

5. VARIATIONAL FORMULATIONS

We made our problem in the total electric field; it can decomposed into $\mathbf{R^3}$ as follows:

$$\mathrm{E}=E_r + E_s \qquad (3)$$

Or E coming of electric field source and **Er** is the electric field reaction. This allows us to show the electromagnetic source in the formulation.

Then the equation (2), here rewritten as:

We called $a(E_r, E_s)$ follows:

$$\left(\int_{\Omega}^{0} \mathrm{rot}E_r\ \mathrm{rot}\acute{\mathrm{E}}\mathrm{d}\Omega + \int_{\Omega}^{0} \left(\mathrm{i}\omega\mu\sigma - \omega^2\mu\varepsilon\right)E_r\ \acute{\mathrm{E}}\mathrm{d}\Omega + \int_{\Gamma}^{0} \acute{\mathrm{E}}\ (\mathrm{n} \wedge \mathrm{rot}\,E_r)\mathrm{d}\Gamma\right)$$

$$= \left(-\int_{\Omega}^{0} \mathrm{rot}E_s.\,\mathrm{rot}\,\acute{\mathrm{E}}\mathrm{d}\Omega + \int_{\Omega}^{0}\left(\mathrm{i}\,\omega\,\mu\,\sigma - \omega^2\mu\varepsilon\right)E_s\acute{\mathrm{E}}\mathrm{d}\Omega + \int_{\Gamma}^{0} \acute{\mathrm{E}}.\,(\mathrm{n} \wedge \mathrm{rot}\,E_s)\,\mathrm{d}\Gamma\right) \qquad (4)$$

$$a(E_r, E_s) = \int_{\Omega}^{0} \mathrm{rot}E_r\ \mathrm{rotE}\ \mathrm{d}\Omega + \int_{\Omega}^{0} (\mathrm{i}\omega\mu\sigma - \omega^2\mu\varepsilon)\ E_r\acute{\mathrm{E}}\ \mathrm{d}\Omega \qquad (5)$$

And $R(E_r, E)$ the following integro-differential operator:

$$R(E_r, E) = \int_{\Gamma}^{0} \acute{\mathrm{E}}.\,(\mathrm{N} \wedge \mathrm{rot}\,E_r)\ \mathrm{d}\Gamma \qquad (6)$$

And the term $S(E_s, E)$ binds to the source

$$S(E_s, E) = E_s - \int_{\Omega}^{0} \mathrm{rot}\,\acute{\mathrm{E}}\ \mathrm{rot}\,E_s\mathrm{d}\Omega + \int_{\Omega}^{0}(\mathrm{i}\,\omega\,\mu\,\sigma\ -\ \omega^2\mu\varepsilon)E_s\ \acute{\mathrm{E}}\mathrm{d}\Omega + \int_{\Gamma}^{0} \acute{\mathrm{E}}\ \mathrm{d}\Omega\ +\ (\mathrm{n} \wedge \mathrm{rot}E_s)\ \mathrm{d}\Gamma \qquad (7)$$

Taking into account these definitions, the wording of (5) then becomes:

$$a\left(E_r, \acute{\mathrm{E}}\right) + R(E_r, E) = S(E_s, E) \qquad (8)$$

We want to study the propagation of an electromagnetic wave in a bounded domain, including two different mediums. For theses, we will establish the variational formulations in each medium

In the environment of the head with interior and exterior parameters: (ε ,μ, σ) [3]

$$\int_{\Omega}^{0} \mathrm{rotE}\ \mathrm{rot}E_r\ \mathrm{d}\Omega + \int_{\Omega}^{0} (\mathrm{i}\ \omega\ \mu\ \sigma\ -\ \omega^2 \mu\varepsilon) E_s\ \acute{\mathrm{E}}\mathrm{d}\Omega + \int_{\Gamma}^{0} \acute{\mathrm{E}}\ \mathrm{d}\Omega\ +\ (\mathrm{n} \wedge \mathrm{rot}E_r)\ \mathrm{d}\Gamma = \mathrm{D}\gamma \quad (9)$$

6. FORMULATION OF THE BOUNDARY Γ

First, note that E1 is the field satisfying the following condition: $\mathrm{n} \wedge E_1(x) = E(x)$ on Γ

With: E1 is the unknown on Γ from within.

The tangential vector field already defined which gives:

$$\mathrm{n} \wedge E_{er}(x) = \mathrm{n} \wedge E_1(x) = E(x)$$

$$E(x) = \mathrm{n} \wedge \int_{\Gamma}^{0} \mathrm{K(y)\ G(x, y)\ d\Gamma dy} \quad (10)$$

Finally, we will reach our objective, where overall variational formulation of the problem is defined in the entire space R^3, which gives :

$$A(E_r, E') = R(E_r, E') = S(E_s, E')$$

$$R(E_r, E') = -\mathrm{i}\omega\mu\ \left[\frac{1}{2}\int_{\Gamma}^{0} \mathrm{K(x)E'(x)d\Gamma dx} + \int_{\Gamma}^{0} \mathrm{T\ K(x).\ E'(x)\ d\Gamma dx}\right] \quad (11)$$

7. DISCRETIZATION OF THE VARIATIONAL PROBLEM

We recall the variational formulation:

$$A(E_r, E') = R(E_r, E') = S(E_s, E') \quad (12)$$

Since the formulation of the problem obtained earlier, so we will proceed to the next step, which is to complete the grid, and realizing the variational problem presented above elements of edges in an approximate space the interpolation of the electric field Ea E'∊ (Ω ') in the domain Ω' given by:

$$E' = \sum_{i=1}^{Na} W_i\ \mathrm{E_i} \quad (13)$$

Terms of basic functions Wij associated with the edges of these elements numerically solve the problem, the volume of study split into tetrahedral elements and the electric field vector E described in:

$$e\ =\ \sum_{i=1}^{N} W_{ij}\ \cdot e_i \quad (14)$$

$$W_{ij} = \lambda_a \nabla \lambda_b - \lambda_b \nabla \lambda_a \quad (15)$$

Where N is the total number of edges of the mesh, Wij is the basic function of the vector associated with edge (ij) and e ij is the unknown problem that represents the flow of electric field along the edge (ij). i is the bar centric coordinate i.λ. Tetrahedral associated with the node.

We have developed the K currents on the basis function:

$$\omega_i(x) = n(x) \times grad\ \ \lambda_i \quad (16)$$

And

$$K(x) = \sum_i P_i \cdot \omega_i(x) \quad (17)$$

Where:

.Γi : Describes the top
Pi: the value of K in vertex i.
i: the coordinated barycentric.λ
..Γn (X): normal vector on

Our variational formulation can rewritten as the following linear forms:

$$M_{GR} \cdot e_V = S_V \quad (18)$$

$$M_{GC} \cdot e_C = S_C \quad (19)$$

Where:

$$M_{GV} = M_1 + R + j\,\omega\,\sigma\,\mu \cdot M_2$$
$$M_{GC} = M_1 + R$$

A: is a complete matrix of dimension

(nbat × nbat) it represents the boundary term of the approximate variational problem.

M1 and M2. Are two matrices; their dimensions are

(nbat × nbat) an element of these matrices is equal to zero only if (ij) and (kl) are not part of the same tetrahedron.

Finally, the global matrix of the boundary term, R_m in edge variables, written as:

$$R_m = \sum_i \left[1/2\mathrm{B}^t + \mathrm{M}\right]_{ij} (Q_i^{-1}\mathrm{B})_{ij} \qquad (20)$$

The overall matrix system denoted **MAT** written:

$$MAT = E\{[T_1] + (i\omega\mu\sigma - \omega^2\mu\varepsilon)[T_2] + R_m\} = S \qquad (21)\ [4]$$

8. NUMERRICALRESULTS

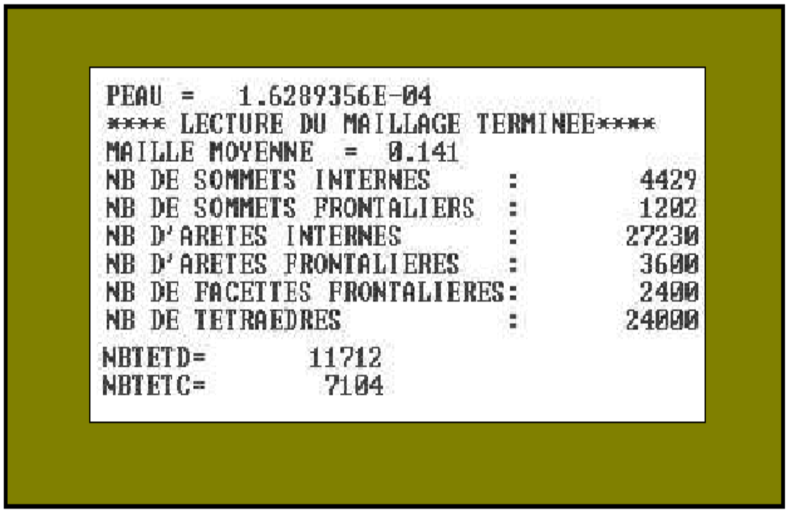

Fig. 3. Reading of the mesh

9. REPRESENTATION OF ELECTROMAGNETIC FIELDS

With:

Js = 200, R = 0, 4, VN1=-1, VN2 = 0, VN3=0

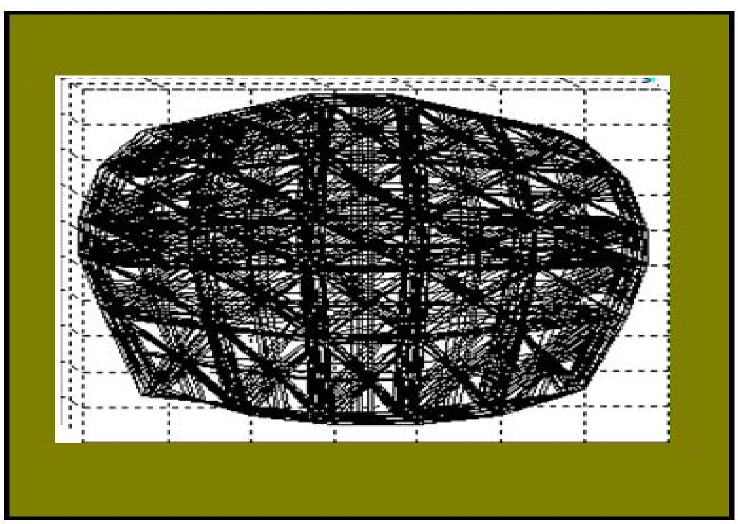

Fig. 4. Representation a mesh of the grid

In this part, we had meshed our system, with a mesher elaborated Fig. 3, we had obtained numerical results which showed us a human head mesh in transparency, which helps us see the vectors of electromagnetic field in the interior of human head Fig. 5 [5].

After the mesh, we went towards our goal, who is a finding of variation of the amplitude of vectors of the electromagnetic field. We have fixed frequency of the electromagnetic source, then we use the different values of parameters characteristic (ε,σ,μ), and we have obtained results which are shown in Figs. 6-15.

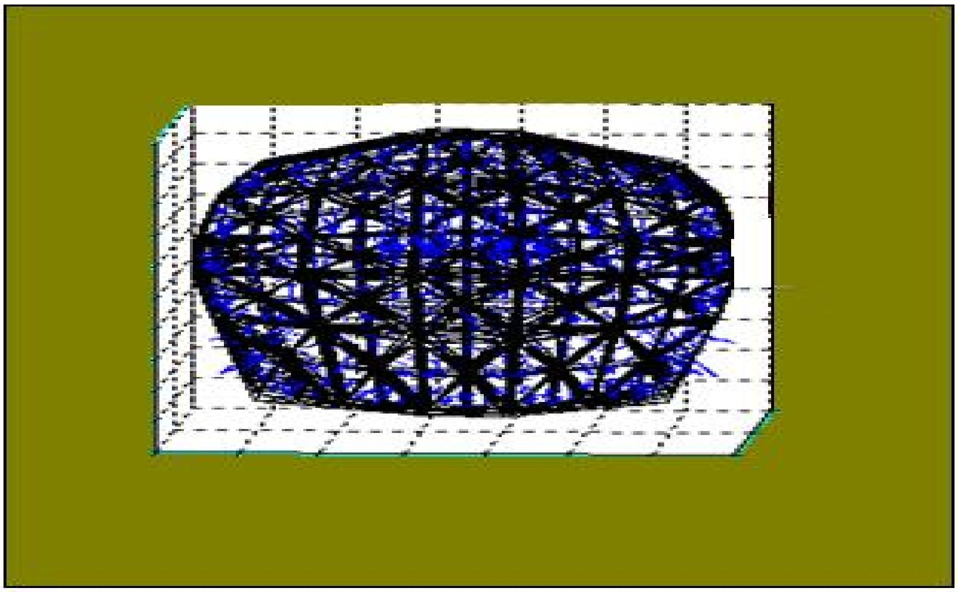

Fig. 5. The representation a mesh of the grid with the electromagnetic field distribution

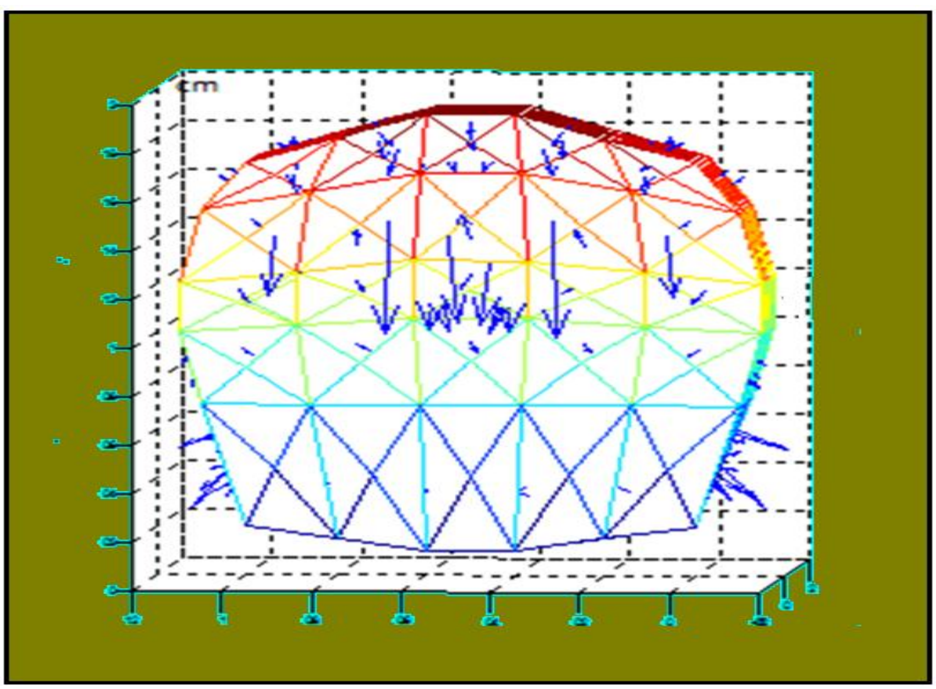

Fig. 6. Distribution of electromagnetic field, f = 835MHz, (ε,σ,μ), minimum energy

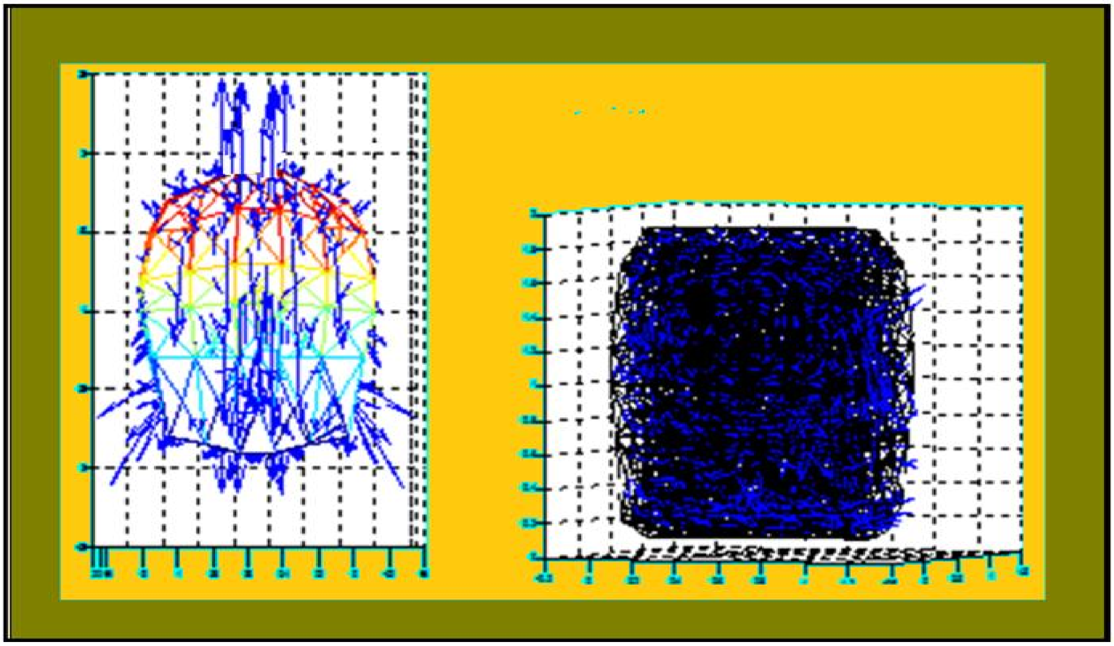

Fig. 7. Distribution of the electromagnetic field, f =835MHz, (ε,σ,μ), interior and exterior views

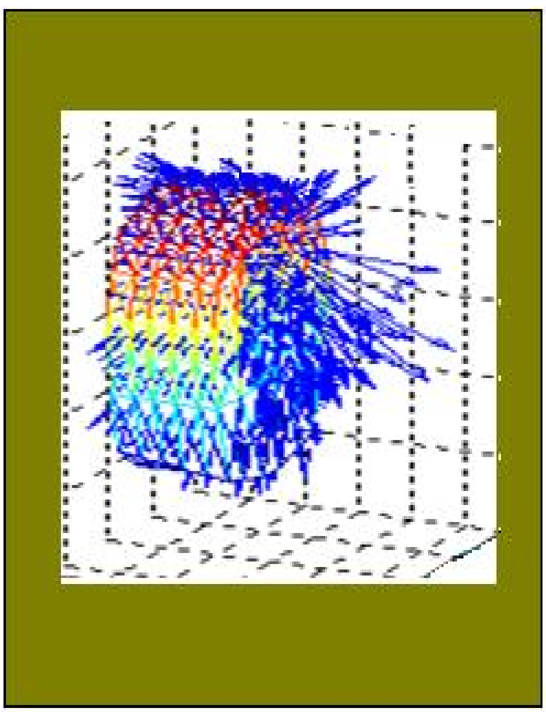

Fig. 8. Distribution of electromagnetic Field f = 835MHz, et ($\varepsilon_1,\sigma_1,\mu_1$)

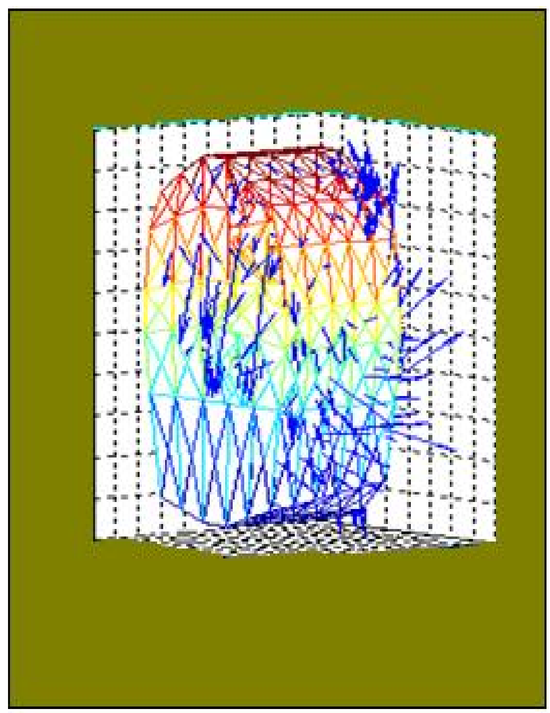

Fig. 9. Distribution of magnetic field f = 835MHz, et ($\varepsilon_2,\sigma_2,\mu_2$)

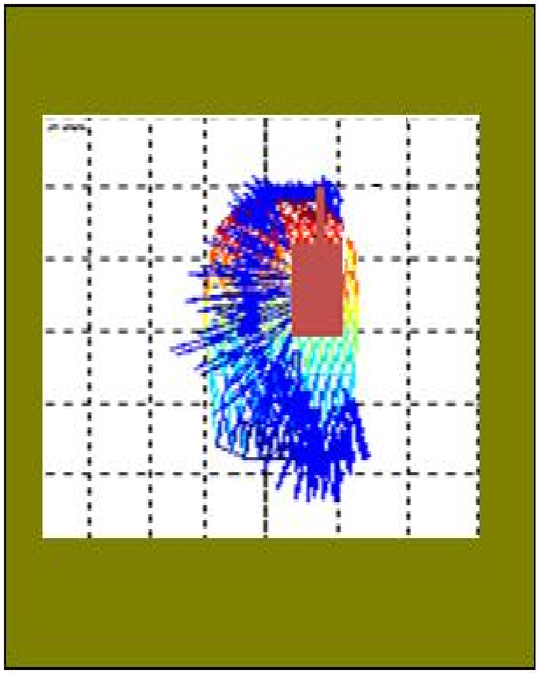

Fig. 10. Distribution of the electromagnetic field f = 1900MHz et ($\varepsilon_1,\sigma_1,\mu_1$)

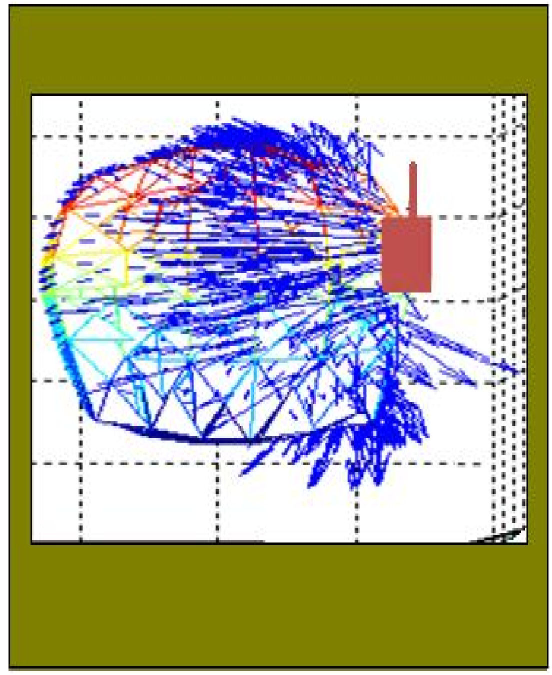

Fig. 11. Distribution of magnetic field f = 1900MHz, et ($\varepsilon_2,\sigma_2,\mu_2$)

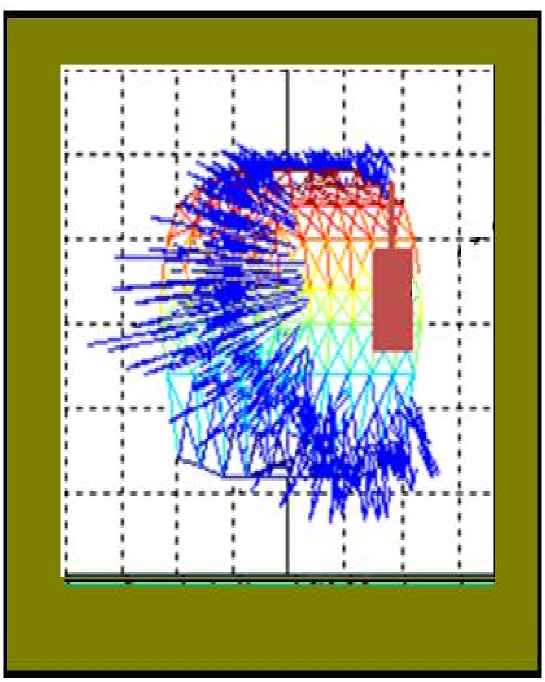

Fig. 12. Distribution of electromagnetic field f = 835MHz, et ($\varepsilon_3,\sigma_3,\mu_3$)

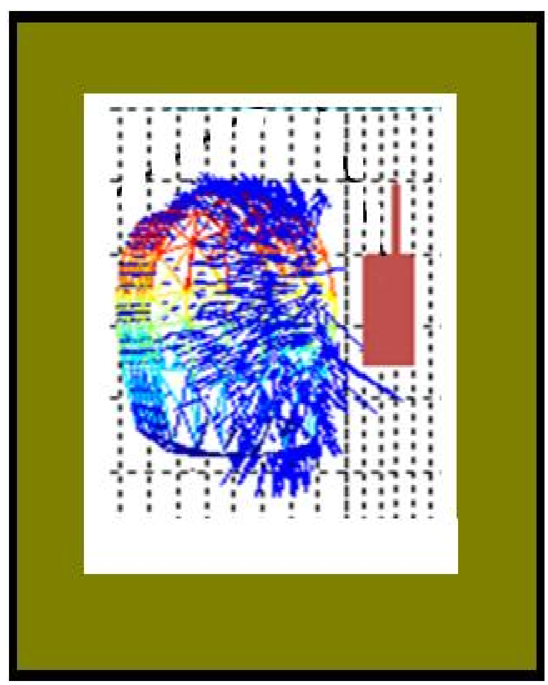

Fig. 13. Distribution of electromagnetic field f = 835MHz, et ($\varepsilon_3,\sigma_3,\mu_3$) exterior view

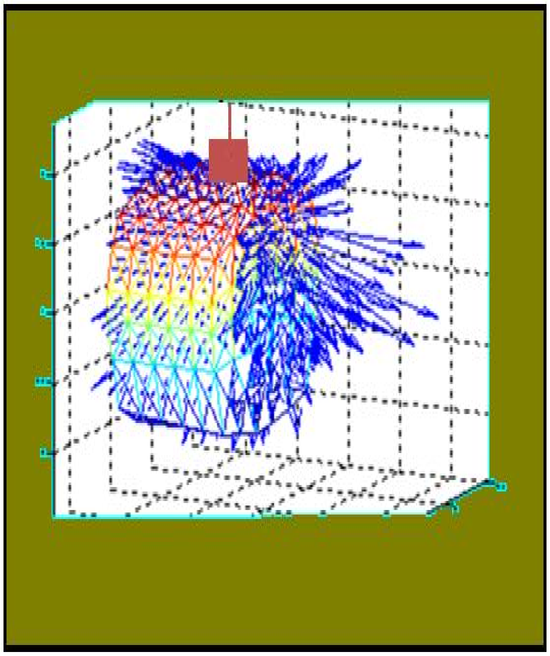

Fig. 14. Distribution of electromagnetic field f = 835MHz, et (ε_3,σ_3,μ_3)

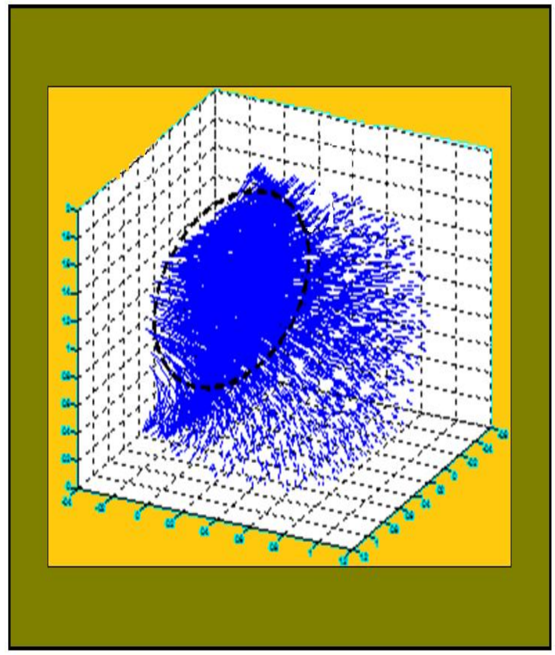

Fig. 15. Distribution of electromagnetic field f = 835MHz, et (ε_3,σ_3,μ_3) Interior view

We see its results who are the amplitude of vectors of electromagnetic field inside the human head, where is based on the variation of characteristic parameters (ε,σ,μ), and these last have a variation with the material and the frequency of the electromagnetic source Fig. 16 and Fig. 17, which leads to testing of several materials [8,9].

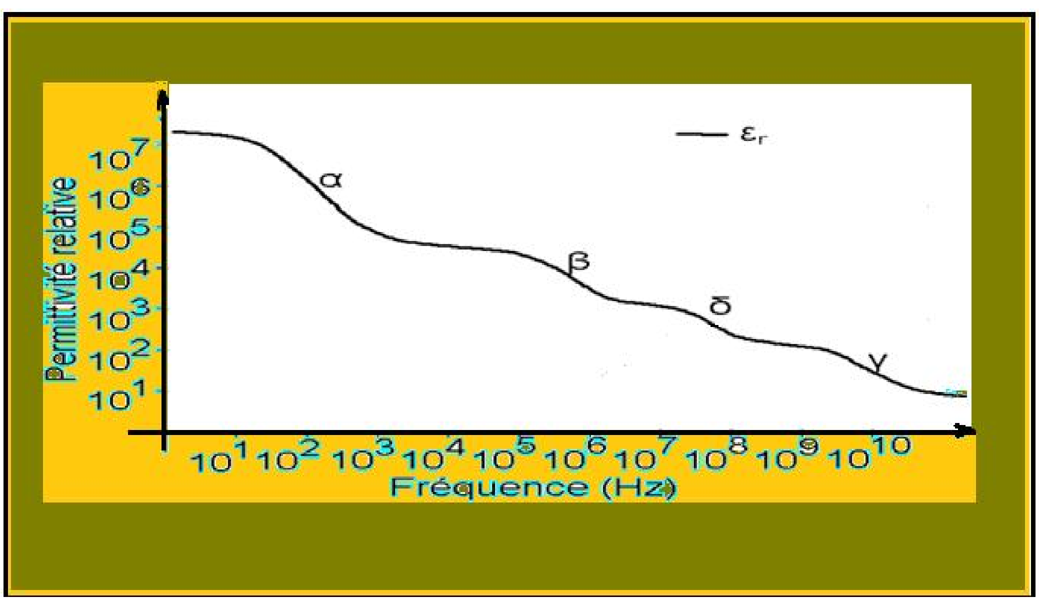

Fig. 16. variation of parameter (ε_r) as a function of the frequency [6]

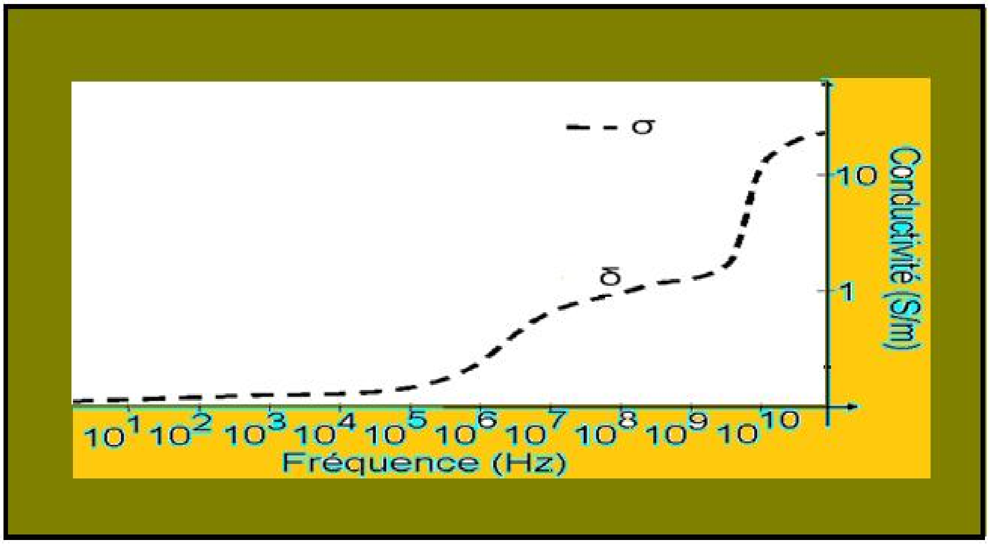

Fig. 17. variation of parameter (σ) as a function of the frequency [7]

10. CONCLUSION

This article is part the object of research on the problems of interaction of electromagnetic fields with the human body. Therefore, we had made synthesis of various variational formulations for resolving the diffraction problems of electromagnetic wave with a spherical obstacle, which represents the human head, and the construction of a numerical model, with an elaborate numerical method. For the implementation of the proposed formulations, we had used the finite element method, which effectively treating the problems with complex geometries and including heterogeneous mediums. Knowledge of electromagnetic field at any point of interior medium and the surface obtained by an integral formulation, based on boundary integral method. To determine the local vector field, we had solved the wave equation with double rational. The propagation of electromagnetic wave through the dielectric medium has correctly modeled and the use of the absorbing condition, which permits the analysis of the open field problem, (the behavior of the field at infinity). The results presented, it possible to calculate and to facilitate choice our model, with use of computational code we have studied the behavior of the electromagnetic field inside the human head for different points at two frequencies, f = 835 MHz and f = 1900MHz. This allowed us a properly select the material of the interface between the human head and the radio frequency source based on different electromagnetic parameters (ε,σ,μ). Therefore, our choice is a material, which gives the minimum energy in different points in the internal medium of our model. Given the number of parameters, we cannot expose all our results in this article [10,11].

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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