# Interactions between Electromagnetic Fields and Biological Tissues: Questions, Some Answers and Future Trends.

*Abstract* ¾ **This paper deals with the electromagnetic field computation in biological tissues. It is actually one of the important challenges for the computational electromagnetics community for the next years. The major difficulties that appear are related to the material properties, to the formulation of the electromagnetic problem and to the thermal model of the human body.**

## I. INTRODUCTION

The daily exposure to an electromagnetic environment raises the question of the effects of electromagnetic fields on human health. The accurate assessment of the currents induced in the human body by an electromagnetic field is a major issue, not only for its relevance in medical research, but also for its implications on the definition of industrial standards [1]. Two types of applications may be highlighted.

On one hand, electromagnetic fields can be considered as harmful to the health. Using the results of epidemiological studies and by application of the ALARA (As Low As Reasonably Achievable) principle, the governments have imposed some limitations to the authorized radiated fields by the power systems. It has been proposed a set of maximum values of current density or specific absorption rate (SAR), according to the frequency. These values are called the basic restrictions, and reference levels for the fields are derived from these restrictions using measurement or computational techniques performed on very simple models. Unfortunately these reference levels are only external values. They cannot take into account the way the field develops inside the body and they do not take into account the environment of the exposed person. It is now necessary to increase the knowledge of the distribution of the fields inside the body in order to give a more acceptable limit to these radiated fields.

On the other hand, electromagnetic fields are used for medical diagnosis (medical scanning MRI) or for medical treatment. As example, hyperthermia is used in oncology treatment to treat localized cancerous tumour [2]. The elevation of temperature in the tumour is obtained by submitting locally the patient to a radiofrequency (RF) electromagnetic field. The focalization of the heat inside the tumour is obtained by using several RF sources having specific phases and amplitude. The values of optimized source currents are obtained by coupling the electromagnetic field computation inside the body with an optimization process.

In both cases the electromagnetic field distribution has to be computed in the human body, taking into account all the particularities of that "system":

- the "material" (the human body) has very unusual electromagnetic properties values: electric permittivity, electric conductivity,
- these properties are not well known and depend on the activity of the person,
- this material is an active material at the cell scale,
- in most cases, the problem is actually a coupled problem : the thermal effect is one of the major effects and it is affected by the blood circulation,
- the geometry is complex and generally environment of the human body has to be taken into account.

The objective of this paper is to show the present difficulties related to the computation of induced electromagnetic quantities in biological tissues. The first part deals with the biological material properties. Second part deals with the formulation of the electromagnetic problem. In the third part, an hybrid bioheat transfer model is presented.

## II. THE BIOLOGICAL MATERIAL PROPERTIES

Compared to the material usually used in classical electromagnetic systems, the human body is made of a large number of materials, each of them having specific properties. These properties have been extensively studied in the last fifty years from 10 Hz to almost 10 GHz [3,4]. In [5,6,7,8], a parametric model able to represent them is presented together with the values of the model parameters for 45 different tissues. Since biological tissues mainly consist of water, they behave neither as a conductor nor a dielectric, but as a dielectric with losses. It is also shown that electromagnetic properties values are highly depending on the frequency. Compared to classical dielectric materials, the dielectric permittivity is high: for example, at 1kHz, the relative permittivity of the blood is 435000. It generally decreases with the frequency. The electric conductivity is low but not
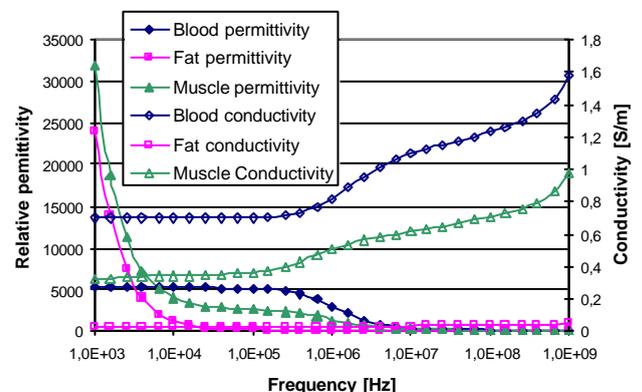


Fig.1. Variation with the frequency of the electromagnetic properties values of three representative tissues : blood, fat and muscle.

zero. As example, the conductivity of the muscle varies from 0.3211 to 0.9982 in the 1kHz-1GHz frequency band. The wetter a tissue is, the most lossy it is; the drier it is, the less lossy it is. On the other hand, the permeability of biological tissues is that of free space. Fig.1 shows the variation of electromagnetic properties for three representative tissues in the range 10kHz-1GHz: blood (very high water content), muscle (high water content) and fat (low water content).

### Why are electromagnetic properties values of biological materials so special?

These non-usual values of the electromagnetic properties change the way that Maxwell's equations are dealt with. According to the frequency-domain Ampere's law, the ratio between conduction current and displacement current densities is given by the ratio $\omega\varepsilon/\sigma$. Fig.2 shows the variation of this ratio for the three previous tissues in the range 10kHz-1GHz (blood, muscle and fat). Fig.3 shows a zoom in the range 1kHz-10MHz. Clearly, displacement currents cannot be neglected at low frequencies, posing the problem of the choice of the formulation: quasi-static formulation, or wave equation formulation?
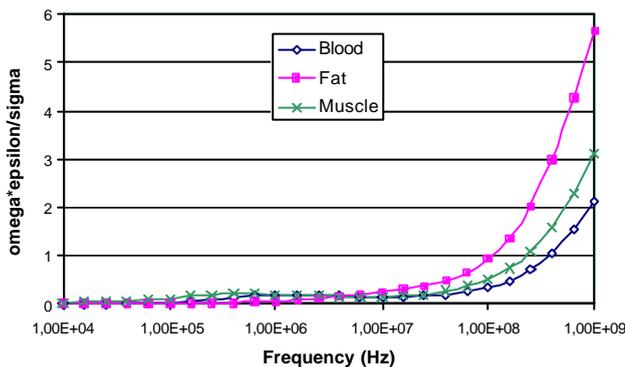


Fig.2. Variation with the frequency of the ratio $\omega\varepsilon/\sigma$ of three representative tissues : blood, fat and muscle.
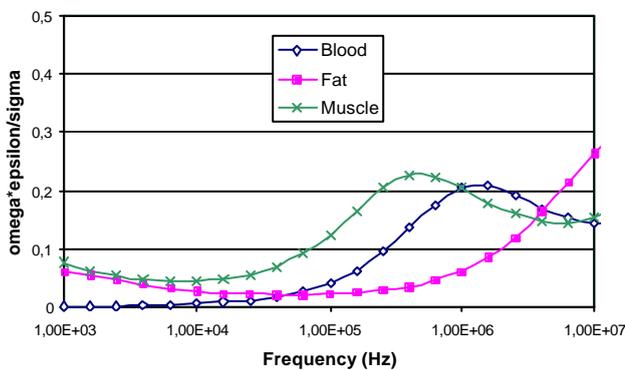


Fig.3. Variation with the frequency of the ratio $\omega\varepsilon/\sigma$ of three representative tissues – zoom on the 1kHz-10MHz band.

### Have the electromagnetic properties of the biological tissues to be accurately determined?

Dosimetric studies are performed to quantify the interactions of electromagnetic fields with biological tissues. Whether they are numerical or experimental, the Specific Absorption Rate (SAR) distribution has to be determined since it gives a measure of the energy absorption which can be manifested as heat, and since it gives a measure of the internal fields which could affect the biological system without heating (non-thermal interactions). The SAR (W/kg) is defined as:

$$SAR = \sigma |E|^2 / \rho_m \qquad (1)$$

where $\sigma$ is the conductivity (S/m), E is the root-mean-square magnitude of the electric field (V/m) at the considered point, and $\rho_m$ is the mass density (kg/m$^3$) of the tissue at that point. Determining the electromagnetic properties values of biological tissues is a critical step when calculating the SAR. There is not a real consensus on these values: straight comparison of the published data shows significant differences among permittivity values for the same tissue type [9]. Variability in reported values for a single organ may result from different reasons, such as the heterogeneous nature of the biological tissues, the freshness of the sample, the tissue preparation procedure, or metabolic changes in samples that occur after death. This poses the question of the effect of these values on calculated SAR values in biological systems. In [10], it is underlined that the dependence of SAR on permittivity changes is important. We have obtained slightly different results: in [11], the effect of the tumour properties (which are actually not well known) on SAR distribution in local hyperthermia is analyzed. It is shown that neither the permittivity nor the conductivity has a great effect on the mean electric field inside the tumour (Table I). On the other hand, since the SAR is directly proportional to the conductivity, the SAR value in the tumour is affected by the conductivity value. The temperature will consequently be modified: a SAR value of 20 W/kg (configuration C) induces an elevation temperature of 5°C, while a SAR value of 35 W/kg (configuration D) increases the temperature in the tumour by 9°C.

TABLE I. LOCAL RF HYPERTHERMIA. SIMULATION OF THE EFFECT OF DIFFERENT TUMOUR PROPERTIES ON THE SAR AND ELECTRIC FIELD VALUES [11].

| Tumour | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| $\varepsilon_r$ | 60 | 60 | 95.8 | 95.8 | 106 | 183 | 243 |
| $\sigma$ | 0.8 | 0.65 | 0.65 | 1.14 | 1.14 | 0.91 | 0.74 |
| Mean E (V/m) | 269.6 | 269.1 | 269.1 | 270 | 270 | 269.1 | 268.7 |
| SAR (W/kg) | 24.7 | 20.0 | 20.0 | 35.3 | 35.3 | 28.0 | 22.7 |

Sensitivity analysis of electromagnetic properties of the biological tissues is consequently a crucial step to solve this question.

*Are these macroscopic values representative of the electromagnetic phenomena inside the tissues ?*

A biological body is represented as a heterogeneous and lossy dielectric, whose macroscopic electrical properties are described by complex permittivity. Interfacial processes, such as Maxwell-Wagner effects, dipolar relaxation effects or counterion relaxation effects, play an important role in the electrical properties of tissues [12]. This poses the problem of modelling assemblies of biological cells exposed to electric fields. When exposed to electric fields, a potential difference is induced across the cell membrane. This transmembrane potential (TMP) may be of sufficient magnitude to be biologically significant.

The simpler model of biological cell consists of cells contents or cytoplasm surrounded by a very thin, low-conductivity membrane, and placed in a conductive medium. Most cells in tissues are connected by gap junctions that permit certain substances to be exchanged between cells, providing local cell communication. These gap junctions connect electrically the cells, thus increasing the sensitivity of the cell to externally applied electric fields. As example, the disruption of gap junction may lead to disease processes, including cancer [13].

Several approaches to simplified modelling of gap-connected cells have previously been reported. For spheroidal cells, the TMP can be estimated analytically by solving Laplace's equation [14]. The leaky cable model has also been used, but this approach does not accurately predict the frequency behavior compared to a Finite Element approach [15]. This type of modelling is an interesting problem from both mathematical and numerical points of view: there is a high contrast between the conductivities ($10^{-7}$ S/m to 1 S/m) and between the dimensions (the membrane thickness is about 10 nm, compared to a 1 μm-diameter). Fig. 4 shows a chain of 2 cells connected by gap junction, including the dimensions and the electrical properties. The dielectric formulation of the Flux2d package [16] is used to solve this problem in the axisymmetric case:

$$\nabla \cdot (\sigma \mathbf{E} + j\omega \varepsilon \mathbf{E}) = 0 \qquad (2)$$

As example of result, the frequency response of circular cell and chain of 2 cells is given in Fig. 5. The circular cell behaves as a low-pass filter and has one relaxation frequency. On the other hand, the chain of 2 cells shows 2 relaxation frequencies. The curve describing the frequency behavior of the chain and cell coincide after the chain's second relaxation.
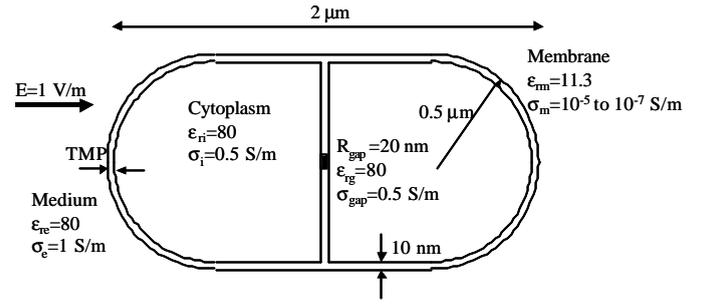


Fig.4. Cross section of a chain of 2 cells connected by a gap junction, typical dimensions and electrical properties values.
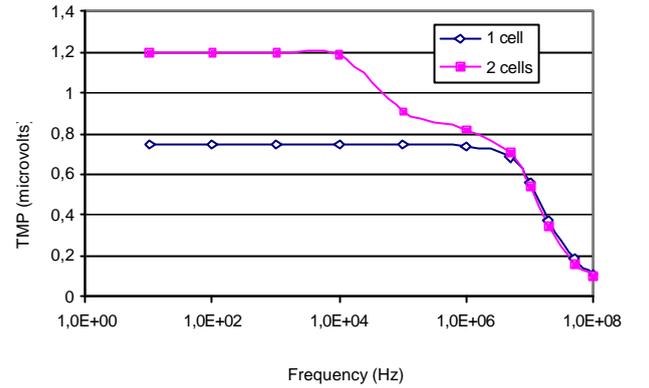


Fig.5. Frequency response of spherical cell and chain of 2 cells.

A challenge for the next years could be to link the electromagnetic model of cells to the electromagnetic properties values of the tissues. Homogenization technique is one of the possible ways.

III. FORMULATION OF THE ELECTROMAGNETIC PROBLEM

Computational electromagnetics in human body can be classified into two classes of problems, depending on the frequency of the electromagnetic phenomena: low frequency problems, when a quasi-static approach may be used, and high frequency problems. Three conditions have to be verified in order the quasi-static condition to be applied:

• the displacement current density are small in comparison with the conduction current density (fig. 2),

• the magnetic fields produced by the induced currents are negligible,

• the electric and magnetic fields are decoupled and may be calculated separately.

With such conditions, the problem may be broken into two steps. In the first step, the solution of the static field equations

allows to evaluate the electric or magnetic field external to the exposed body. At this level, the body is usually seen as homogeneous, equipotential and perfectly conductive (case low frequency, E-field exposure), or is not taken into account at all (case low frequency, H-field exposure). In both cases, the physical quantities are determined inside the body in the second step, internal electric fields and currents densities being computed on the basis of the results of the first step. On the other hand, in the high frequency case, the wave equation has to be solved.

*Coupling to the magnetic field : low voltage, high current, low frequency systems (H-field exposure)*

Classical magnetodynamic 3D A-$\Phi$ or T-$\Omega$ formulations can be used. On the other hand, specific A-$\Phi$ 3D formulations have also been developed [18], where the A-source is computed from analytical formulae or simplified models, or from measurements :

$$\nabla.(\sigma\nabla\phi) = -\nabla.(\sigma\frac{\partial \mathbf{A}}{\partial t}) \tag{3}$$

with the boundary conditions on the body surface :

$$\mathbf{n}.\mathbf{J} = 0 \text{ and } \mathbf{J} = \sigma\mathbf{E} = -\sigma(\nabla\phi + \frac{\partial \mathbf{A}}{\partial t}) \tag{4}$$

Finite Differences, Finite Elements or Impedance methods are generally used for the numerical solving.

*Coupling to the electric field :High voltage, low intensity, low frequency systems (E-field exposure)*

Scalar potential formulation $\Phi$ for a solution in both air and human body can be used [19]. On the other hand, when decoupling external and internal problems, a reduced scalar formulation to the body has been developed [20]:

$$\nabla.(\sigma\nabla\phi) = 0 \tag{5}$$

with boundary condition on the body surface :

$$\sigma\mathbf{n}.\nabla\phi = -\frac{\partial \rho_s}{\partial t} \text{ and } \mathbf{n}.\mathbf{E}_{ext} = \frac{\rho_s}{\varepsilon_0} \tag{6}$$

The external electric field $E_{ext}$ at the body surface is previously obtained from Laplace equation solution. Equivalent charges, Boundary Integral Equation and Finite Element methods are particularly used in this case.

*High frequency systems*

In this case, the numerical formulation has to be based directly on the vector wave equation. In frequency domain:

$$\nabla\times\nabla\times\mathbf{E} - w^2 e m\mathbf{E} + jwms\mathbf{E} = -jwm\mathbf{J}_0 \tag{7}$$

Several methods have been reported for such applications [21]: Finite Difference Time Domain method, Finite Element method, Finite Integration Technique. The main problem is the truncation of the domain of calculation in such a way that the electromagnetic energy is able to propagate toward infinity. Depending on the numerical method used, this can be achieved using absorbing boundary conditions or perfectly matched layers.



Fig. 6. Example of high frequency problem, solved with the FEM coupled to absorbing boundary condition. Local RF hyperthermia (27.12 MHz) [22]

The question which arises now is the link between these formulations: is there a real continuity between the different models and for which frequency domain are they valid? Such comparison between the formulations could be done in the scope of the TEAM workshop. Experimental values for validation (current, voltage, field) could be measured in phantom whose electromagnetic properties are controlled. If this method has been extensively used in high frequency, several difficulties (noise, contact impedance, electrode polarization) make it difficult in the intermediate frequency range [17]. However, the challenge deserves to be accepted.

IV. FORMULATION OF THE THERMAL PROBLEM

The electromagnetic formulation is used to calculate the electromagnetic quantities inside the biological tissues and the SAR distribution. It has been shown that, in a first approximation, the SAR distribution may be directly related

to the temperature distribution [23]. However, in order to get an accurate description of the thermal effects, it is necessary to consider the heat transfer problem. It is not an easy problem: the human body is constituted of $10^6$ meters of blood vessels. Diameters of the vessels vary from 1 cm for the aorta or the vena cava to few micrometers for the arterioles and veinules. Moreover, the blood flow is between 0.1 and 50 cm/s depending on the type of vessel, and it can vary roughly with the temperature.

At a point P of the body, the temperature is the result of complex heat transfer mechanism including the thermal conduction of the tissues, the thermal convection by the blood flow, the heat generation by metabolism, and the heat generation by SAR deposition.

*Are conventional thermal models adapted for the whole body problem?*

Several models have been previously proposed. The conventional Pennes bioheat equation [24] is given by:

$$\rho_t C_t \frac{\partial T}{\partial t} = \nabla \cdot k_k \nabla T - \omega_b C_b (T - T_{art}) + \rho SAR + M \qquad (8)$$

where $\rho_t$ is the tissue density (kgm$^{-3}$), $C_t$ is the specific heat of the tissue (Jkg$^{-1}$C$^{\circ -1}$), $k_t$ is the thermal conductivity, $\omega_b$ is the blood flow (kgm$^{-3}$s$^{-1}$), $C_b$ is the specific heat of the blood (Jkg$^{-1}$C$^{\circ -1}$), $T_{art}$ is the temperature of the arteries and M is the heat generation produced by metabolism (generally considered as negligible). But it has been shown that only large vessels can actually be described by such a model. For small vessels (diameter lower than 0.5 mm), the effective conductivity model is more adapted, since it deals with the conduction of the tissues and the heat transfer between pairs of counter current vessels [25]:

$$\rho_t C_t \frac{\partial T}{\partial t} = \nabla \cdot k_{eff} \nabla T + \rho SAR + M \qquad (9)$$

where $k_{eff}$ is the effective thermal conductivity depending of the size of the vessel, the flow and the vascular structure.

It is now suggested to use an hybrid model combining both previous models [26]:

$$\rho_t C_t \frac{\partial T}{\partial t} = \nabla \cdot k_{eff} \nabla T - f \omega_b C_b (T - T_{art}) + \rho SAR + M \qquad (10)$$

In (10), the effective thermal conductivity $k_{eff}$ replaces the intrinsic thermal conductivity as previously, it is two to ten times larger than $k_t$. The factor f ranges from 0 to 1, depending on the unknown heat escape in venous vessels. Note that the conventional Pennes model is obtained for f=1 and $k_{eff}$=$k_t$, and the effective conductivity model is obtained

for f=0. But in any case, values of f and $k_{eff}$ cannot be given exactly.

This hybrid model is still not sufficient. Large vessels, such as aorta, for which there is no possible thermal equilibrium with the adjacent tissue, have to be taken into account separately as much as possible [26]. A discrete model may then be used as suggested in [27]. However, this leads to two major problems. First, a high space resolution (obtained from MRI-angiography) is required to determine the vasculature. Second, this leads to a large number of unknowns due to the space discretization of the vessels.

*Is the thermal model a closed problem?*

In the previous section, several difficulties have already been reported: unknown values of f and $k_{eff}$, large number of unknowns when discretizing the large vessels. Anisotropy in the conduction term has also to be evaluated. On the other hand, both specific heat $C_t$ and thermal conductivity $k_t$ of the tissues are known with sufficient accuracy to lead to good results. The main problem remains the incapacity to take into account in real time the local variation of blood flow with the temperature. As example, it is reported in [28] that the blood flow in a patient exposed to a microwave hyperthermia radiation increases from 4 ml/mn/100g at 35°C to 28 ml/mn/°C at 44°C (fig. 7). This variation depends actually on the biological organ, the temperature in the organ, and the time. This is specially crucial when the local heating from electromagnetic sources is required, such as in hyperthermia treatment. Variation of the blood flow is particularly high when the temperature of the tissue is greater than 42°C. Furthermore, in this particular case, the vascular characteristics of the tumour are even obtained with difficulty.

Finally the verification of thermal models is extremely difficult: no easy phantoms solutions are available. Verification using on-line information is also difficult because of the non availability of vascular data.
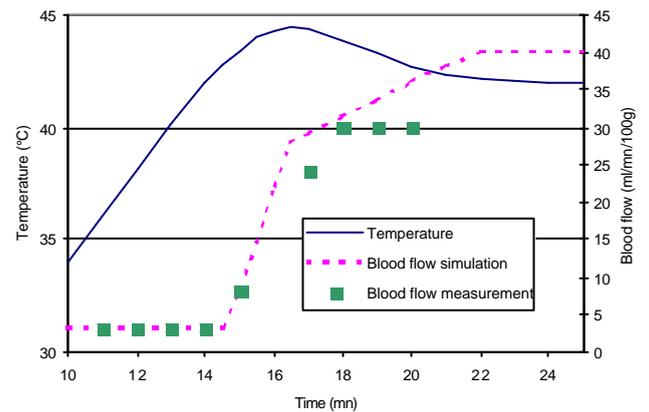


Fig.7. Transient temperature and blood flow in the thigh of a patient exposed to microwave hyperthermia [28].

## V. Conclusion

An increasing use of the electromagnetic fields in medical applications can be forecast. Modelling the electromagnetic field distribution in these devices will allow to design optimized systems. On the other hand, a large number of equipment used everyday are electric or electronic ones, and thus generate electromagnetic fields. People are more and more concerned with the consequences of the exposure to the electromagnetic fields. Modelling the electromagnetic field distribution in the human body allows to provide a good answer to the worried persons. In both cases specific developments are required. From the previous sections, several future axes may be envisaged: link the electromagnetic phenomena into the cells to the electromagnetic properties values of the tissues, link the existing formulations to get accurate results on the whole frequency range, validate the electromagnetic-thermal coupling. But in any case, the control of the interaction between electromagnetic fields and biological tissues is one of the challenges for the next years for which the Compumag community may play an important part.

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