Electromagnetic fields and human body: a new challenge for the electromagnetic field computation

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Electromagnetic Fields and Human Body : a New Challenge for the Electromagnetic Field Computation.

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Abstract-- The electromagnetic fields have a great influence on the behaviour of all the living systems. The ALARA principle imposes, in case of long exposures to low (i.e. power systems) or high frequency (i.e. microwave systems or cell phones) fields, some limitations to the radiated fields by the industrial equipment. On the other hand, some benefits can be taken from the effects of the electromagnetic fields on the living being : the hyperthermal technique is well known for the treatment of the cancer.

Either we want to be protected from the fields, or we want to take benefit of the positive effects of these fields, all the effects as well thermal as genetic have to be well known. Like in any industrial application, the electromagnetic field computation allows a better knowledge of the phenomena, and an optimised design. Hence, there is a very important challenge for the techniques of computation of electromagnetic fields. The major difficulties that appear are :

- related to the material properties :
  - the "material" (the human body) has very unusual properties (magnetic permeability, 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.
- related to the phenomena coupling :
  - the problem is actually a coupled problem : the thermal effect is one of the major effects and it is affected by the blood circulation.
- related to the geometry :
  - the geometry is complex and one has to take into account the environment.

The problems that we have to face with are :

-the identification of the properties of the "material",
-the coupled problem solution,
-the representation of the simulated phenomena.

I. INTRODUCTION

The electromagnetic fields are very usual in our daily life. The increasing number of power systems and telecommunication systems makes the exposure to these fields more and more important. On the other hand it appears that the electromagnetic fields can be used either for the medical diagnosis or for the treatment of some specific diseases. When analysing the interaction between the electromagnetic fields and the human body, two main objectives or categories can be identified :

1 - First of all, these 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 authorised radiated fields by the power systems. The biologists and the physicians have made a lot of clinical tests for many years. They have proposed a set of maximum values of the radiated fields, according to the frequency. 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.

The only way to get these results is the computation of the electromagnetic fields inside the human body. The human body is made of very unusual materials for numerical models that are used to handle more classical systems (such as electrical machines) and we shall see that these specific characteristics impose the development of particular models. Some other particularities of such problems appear with the complex geometry, the kind of information to get and the coupled problems to be solved. The electromagnetic field computation appears necessary to increase the knowledge, but also imposes the development of a specific approach.

2 – The electromagnetic fields can have very positive properties for the treatment of some disease and for the diagnosis of some health problems. Two examples can illustrate these properties :

- The medical scanning (MRI) uses magnetic fields. To get an optimal design of such a scanner it is necessary to have a very good understanding of the distribution of the fields in the human body and particularly in the area where they interfere with cells under scanning.
- The treatment of some cancerous tumour by the hyperthermia technique is well known since many years. The way to increase the temperature of the tumour can be a microwave technique. The heat has to be concentrated only in the cancerous tumour if we want to keep the neighbour cells healthy. The electromagnetic field computation inside the body by solving the coupled electromagnetic-fluid mechanics problem (in order to take into account the blood flow) will allow to design an optimised system for an optimal treatment.

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

In this paper, we shall see what kinds of computations have been made and are currently done, and what are the particularities of an optimal computation. This point will be illustrated by the development of an optimal design of a system for the treatment of cancerous tumour by an hyperthermia technique.

II. STATE OF THE ART

Computational electromagnetics in human body can be classified into two classes of problems, depending on the frequency of the electromagnetic phenomena: low frequency problems, if the electrical and magnetic fields are decoupled, and high frequency problems, when displacement currents appear. Compared to classical electromagnetic devices, the boundary between both classes appears at much more lower frequencies in living devices, owing to higher values of the permittivity of biological tissues. The ratio between the conduction currents and the displacement current is characterized by the value of $\varepsilon.\omega/\sigma$. The specific values of the material properties of a human body (table I) makes the "high frequency" problem appear at a frequency around 10kHz.

A. Low Frequency problems

At low frequency (that is, when the displacement currents can be neglected), the magnetic field H and the electric field E can be supposed to be decoupled. Thus it is possible to study and compute independently their effects on the human body.

When considering the human exposure in the daily life and in the industrial environment, it is possible to consider that the human body is exposed to two kinds of electromagnetic fields generated by low frequency power systems :

- Low voltage and high intensity systems: inductance, transformers, electrical machines, induction heating systems, … The main radiated field is the magnetic one. The specificity of this kind of exposure is that the field is high close to the source, and decreases quickly as the distance from the appliance increases. In this case the induced currents are located in a precise area, and appear as loops in the body.
- High voltage and low intensity systems (high voltage apparatus, power transmission lines, ... In this case the most influent field is the electric one. This field decreases according to a 1/r law. The induced currents are generally flowing along the main dimension of the body.

Due to the low relative magnetic permeability of the body (μ_r#1) one can assume that the magnetic field distribution is not modified by the induced currents. On the other hand, the relative dielectric permittivity is high (ε_r>100) and the body modifies the distribution of the electric field E. Consequently, depending upon which field is sought, the objective is to compute the current distribution assuming no perturbation of the inductor magnetic field H, or the Specific Absorption Rate (SAR) in the human body, by taking into account the perturbation of the electric field E source.

The first models which have been developed have been 1D. The results are not very accurate because the human body is modelled as a very simplified geometry (disc, ellipsoid) and the material properties (ε, σ) are supposed constant. Nevertheless, these models have been used to define the safety standards, as the guidelines of the ICNIRP for the exposure levels reference (ICNRP, 1998). 2D models can be used in order to take into account the fast decreasing of the magnetic field H close to the radiating systems, and give more realistic results (Burais, 1995). However 3D models remain necessary. Some of them have already been developed (Baraton, 1995), (Bossavit, 1993), (Renhart, 1992), (Dawson, 1998), (Wang, 1994), (Dymbylow, 1998), (Ghandi, 1992), (Chiba, 1984), (Stuckly, 2000), (Bottauscio, 1997), (Chen, 1986), (Yildirim, 1997), :

1) Low voltage, high current systems (H-field exposure)

Classical magnetodynamic 3D A-Φ [5] or T-Ω formulations can be used.

On the other hand, specific A-Φ 3D formulations have also been developed (Dawson, 1998), (Wang, 1994), (Dymbylow, 1998), where the A – source is computed from analytical formulae or simplified models, or from measurements :

$$\nabla.(\sigma\nabla\phi) = -\nabla.(\sigma\frac{\partial A}{\partial t}) \quad (1)$$

with the boundary conditions on the body surface :

$$n.J = 0 \text{ and } J = \sigma E = -\sigma(\nabla\phi + \frac{\partial A}{\partial t}) \quad (2)$$

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

2) High voltage, low intensity systems (E-field exposure)

Scalar potential formulation Φ for a solution in both air and human body (Chiba, 1984) can be used :

$$\nabla.(\sigma\nabla\phi + \frac{\partial}{\partial t}(\varepsilon\nabla\phi)) = 0 \quad (3)$$

Reduced scalar formulation to the body is also used (Stuckly, 2000):

$$\nabla.(\sigma\nabla\phi) = 0 \quad (4)$$

with boundary condition on the body surface :

$$\sigma n.\nabla\phi = -\rho_s \quad (5)$$

Charge surface density ρ_s is defined by :

$$n.E_{ext} = \frac{\rho_s}{\varepsilon_0} \quad (6)$$

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.

B. High Frequency problems

Two main applications belong to this class of problems: hyperthermia simulation and cell phone – human interaction. For such high frequency problems, one must truncate 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 (Givoli, 1991) or perfectly matched layers (Berenger, 1994).

The Finite Difference Time Domain (FDTD) method may be seen as the most popular technique (Kunz, 1993), (Taflove, 1995): it is simple to use, and it is able to deal with the large number of unknowns required. Subgridding techniques allow to obtain refined mesh into a subregion without using exceedingly large computer resources (Okoniewski, 1997). Coupling with thermal problems have also been reported (Tsiboukis, 2002). On the other hand, the main disadvantage of the method is the use of cubic elements, which do not conform exactly with the complexity of human geometries. Also, the error introduced by the numerical dispersion of the algorithm may become large.

Another time-domain method which is able to modelize the electromagnetic interactions with human models is the finite integration technique (FIT) (Gjonaj, 2002). The electromagnetic field voltages and fluxes are defined on a staggered grid pair, and are coupled through the cell-averaged dielectric properties of materials. Time domain integration is performed using an explicit leapfrog scheme. Large size problems can be dealt with, and the FIT discretization guarantees the long-time stability of the model. In (Gjonaj, 2002) the calculation of the transient temperature is also performed.

On the other hand, the finite element (FE) method is mainly useful for frequency domain problems (Nicolas, 1993), due to the time required to solve the matrix system. Its capability of modelling strongly heterogeneous structures has been proved. It allows to handle irregular structures through the utilization of tetrahedral elements. It can be used either with scalar and vector potentials formulations (Boyse, 1993) or directly with field formulations.

Several other formulations have also been reported for such high frequency applications, such as the Method of moments (Jakobus, 1997) or the Volume Surface Integral Equation (Wust, 1999), but their use seems to be less widespread.

III. SPECIFIC MODELLING PROBLEMS

Either we want to be protected from the fields or we want to take benefit of the positive effects of these fields, all the effects as well thermal as genetic have to be well known. Like in any industrial application, the electromagnetic field computation allows a better knowledge of the phenomena, and an optimised design. Hence, there is a very important challenge for the techniques of computation of electromagnetic fields. The major difficulties appearing are :

- **related to the material properties :**

Compared to the material usually used in the classical electromagnetic systems, the human body is made of a large number of material, each of them having specific properties (magnetic permeability, dielectric permittivity, electric conductivity). First, these material have to be identified, and then their properties have to be defined. The table I gives some classical values of these properties.

These properties have some particularities :

- Their values are not of the same order of magnitude than the usual materials. That means that some models, even if they are valid, can give inaccurate results due to a bad conditioning of the matrix system.
- These properties are not well known (even if they are well identified), and depend on the activity of the person.
- This material is an active material at the cell scale : a specific work has to be done in order to understand what is the process of the transmission of electric information between cells.

	ε_r	ε_i	σ	λ	δ
			(S/m)	(m)	(m)
Fat	20.0	33.19	0.05	2.04	0.580
Muscle	113.0	404.9	0.61	0.680	0.142
Bone	7.3	19.91	0.03	2.93	0.670
Kidney	187.9	414.2	0.624	0.620	0.150
Spleen	188.2	423.5	0.638	0.613	0.150
Liver	119.7	253.5	0.382	0.782	0.196
Aorta	88.8	248.9	0.375	0.833	0.188
Veins	118.0	730.1	1.10	0.534	0.100
Intestine	202.5	979.6	1.476	0.451	0.088
Bladder	231.4	183.2	0.276	0.682	0.312
Tumour	60.0	531.0	0.800	0.642	0.114
Air	1.0	0	0	11.06	-

ε_r : Real part of the permittivity	σ : Conductivity
ε_i : Imaginary part of the permittivity	
δ : Electromagnetic skin depth	λ : Wavelength

TABLE I. ELECTROMAGNETIC PROPERTIES OF THE DIFFERENT MEDIA FOR THE FREQUENCY 27.12 MHZ.

- **related to the phenomena :**
  - Generally we have to face with a coupled problem : the thermal effect is one of the major effects and it is affected by the blood circulation. If the effects to be identified are the thermal ones, this coupling is of a great importance.
  - The phenomena can also be widely different. We can be interested by the magnetic field, the current density, the power density or the temperature distribution.

- **related to the geometry :**
  - The geometry of a human body or of a part of it is very complex. It is made of many regions with different properties. Fig. 1 shows a body with an accurate mesh. The number of unknowns is equal to 5.10^6.
  - On the other hand, the sources that generate the electromagnetic fields have to be described with accuracy. It is easy to describe the antenna of a cell phone, it is more complicated to describe an electrical machine under operation. Today it is impossible to describe with a fine meshing a human body exposed to the field radiated by an electrical machine or any electromagnetic converter. The specific approach for modelling the distribution of the electromagnetic fields should include an analysis of the domain where the accuracy has to be the most important :
    If the most important result is the distribution in the body, is it possible to describe the source by an equivalent one?
    If the most important result is the minimization of the field generated by a system is it possible to use a simplified model?

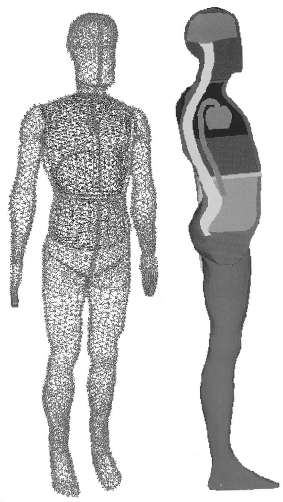

Fig 1. Accurate finite elements mesh of a man - Doc. EDF (Baraton, 1995)

Modelling the electromagnetic phenomena in the human body imposes to develop a specific approach for that modelling. In addition to the complexity of the geometry of both the electromagnetic field sources and the human body itself, a particular attention has to be paid to the material identification and modelling, the use of the most suitable simplified scheme (i.e. equivalent sources) for the field sources or for the human body.

IV. Example of Field Computation in Human Body: Local RF Hyperthermia Modelling

In this section, a 3D FE formulation used for radiofrequency (RF) hyperthermia problems is described. Edge finite elements are coupled with absorbing boundary condition. It is shown how the model may be used on a real geometry coming from computerized tomography scans.

A. Objective of the modelling

Local hyperthermia is used as adjuvant therapy in oncology treatment. It can be used alone or together with chemotherapy or radiotherapy to increase their effects (Nielsen, 2001). The purpose of hyperthermia is to heat (42-44°C) a localized cancerous tumour without overheating the surrounding normal tissue. When using electromagnetic sources, this elevation of temperature is obtained by submitting locally the patient to a radiofrequency electromagnetic field using external applicators. The operating frequency of the applicators varies accordingly to the depth of the tumour. Either 13.56 MHz or 27.12 MHz frequency are used for heat deep-seated tumours located at 90 mm below the skin surface (Chou, 1998).

All the success of this technique lies in the good focalization of the heat, which is actually related to the electromagnetic field inside the cancerous tumour. Furthermore, it is required to avoid the overheating in close organs. It is therefore essential to know with accuracy the electromagnetic fields distribution. The absorption of energy in a medium is represented by the Specific Absorption Rate (SAR), which is actually related to the distribution of temperature in a first approximation (Ratnajeevan, 1990).

Our main objective is to develop a method, based on the 3D numerical modelling of electromagnetic phenomena in the human body, in order to optimize the treatment of deep-seated cancerous tumours.

B. The finite element formulation

Although the frequency is rather low (27.12 MHz), we cannot ignore the displacement current, according to the permittivity values of the human tissues. The time harmonic FE formulation is obtained by applying the Galerkin weighted residual method to the vector wave equation, and by using then some mathematical identities:

$$
\begin{aligned}
&-\int_v \nabla W \times \frac{1}{\mu_r} \nabla \times \mathbf{E}.dv - \int_v W k_0^2 \varepsilon_r \mathbf{E}.dv + \\
&\int_{s_{ext}} n \times (W\nabla \times \mathbf{E}).ds = -j\omega\mu_0 \int_\Gamma W\mathbf{J}.dv
\end{aligned}
\qquad (7)
$$

Where W is the weight function, $k_0 = \omega\sqrt{\mu_0 \varepsilon_0}$ is the constant of propagation of the electromagnetic field, J (A/m^2) the density of the electric current source and S_{ext} is the external surface.

In order to take into account the wave propagation through the FE domain, the FE formulation is coupled with Engquist Majda absorbing boundary condition (ABC) (Yao Bi, 1996). Only first order ABC is used since the field values are low at the boundaries. This is due to the values of the electromagnetic skin depth in the human tissues at the considered frequency, which avoid a large part of the field to come out from the body.

$$n \times \nabla \times \mathbf{E} \cong g_{ABC}(\mathbf{E}) = jk_0 \mathbf{E}_t \qquad (8)$$

Where $\mathbf{E}_t$ is the tangential electric field.

The discretization is obtained by using classical mixed elements (Nédélec, 1980), which ensure the continuity of tangential field components across interface between different media. Since the matrix is sparse and symmetric, a conjugate gradient solver with SSOR preconditioning technique is used to solve it.

This formulation has been validated by comparison with experimental measurements performed on a phantom having equivalent electromagnetic properties to human tissues (Siauve, 2001).

C. Utilization of the 3D model on real human organs meshes

The calculation code is used to modelize the distribution of electric field in a human body when illuminated by a RF source. The source is a dipole antenna radiating at 27.12 MHz. The external boundary is a 3D rectangular box located close to the body (Fig. 2).

The mesh is obtained from 59 CT scans, allowing to take into account the real shape of the patient (Fig. 2). It is obtained using the Amira package (Amira, 2001). It is made of 33181 nodes and 182650 tetrahedral elements, leading to 221606 degrees of freedom. This geometry includes 12 different media. The properties of these tissues are given in Table I for the 27.12 MHz frequency (Gabriel, 1996), (Gabriel(2), 1996).

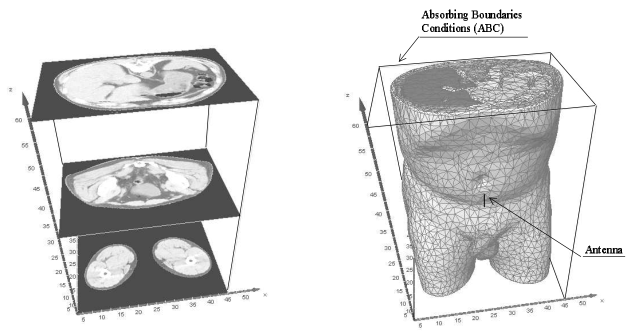

Fig. 2. CT scans and mesh of the modelled geometry.

This problem is solved in 40478 seconds (6287 iterations) on a HP J 5000 station. The most CPU-expensive operation is the matrix solving (70% of the total computation time).

As result, Fig. 3 shows the calculated electric field distribution on the exterior surface (muscle and fat) of the patient, and the SAR distribution on the bone and on the tumour.

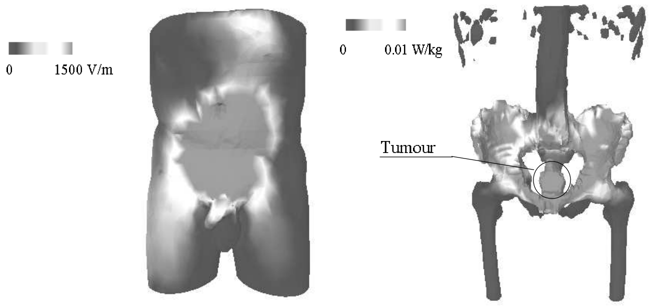

Fig. 3. Calculated electric field distribution on the muscle and the fat (left) and SAR distribution on the bone and on the tumour (right).

Fig. 4 shows the simulated electric field distribution on a section (z=30 cm) for different configurations of radiation antenna. The patient is first exposed to only one RF source, and then to two RF sources. It is clearly shown that the use of two antennas changes largely the distribution of electric field in the cross-section. So, by optimizing the location and the source values of the antennas, one can easily imagine to focus the radiation on the tumour.

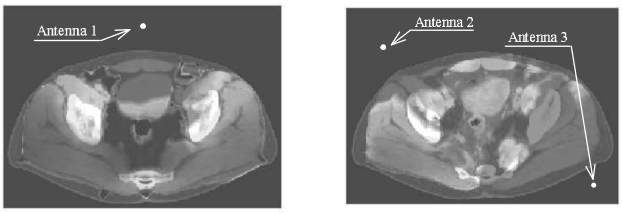

Fig. 4. Visualization of the calculated electric field distribution in a section (z=30 cm) when illuminated with one antenna (left) and with two antennas (right).

D. *Conclusions and perspective*

A 3-dimensional model based on the FE method implemented with edge elements has been developed. The numerical results have been compared with experimental measurements and show a good agreement. The developed model is able to handle heterogeneous structures and real human organs meshes assembled from CT scans.

The final objective is the optimization of the treatment of patients. This is done using several applicators functioning simultaneously, with the correct values of current excitation, to obtain the best possible focalization of the heat in the desired area. For such a purpose, the FE formulation will be coupled to a genetic optimization algorithm, in order to optimize both the location of the applicators and the values of the current sources (amplitude and phase).

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 optimised systems. A large number of equipment used everyday are electric or electronic, and thus generate electromagnetic fields. People are more and more sensitive to 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 it requires specific developments. An important work has to be done in order to get a good model for the electromagnetic behaviour of the materials constituting the human body.

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Figures

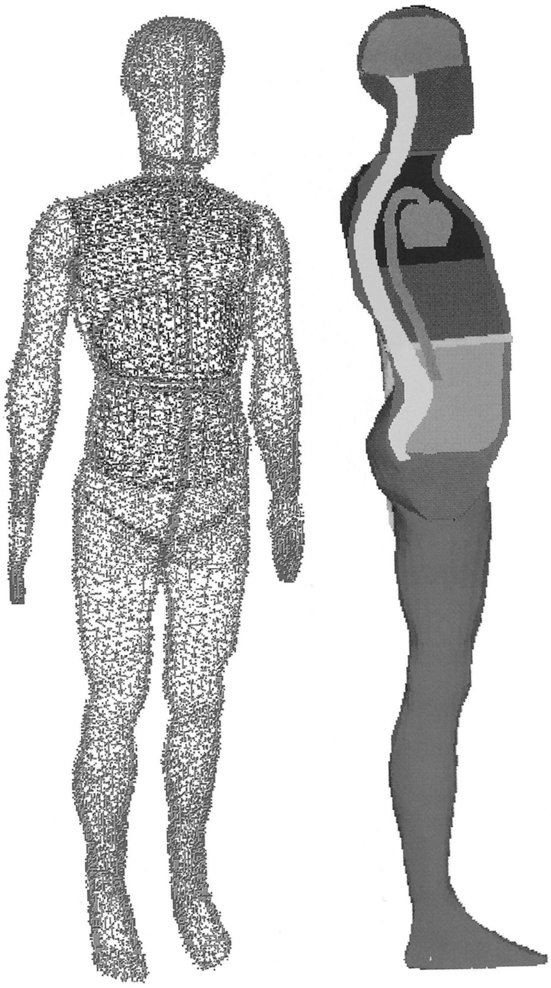

Figure 1

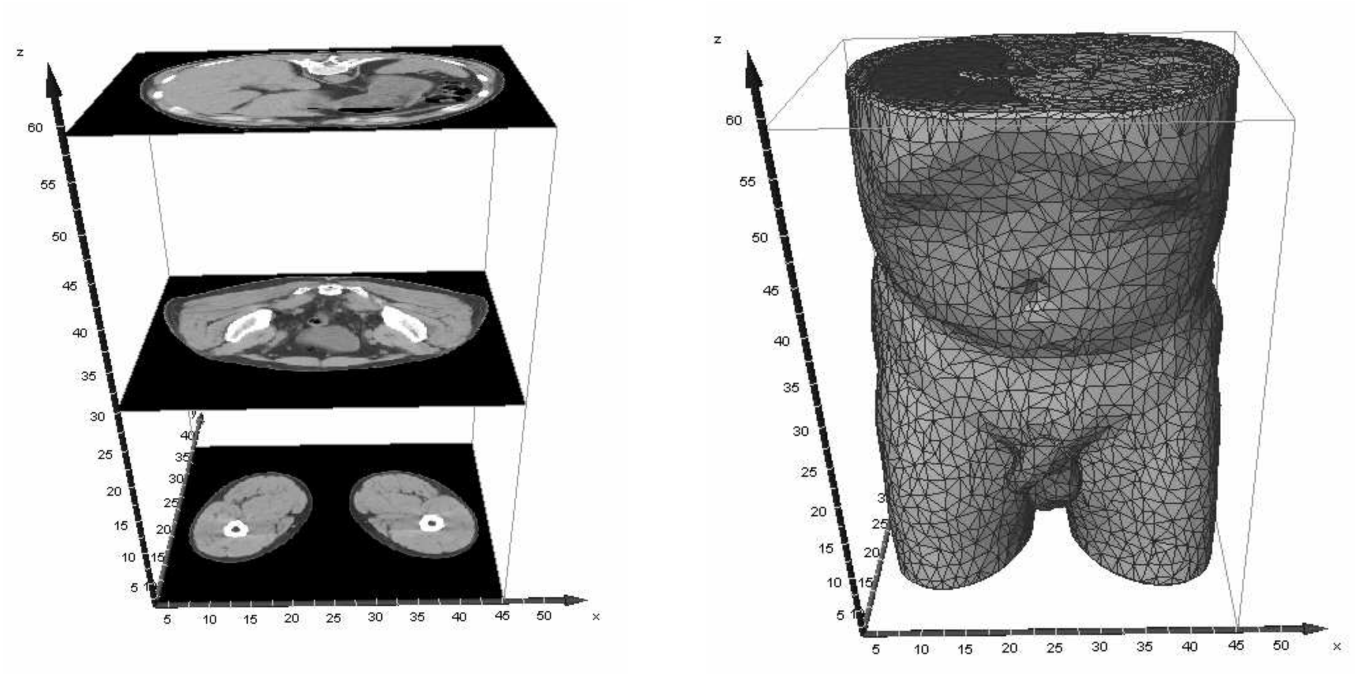

Figure 2

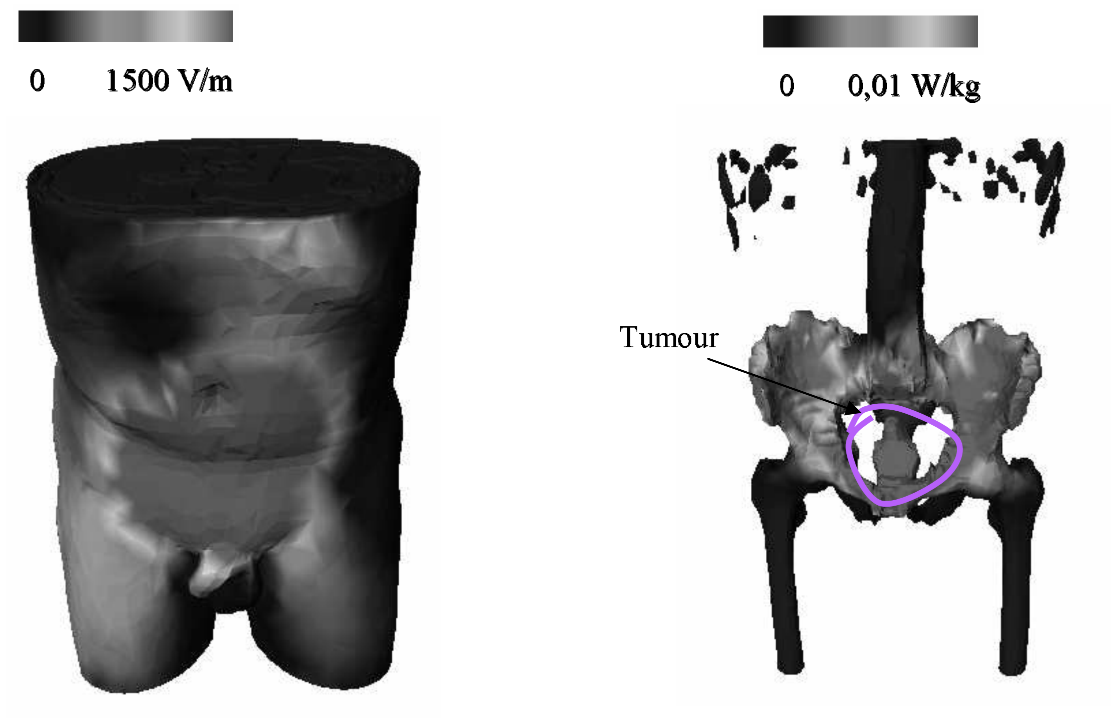

Figure 3

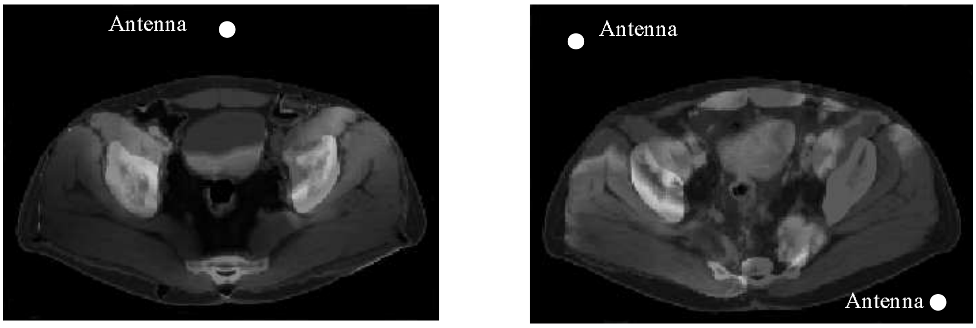

Figure 4

Professional biographies

Riccardo SCORRETTI (rscorret@conmet.it) was born in 1973 in Prato (Italy). In 1999 he received the MS degree in engineering at the university of Florence. From 1998 to 2000 he worked at the Ecole Normale Supérieure de Lyon (France) on the statistical properties of the fracture. He is now working as PhD student in the CEGELY (Lyon) on the computation of induced currents in the human body by LF magnetic fields.

Nicolas SIAUVE (Nicolas.Siauve@eea.ec-lyon.fr) was born in 1975 in Saint-Etienne, France. He received his MS degree in electrical engineering from the University of Lyon 1 in 1999 and in 2002 the PhD degree from the Ecole Centrale Lyon. His current research interests are concerned with the electromagnetic fields computation in hyperthermia.

Noel BURAIS (Noel.Burais@eea.ec-lyon.fr) was born in Lyon, France, in 1954. He received his Doctorate degree in Electrical Engineering from Ecole Centrale de Lyon in 1981. He is currently Professor at the Ecole Centrale de Lyon. His main interest research domain in the CEGELY concerns the numerical modelling of Electromagnetic phenomena (Finite Element, Optimization,..). The application domains are the Non Destructive Testing, the Induction Heating, the high Power Transformers, and the Phenomena induced by Magnetic and Electric Fields in the Human Body.

Laurent NICOLAS (Laurent.Nicolas@ec-lyon.fr) received his engineering degree in 1982 from Institut National Polytechnique de Grenoble and his PhD degree in 1986 from Ecole Centrale de Lyon (France). He is now Senior research associate in the CNRS and the head of the CEGELY. His research activities are related to the electromagnetic field computation and the EMC applications

Alain NICOLAS (Alain.Nicolas@ec-lyon.fr) received his engineering degree in 1972 and his doctorate degree in 1983 from Ecole Centrale de Lyon (France). He is now professor in Electrical Engineering in Ecole Centrale de Lyon. His research activities in the CEGELY are related to the electromagnetic field computation and the eddy current applications.

Keywords

Bioelectromagnetics,
Modelling,
Optimization,
Hyperthermia,
Finite element method