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# Low frequency numerical dosimetry of electric field by using multipolar sources defined on an arbitrary surface

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**Computation of low frequency induced electric fields in the human body requires the knowledge of the source field. The source field can be reconstructed by measuring the magnetic field over a regular grid, or by identifying a model, among which multipoles. Spherical multipoles are easy to compute, but cannot be used close to the source. In this work it is proposed to use a new multipolar model which holds outside an arbitrary geometry – not limited to a sphere.**

*Index Terms*—Finite Element method, inverse problem, multipoles, numerical dosimetry.

## I. INTRODUCTION

**C**OMPUTATION of induced electric field inside the human body is crucial to assess the respect of regulation [1]. In the case of exposure to low frequency magnetic fields, it is natural to use scalar potential formulations, where the source term is given through a magnetic vector potential  $\mathbf{a}_0$ . Whatever the numerical method, the formulation writes:

$$\operatorname{div}[-\sigma(\operatorname{grad} v)] = \operatorname{div}[\sigma(j\omega\mathbf{a}_0)] \quad (1)$$

where  $\sigma$  is the conductivity of tissues [2], the magnetic flux density  $\mathbf{b} = \operatorname{curl} \mathbf{a}_0$  is known through  $\mathbf{a}_0$  (the term from eddy currents is neglected) and the electric field writes  $\mathbf{e} = -j\omega\mathbf{a}_0 - \operatorname{grad} v$ . The formulation is solved on the human body only, with boundary condition  $\mathbf{n} \cdot \mathbf{j} = 0$ .

The determination of the source term  $\mathbf{a}_0$  can be done by using several approaches. Direct computation is possible only if a model of the source is available, which is seldom the case. Most often, the magnetic field is measured on a regular grid containing the human body. Then a vector potential can be computed by using so called uncurl methods [3], [4]. By using this approach, a large number of measurement points are required, and the body cannot be displaced outside the volume defined by the measurement grid. In a recent work [5], it has been proposed to model the source by using spherical multipoles. This allows to recompute quickly the source term  $\mathbf{a}_0$  for any position of the human body, but it has the major drawback that the body cannot lay inside a sphere centered on the source. This hinders using this method in proximity of the source – that is, precisely where the field is the more intense!

In this work we propose a model of (non-spherical) multipolar source which is defined on an arbitrary surface, and therefore aims at overcoming the limitations of [5].

## II. MATERIALS AND METHODS

### A. Multipolar source

Let  $S$  be an arbitrary surface which encloses all the sources. It is possible to find an equivalent double-layer potential  $\tau_0$  which generates exactly the same field as the source in the space comprised between  $S$  and the Brillouin sphere [6], which is the smallest sphere which encloses the source.

We generate a basis for this double-layer potential by using the procedure described in [7]. Hence  $\tau_0$  writes:

$$\tau_0(\mathbf{x}) = \sum_{k=1}^{\infty} \sum_{m=-k}^k b_{km} \tau_{km}(\mathbf{x}) \quad (2)$$

where  $\tau_{km}(\mathbf{x})$  are the terms of the basis of order  $k$  and degree  $m$ ,  $b_{km}$  are the coefficients of the development and  $\mathbf{x}$  the points of the surface  $S$ . By construction, the following gauge condition is enforced:

$$\iint_S \tau_{km}(\mathbf{x}) d\mathbf{x} = 0 \quad (3)$$

Outside the Brillouin sphere, the field generated by each distribution  $\tau_{km}$  decreases at least as fast as the one of a multipole of the same order.

In order to make the problem computationally tractable, we truncate the basis up to a given order  $N$ , so that we obtain an approximate distribution  $\tau$ :

$$\tau(\mathbf{x}) = \sum_{k=1}^N \sum_{m=-k}^k b_{km} \tau_{km}(\mathbf{x}) \simeq \tau_0(\mathbf{x}) \quad (4)$$

In principle when  $\tau_0$  is known, the coefficients  $b_{km}$  can be found by projecting  $\tau_0$  on the basis. The parameters can be identified via a model of the source. In practice, an inverse problem has to be solved from available experimental data. The vector potential  $\mathbf{a}$  is computed from  $\tau$  at any point as [8]:

$$\mathbf{a}_0(\mathbf{x}) = \iint_S (\operatorname{grad}_S \tau(\mathbf{y})) \times \mathbf{n} G(\mathbf{x}, \mathbf{y}) d\mathbf{y}. \quad (5)$$

where  $\mathbf{n}$  is the outward normal to the surface  $S$ , and  $G(\mathbf{x}, \mathbf{y})$  is the Green's function, which in 3D writes:

$$G(\mathbf{x}, \mathbf{y}) = \frac{1}{4\pi} \frac{1}{\|\mathbf{x} - \mathbf{y}\|}. \quad (6)$$

### B. Computational phantom

The computational phantom used in this work is Alvar [9]. Alvar is a voxel phantom based on freely available online anatomic atlas, BodyParts3D (<http://lifesciencedb.jp/bp3d>). It is composed of 86 different tissues. It has a native resolution of 0.5 mm, but in this preliminary work it has been undersampled by a ratio 1:8 so as to achieve a resolution of 4 mm.

### C. Dosimetric computation

Equation 1 has been solved with the Finite Element method by using a home-made software written in Matlab. The linear system is composed of 1'080'453 unknowns, and it is solved by using the AGMG algebraic multigrid solver [10].

## III. RESULTS

In this preliminary test, a fictive source is enclosed in a box of dimensions  $0.3 \times 0.3 \times 1$  m located left to the human body. The chosen distribution of double-layer potential  $\tau(\mathbf{x})$  corresponds to a dipole along the  $z$  axis. In the full paper, the considered source will be a wireless energy transfer system. The surface of the box is meshed with 624 triangles. On this mesh,  $\tau(\mathbf{x})$  is represented by linear nodal shape functions.

The computed electric field is depicted at the surface of the human body in Figure 1. It is observed that the induced electric field is higher on the side close to the source, represented by a dashed box. For each tissue we computed the average, maximum and 99% percentile values of the electric field. These values are depicted in Figure 2 for some representative tissues (full data will be available in the extended article).

## IV. CONCLUSION

It is demonstrated that by using non-spherical multipolar sources it is possible to simulate the exposure to a source of magnetic field located any position, including in proximity of the human body. Details on the validation and on the accuracy of the computation with a more realistic source will be presented in the extended article. Moreover, the multipolar source will be identified by solving an inverse problem.

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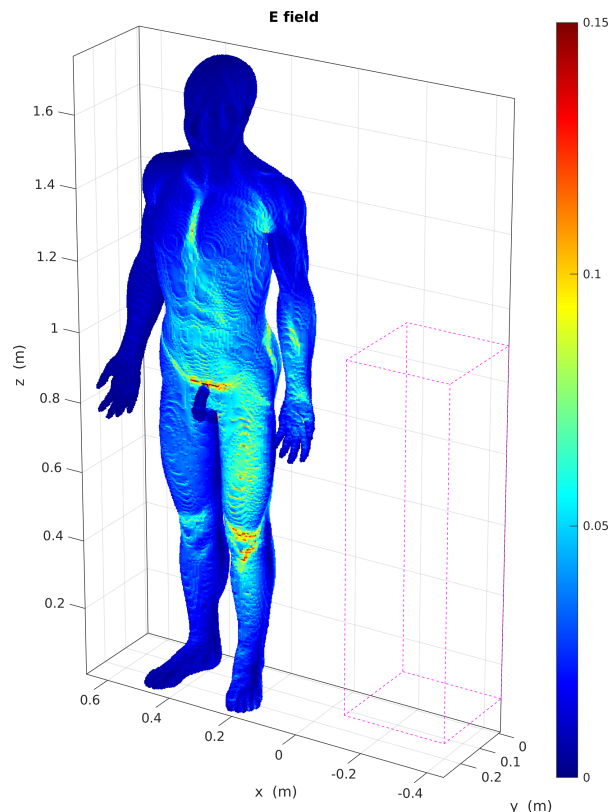


Fig. 1. Electric field induced in the human body by the source enclosed in the surface  $S$ , represented by a dashed box.

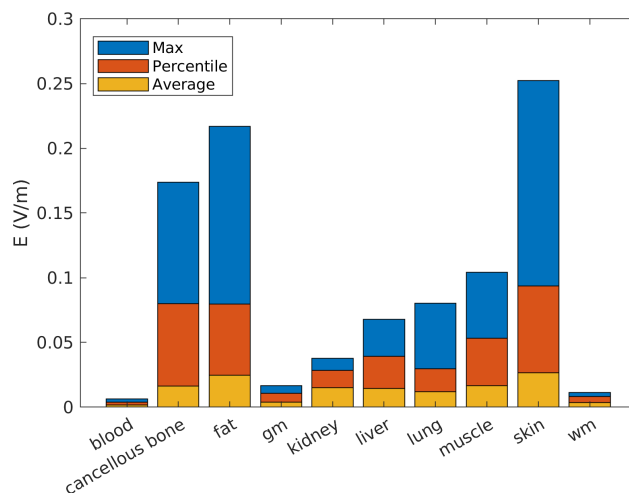


Fig. 2. Electric field induced in the tissues of the human body.