A potential-based formulation for motion-induced electric field in MRI

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This paper presents a potential-based formulation conceived to estimate the electric field induced in a human body which moves through the stray stationary magnetic field produced by magnetic resonance scanners. The formulation is written in the moving reference frame of the body and it is solved numerically, according to a time domain Finite Element approach. Both conduction and dielectric components of the induced currents are taken into account, allowing a discussion about the effect of tissue permittivity, which suffers a very high uncertainty at low frequency. Some examples of exposure assessment in realistic situations are finally presented.

***Index Terms*—Magnetic resonance imaging, Motion induced electric field, Electromagnetic human exposure, Finite element method**

I. INTRODUCTION

ATTENTION has been often paid to human exposure in Magnetic Resonance Imaging (MRI) environment, making reference mainly to the effects produced by gradient and radiofrequency coils (e.g. see [1-2]). More recently, an increasing interest is devoted to the effects on medical workers moving through the strong (on the order of 1 T) MRI stray stationary magnetic field. This kind of exposure may provoke annoying symptoms (vertigo, nausea, magnetophosphenes and peripheral nerve stimulation) and impair working ability, with important impact on patients' safety and, therefore, on the development of innovative applications (e.g. MRI-guided surgery). In March 2014 the International Commission on Non-Ionizing Radiation Protection (ICNIRP) published specific Guidelines providing exposure limits in terms of induced electric field [3]. As already happened for the exposure to sinusoidal fields, in the future the new Guidelines probably will be included in some legislative measure (e.g. the European Directive addressing workers' exposure to electromagnetic fields). This calls for dedicated computational techniques able to estimate such an electric field, a task that still presents some open issues. Among them, the choice of the dielectric properties to be assigned to the human tissues, which at the moment suffer from extremely high uncertainty, is of primary importance.

Even if some numerical schemes have been already proposed to estimate motion-induced fields in MRI scenarios [4-10], no one of them have faced the above-mentioned issue. For this reason, the paper presents a new modeling approach able to estimate motion-induced fields including the contribution of dielectric currents, which also involves the dependence on acceleration. This allows clarifying the effect that permittivity has on the motion-induced electric field, which represents the metric to assess compliance with the limits in force.

II. MODELING APPROACH

The Duke anatomical model, belonging to the Virtual Family dataset [11], is exploited for the description of the human body. It is composed by 77 different tissues and segmented into cubic voxels with a resolution of 4 mm. The dielectric properties of the tissues (conductivity σ and permittivity ε) have been set according to the database provided by the IT'IS Foundation [12]. Concerning this, it must be underlined that these data come from extrapolations obtained through a 4th order Cole-Cole dispersion model, whose validity is a matter of discussion at the extremely low frequencies of interest for motion-induced fields (around 1 Hz). However, since practically they are the only data currently available, they are almost an unavoidable choice, which will be justified *a posteriori* by the results.

The formulation handles rigid body movements , with quite low speed and acceleration (consistent with realistic values for humans). By adopting a reference frame co-moving with the body, the induced electric field $\boldsymbol{E}$ is expressed through a magnetic vector potential $\boldsymbol{A}$ and an electric scalar potential φ:

$$\boldsymbol{E} = -\left(\partial \boldsymbol{A}/\partial t\right) - \nabla\varphi \tag{1}$$

In the human body this field drives a divergence-free electric current density (including conduction and dielectric terms):

$$\nabla\cdot\left[\sigma\boldsymbol{E} + \varepsilon\left(\partial\boldsymbol{E}/\partial t\right)\right] = 0 \tag{2}$$

Since the induced currents are too low to perturb the external magnetic field produced by the MRI scanner, in the laboratory reference frame, $\boldsymbol{A}$ can be seen as an impressed quantity, assigned analytically or computed through the knowledge of the source features (geometry of the coils and magnetomotive force) via classic Coulomb-gauged integrals. Moreover, from a practical side it does not undergo any transformation between different reference frames and thus it can be used as the known term for the electromagnetic problem. By substitution of (1) into (2) and rearrangement of the terms, the final equation is:

$$\begin{aligned}\nabla\cdot\left[\sigma\left(\nabla\varphi\right) + \varepsilon\left(\partial/\partial t\right)\nabla\varphi\right] = \\ -\nabla\cdot\left[\sigma\left(\partial\boldsymbol{A}/\partial t\right) + \varepsilon\left(\partial^2\boldsymbol{A}/\partial t^2\right)\right]\end{aligned} \tag{3}$$

This equation is solved through a Finite Element (FE) code implemented by the authors, directly adopting the set of voxels as a mesh and using the nodal values of the scalar potentials as unknowns. As a boundary condition, the normal component of the current density at the interface with the external air is set to zero. Some mathematical manipulations (not reported for brevity) could be used to put in evidence the dependence of the two time derivatives in the right-hand side of (3) on speed and acceleration, respectively. Such driving terms are approximated numerically by incremental ratios; then, the FE model is introduced into a time-stepping scheme to describe the transient

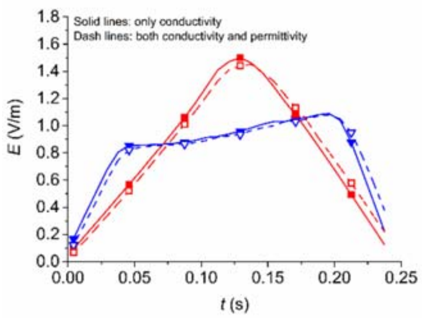

Fig. 1. 99th percentile of the electric field induced in brain. Triangles refer to speed profile *a*, whereas squares refer to speed profile *b*.

evolution of the induced quantities. As an initial condition, the scalar potential and the time derivative of $\boldsymbol{A}$ are set to zero in correspondence of the starting position. In order to get the uniqueness of solution, at each time step the value of φ in one node of the mesh is kept fixed to zero too. The proposed formulation has been checked against some reference solutions, obtaining an excellent agreement.

III. RESULT AND DISCUSSION

The analysis starts with a model problem, where an abrupt 90° rotation of the head, over a total time of 0.25 s, is simulated. In the simulation, the upper part of the body (up to the chest) moves through a uniform field of 1 T parallel to the ground. The motion is composed by three phases: a uniform acceleration, which increases the angular speed from zero to a maximum value, an intermediate stage at uniform speed and a uniform deceleration (with the same duration as the acceleration), which reduces the speed to zero. The movement has been subdivided into 30 angular steps; two different speed profiles (*a* and *b*, with maximum angular speed of 7.54 rad/s and 11.8 rad/s, respectively) have been simulated. The parameters of tissues have been set at the value given in [12] for a reference frequency f = 1 Hz. Note that, under these conditions, the relative permittivity given by the extrapolation assumes extremely high values. For instance, in grey matter it is equal to $45 \cdot 10^6$ (against a conductivity of 20 mS/m), so that the ratio $\sigma/(2\pi f \varepsilon) \approx 8$, is not very far from unity. The results in Fig.1 show the time evolution of the 99th percentile of the electric field magnitude induced in brain. For both profiles *a* and *b*, the figure compares the result obtained by considering only the conductivity (i.e. assuming $\varepsilon = 0$ for all tissues) or conductivity and permittivity together. Despite the very high permittivity values, the result is quite stable with just a small time delay in the dashed curves. Moreover, the curves reflect quite well the shape of the two speed profiles.

The computational procedure is then exploited in a realistic scenario of exposure assessment for. The human model is located in close proximity to a 3 T MRI scanner. At the starting position the body is bent forward, with the face looking at the examination couch. Then, it is rotated of 90° toward the bore of the scanner, in a total time of 0.4 s (maximum angular speed: 4.2 rad/s). The tissue parameters have been set according to [12], for 1 Hz reference frequency. Figure 2 indicates in red the voxels where the exposure index (computed according to the procedure given in [1]) does not comply with the ICNIRP Guidelines in force. If the analysis is restricted to the head, the tissues that are more interested by the exposure are cerebellum, grey matter and white matter, indicating a possible concern for safety. In the full paper the analysis of the contribution of the dielectric currents will be extended (including the effect of the variation with frequency) and other exposure situations will be presented.

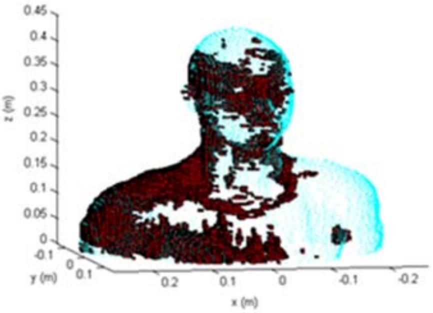

Fig. 2. 99th percentile of the electric field induced in brain. Triangles refer to speed profile *a*, whereas squares refer to speed profile *b*.

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