Evaluation of the Electric Field Induced in Transcranial Magnetic Stimulation Operators

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This work aims at investigating the exposure experienced by the nursing staff executing transcranial magnetic stimulations (TMS). The analysis is carried out through the finite element method, using the Duke (Virtual Family) anatomical model to represent the operator body. The TMS apparatus is a spiral circular coil with axis parallel to the body axis supplied by a short duration sinusoidal current. The electromagnetic field problem is formulated in terms of vector and scalar potentials. The results show that the operator exposure exceeds the basic restrictions, suggested by the Guidelines of the International Commission On Non-Ionizing Radiation Protection, when the distance from the coil decreases below safe limits, so requiring in that case the use of shielding systems.

***Index Terms*—Finite-element method, Magnetic field effects, Medical treatment, Modeling, Transcranial magnetic stimulation**

I. INTRODUCTION

THE TRANSCRANIAL magnetic stimulation (TMS) is both a diagnostic and a therapeutic tool. In the first case it is utilized to test the fast-conducting corticomotor pathways in a variety of diseases [1]; in the second case it can be exploited for the treatment of central nervous system diseases, like Parkinson, depression or psychiatric disorders [2].

A TMS appliance is a circular or figure of eight coil with a power supply, normally fitted with capacitors, able to provide one or more sinusoidal current pulses with peak values of some thousands of ampere. An operator manually controls the coil position so that the corresponding magnetic field pulses are transmitted to the patient organ of interest, usually the head scalp. Few previous studies based on [3] - [4] show that the operator must be at a distance from the center of the coil at least of 70 cm, to limit the field gradient [5] and at least of 110 cm, to limit the induced phenomena [6].

This paper is focused on the computation of the electric field distribution induced in the operator, through a finite element approach, adopting an anatomical voxel model and taking into account the "new" indications provided in [7]. The goal is to provide a further contribution to the literature, useful for the preparation of future guidelines for the safety of the nursery staff. This work shows the areas of greatest exposure in the operator body and the magnitude of the induced electric fields, which exceeds the basic restrictions, when the operator is working at a distance lower than ~ 45 cm from the coil.

II. PROBLEM DESCRIPTION AND NUMERICAL METHOD

The accurate computation of the induced phenomena in a patient subjected to TMS treatment is matter of several recent studies (e.g. [8] – [9]). This work investigates the exposure of an operator close to a TMS apparatus. The features of the appliance are described in Table I. The Duke anatomical model of the Virtual Family dataset [10], with voxel resolution equal to 4 mm, is utilized to describe the operator body.

TABLE I
TMS AND CONSIDERED COIL

Item	Type	Description
TMS appliance	Magpro R30	Medtronic
Coil	MC125	Circular
Pulse	3.45 kHz	Sinusoidal
Current	5.6 kA	Peak value

The electromagnetic field problem is developed under two basic assumptions: 1) the magnetic field generated by the sources is not altered by the weak currents induced in the body (domain Ω); 2) the induced currents are confined inside Ω. The problem is formulated in the frequency domain (angular frequency ω) introducing a magnetic vector potential $\mathbf{A}$ and scalar potential ϕ: $\mathbf{B} = curl\mathbf{A}$ and $\mathbf{E} = grad\phi - j\omega\mathbf{A}$.

Thus, the divergence free character of current density leads to the following weak form field equation in Ω:

$$\int_{\Omega} \tilde{\sigma}\, grad\phi \cdot gradw\, dv - \int_{\partial\Omega} w\tilde{\sigma}\, \left(grad\phi \cdot \mathbf{n} \right) ds = j\omega \int_{\Omega} \tilde{\sigma}\, \mathbf{A} \cdot gradw\, dv - j\omega \int_{\partial\Omega} w\tilde{\sigma}\, \mathbf{A} \cdot \mathbf{n}\, ds \qquad (1)$$

being w the test function and $\tilde{\sigma} = \sigma + j\omega\varepsilon$ the complex conductivity. However, due to the second assumption, in this specific case the surface integrals in Eqn. (1) vanish. In addition, since the magnetic field is unperturbed, the divergence-free vector potential $\mathbf{A}$ only depends on the known sources (within volume Ω_s) and is given by:

$$\mathbf{A} = \mathbf{A}_s = \mu_0 \int_{\Omega_s} \mathbf{J}_s \Psi dv \qquad (2)$$

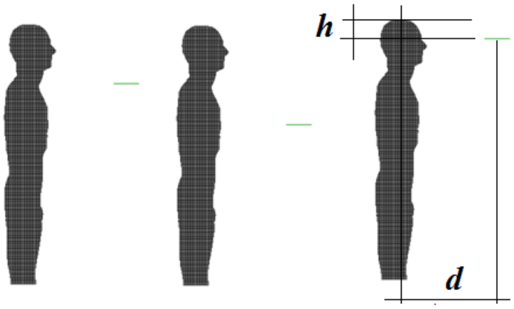
where $\Psi = 1/(4\pi\mathbf{r})$ is the Green function with $\mathbf{r}$ the distance among source point and computational point.

Problem (1) is solved through the finite element method, assuming the voxels of the human model as finite element and the nodal values of the scalar potential as the unknowns. The code, which can be applied to a large variety of EM dosimetric studies, has been tested with experiments on phantoms in [11].

III. ANALYSIS OF THE RESULTS AND DISCUSSION

The investigation is first developed by assuming the coil axis parallel to the body axis. Several coil positions have been simulated, varying both the distance between coil and body (d) and the vertical gap (z axis) between the head top and the coil plane (h). The considered distances are: d = 30 cm, 50 cm, 70 cm, while the h values, corresponding to three different cases (#A, #B and #C) are specified in Fig. 1.

At 3.45 kHz, the ICNIRP Guidelines [7] suggest as basic restriction for the occupational human exposure to time-varying fields, an rms value equal to 0.93 V/m (1.31 V/m peak value, for sinusoidal waveforms). This limit is indicated for all tissues, head and body. For a correct comparison with the ICNIRP basic restrictions, the 99th percentile value of the electric field has been computed and presented in Table II. More details about this computation will be provided in the full paper. The significant discrepancies between peak and 99th percentile values prove the presence of very small "*hot spots*". Table II also shows that the limit is exceeded for distances lower than ~ 45 cm and that the worst position, among the three considered, is the #B one. In any case, at d = 50 cm, the points of greatest exposure appear to be the groin area and the kidneys region, as shown in Figs. 2 and 3. A more complete analysis will be presented in the full paper including rotated positions of the coil, different shape of the coil (e.g. butterfly coil) and the effects of a shielding system capable of reducing the field on the operator side, without affecting the field distribution on the patient side.



a) b) c)

Fig. 1 –TMS coil position with respect to the operator model. a) h = 29.2 cm (case #A), b) h = 49.2 cm (case #B), c) h = 9.2 cm (Case #C). d = 50 cm for all the three figures.

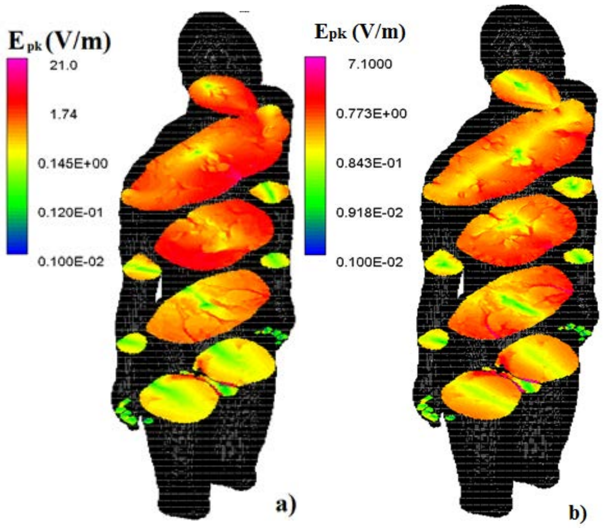


Fig. 2 – Peak values of the electric field distribution at different transverse planes: a) d= 30cm, h= 29.2 cm (case #A); b) d= 50cm, h= 49.2 cm (case #B)

TABLE II

SUMMARY OF RESULTS

Item	Case #A (V/m)	Case #B (V/m)	Case#C (V/m)
d= 30 cm	3.17 / 20.8 (max)	3.81 / 22.5 (max)	2.48 / 11.5 (max)
d= 45 cm	1.20 / 8.42 (max)	1.33 / 8.71 (max)	1.01/ 6.92 (max)
d= 50 cm	0.93 / 6.50 (max)	1.02 / 7.10 (max)	0.80 / 5.79 (max)
d= 70 cm	0.42 / 2.87 (max)	0.43 / 3.95 (max)	0.39 / 2.93 (max)

Peak values of the computed induced electric field in the operator. The form is "num1 / num 2 (max)", where "num 1" is the 99th percentile value of the electric field E whereas "num 2" is the maximum computed value of E.

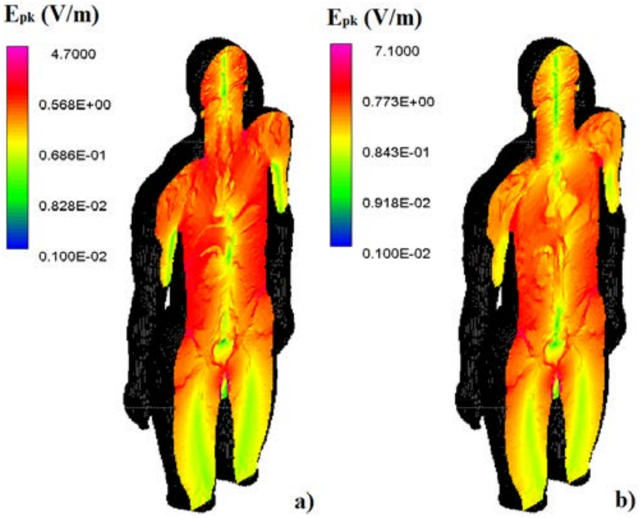


Fig. 3 – Peak values of the electric field distribution, d= 50cm: a) Case #A and b) Case #B.

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