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Evaluation of the Electric Field Induced in Transcranial Magnetic Stimulation Operators

Oriano Bottauscio¹, Mauro Zucca¹, Mario Chiampi² and Luca Zilberti¹

¹Istituto Nazionale di Ricerca Metrologica, Torino, 10135, Italy

²Department of Energy, Politecnico di Torino, Torino 10124, Italy

This work aims at investigating the exposure experienced by the nursing staff executing transcranial magnetic stimulations (TMS) and proposing a shielding system composed of an aluminum half cylinder placed around the coil. The analysis is carried out through a finite element approach, using the Duke (Virtual Family) anatomical model to represent the operator body. The TMS apparatus, a spiral circular coil supplied by a short duration sinusoidal current of ~ 6 kA, has been analyzed with and without shield. Sixty relative positions of the coil with respect to the TMS operator body have been considered, involving distance, orientation angle and vertical height. 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 64 cm, but the minimal distance is reduced to 38 cm by the conductive shield. Moreover, the staff exposure reduces when the coil overlooks the operator head, while it worsens as the position of the coil descends at the height of shoulders and chest.

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

I. INTRODUCTION

THE TRANSCRANIAL magnetic stimulation (TMS) is a modern diagnostic tool for the investigation of the disorders of the spinal cord and motor dysfunctions, but also a recent instrument for the treatment of some psychiatric diseases ranging from depression to schizophrenia [1]. This device gets his diagnostic or therapeutic effect through neuronal activation that occurs by means of the creation of a high electric field gradient in the brain tissue or spinal cord of the patient [2]. Such a field gradient is produced by a capacitor discharge, which generates one or more sinusoidal current pulses with peak value of several kiloampere. These pulses are converted into a magnetic field by a spiral coil, usually circular or having a figure of eight shape. This latter shows a higher focality, while the first one produces higher stray fields [3]. Different computational models (based in particular on the Impedance Method or the Finite Element Method) have been proposed to estimate the intense electric field induced by the time-varying magnetic field in the highly heterogeneous patient body (e.g. [4]-[7]), sometimes taking into account the large uncertainty in the properties of human tissues [8]. The strong magnetic fields and their acute health effects concern not only the patient, for whom the benefits outweigh the possible drawbacks, but also the nursing staff, who is exposed to the magnetic field several hours every day. The operators should be subjected to an exposure that complies with the reference levels specified in the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines [9]

and, in Europe, the Directive of European Commission [10], [11]. In general, safety analysis are rarely addressed to nursery staff [12], even if previous studies have suggested that ICNIRP limits are respected for distance of the operator from the coil of the order of 110 cm, and never lower than 70 cm [13], [14]. However, such a compliance imposes the use of a rod, which greatly reduces the manual dexterity of the operator. At the moment, alternative solutions based on passive or active shields to reduce the distance between operator and coil have not been presented in literature, even if the use of conductive sheets or additional coils has been proposed, but only with the aim of improving the field focality on the patient (e.g. [15], [16]).

This paper proposes and discusses the use of a passive conductive shield to limit the electric field induced in the body of a TMS nurse specialist, allowing to operate at a reasonable distance from the apparatus and the patient. The computations, performed through a Finite Element code deeply validated [17], show how the shield reduces the operator exposure to levels that are compliant with the ICNIRP limits, when the operator is at ~ 38 cm or farther from the patient, whereas the distance of ~ 64 cm is required without screen.

II. MODELING APPROACH

Measurements performed on the TMS magnetic flux generated [18] show that the measured induction waveform differs very little from a pure sinusoid, with a deviation less than 7% between positive and negative peaks. This result allows us to assume the evolution of the field quantities as purely sinusoidal. Moreover, according to [19], the guidelines [9] can be utilized for assessing the exposures by considering the peak amplitude obtained by multiplying the rms field value at the carrier frequency by $\sqrt{2}$.

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Having assumed a sinusoidal behavior, the problem is formulated in the frequency domain (angular frequency ω), representing the related field quantities in terms of phasor.

The computations are performed inside the operator body (domain Ω) when subjected to a magnetic field generated by an external source (TMS coil). The human body is described by the Duke anatomical model of the Virtual Family dataset [20], with voxel resolution equal to 4 mm.

Under low frequency operating conditions, two basic assumptions can be introduced:

- 1) the magnetic field generated by the sources is not altered by the weak currents induced inside the body;
- 2) the induced currents are confined inside Ω .

Thanks to the divergence free character of the current density, the second hypothesis allows the introduction of an electric vector potential \mathbf{T} ($\mathbf{T} = \text{curl}\mathbf{J}$) to represent the electric field. Thus, developing the third Maxwell equation in weak form, the equation governing the field problem becomes:

$$\int_{\Omega} \frac{1}{\tilde{\sigma}} \text{curl}\mathbf{T} \cdot \text{curl}\mathbf{w} \, dv = j\omega\mu_0 \int_{\Omega} \mathbf{H}_s \cdot \mathbf{w} \, dv \quad (1)$$

with boundary conditions $\mathbf{n} \times \mathbf{T} = 0$ on $\partial\Omega$.

In (1), \mathbf{w} is the test function and $\tilde{\sigma} = \sigma + j\omega\epsilon$ is the complex conductivity. The known distribution of the source magnetic field \mathbf{H}_s can be derived either by the Biot-Savart law (in a magnetically homogeneous space) or by the preliminary solution of an electromagnetic field problem without the body (in presence of conductive or magnetic shields).

Problem (1) is solved through the Finite Element Method using edge elements and adopting as finite elements the voxels defined in the Duke model. The computational code has been developed by the authors in a more general version without the simplifying assumption of disregarding the magnetic effects of the induced body currents. It has been applied to a large variety of EM dosimetric studies, and has been severely tested by comparison with experiments performed on phantoms [17].

III. CASE STUDY AND RESULTS

The features of the considered TMS device are described in Table I. At 3 kHz, the ICNIRP Guidelines [7] suggest, as basic restriction for the human exposure to time-varying fields, the value of 400 mV/m. This limit is indicated for all tissues, head and body, for the general public exposure. ICNIRP guidelines specify that “exposure in controlled environments, where workers are informed about the possible transient effects of such exposure, should be limited to fields that induce electric fields in the head and body of less than 800 mV/m in order to avoid peripheral and central myelinated nerve stimulation [...] Such restrictions rise above 3 kHz”. At 3.45 kHz, the ICNIRP basic restriction is $(1.35 \cdot 10^{-4} \cdot f)$ V/m where f is the frequency in hertz, that is ~ 0.46 V/m. The corresponding value for workers is ~ 0.93 V/m. In the following, we refer to these limits computing the 99th percentile value of the electric field evaluated in each voxel. In the analysis, we have considered sixty situations, resulting from the combination of:

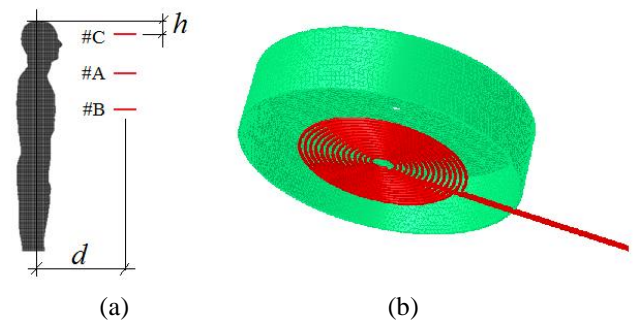


Fig. 1 – On the left: TMS coil position with respect to the operator model: $h = 29.2$ cm (case #A), $h = 49.2$ cm (case #B), $h = 9.2$ cm (Case #C). On the right: shield and coil layout. Representation of the coil and of the shield in the numerical preprocessor.

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
Diameter	13 cm	--

- i) three vertical positions of the coil with respect to the operator body (see Fig. 1a);
- ii) five distances of the coil center from the operator body axis (30, 40, 50, 60 and 90 cm);
- iii) four angular positions of the coil (0° , 30° , 60° and 90°), where 0° means that the axis of the operator body and of the coil are parallel and 90° indicates that the coil axis is perpendicular to the operator chest.

The considered situations have been analyzed with and without the shield. This latter is a hollow cylinder made of aluminum, with a welded cap only on one side, while the other side is free to host the coil positioned on the patient scalp. A padding, based on polyethylene foam, is included in the shield to set the distance between coil and metal and reduce mechanical actions and associated noise. Fig. 1b shows the coil and the shield layout. The computational analysis has shown that the shield negligibly affects the field distribution in the patient body [18].

Fig. 2 presents the 99th percentile values of the maximum induced electric field in the operator body, for the distance of 30 cm between coil and operator. The results for three heights #A, #B and #C, specified in Fig. 1, and four angular positions, show that the most critical conditions are always reached in case #B. The worst exposure condition without shield is found for the #B case with 90° coil orientation. Indeed, when the coil axis is normal to the operator chest or face, the magnetic flux produced by the coil is addressed toward the operator and the field inside the body reaches its maximum value. However, the presence of the shield reverses this behavior. In fact, with an orientation of 90° the cap of the screen, located along the flux closure path, holds the reclosing flux without significantly affecting the field distribution on the patient side. On the contrary, at 0° the lateral side of the conductive cylinder cannot prevent that a portion of leakage flux, flowing through the open side of the shield, reaches the operator body, so

reducing the shielding efficiency. Thus, in the most critical position #B, the worst situation is at 90° without the screen, while it corresponds to 0° with the screen. This behavior does not change as the distance increases (Fig. 3).

In the worst case (#B without screen), one can deduce from Figs. 2 and 3 that the exposure certainly exceeds the ICNIRP limit when the operator trunk is located between 40 and 50 cm from the coil, which is a comfortable working position for the nursery staff. In this case, indeed, to decrease the exposure below 0.93 V/m, the distance must be not lower than 64 cm, so that the operator must work with the arms outstretched. Conversely, in presence of the shield, the exposure of the operator trunk complies with the ICNIRP limits from a minimum distance of 38 cm. The exposure can be furtherly reduced, for heights #A or #C, as it can be seen from Fig. 2 and Table II, but these positions imply a change of the typical layout of a TMS sessions, where the patient is sitting, and the operator is standing (case #B). It is to raise the patient sitting, or to operate the patient standing, with the operator on a footboard. The objective is to raise the position of the coil up to the height of the area of the operator neck, to return at least to height #A.

IV. DISCUSSION

The study here presented puts in evidence that the operator exposure worsens when the coil is held down to the chest and belly, whereas the exposure reduces when the TMS coil rises towards shoulders and head. In addition, the nursing staff should remain on the coil side when this latter is not shielded, namely, the coil axis should not intersect the operator body. Otherwise, when shielded, the coil axis perpendicular to the operator chest is welcomed.

As for the map of the induced phenomena in the operator body, one can refer to Fig. 4. This latter shows, for a distance of 30 cm between operator and coil, the peak values of the maximum induced electric field in the operator body, for cases #B and #C. The worst situations are considered (coil at 90° without shield and coil at 0° with shield). At the height #B, with the coil overlooking the operator chest, the induced phenomena are concentrated in the area of the trunk, between the neck and groin. In the case #C, with the coil facing the operator eyes, the induced phenomena are concentrated in the area of head and neck. However, in case #C the values are approximately halved in comparison with case #B, which is consistent with Fig. 2. It must be noted that the peak values shown in Fig. 4 are in their turn more than double compared to those calculated as 99th percentile and presented in Fig. 2. Anyway, as specified by the ICNIRP guidelines, “for a specific tissue, the 99th percentile value of the electric field is the relevant value to be compared with the basic restriction”. To this purpose, the induced electric field is determined as its value in the barycenter of each voxel having 4 mm side. The cited guidelines suggest averaging the electric field on 2 mm cubic volumes and propose different basic restrictions for the central nervous system (CNS) and the remaining tissues, which actually coincide at around 3 kHz. Thus, the computations have been repeated with 2 mm voxels for the

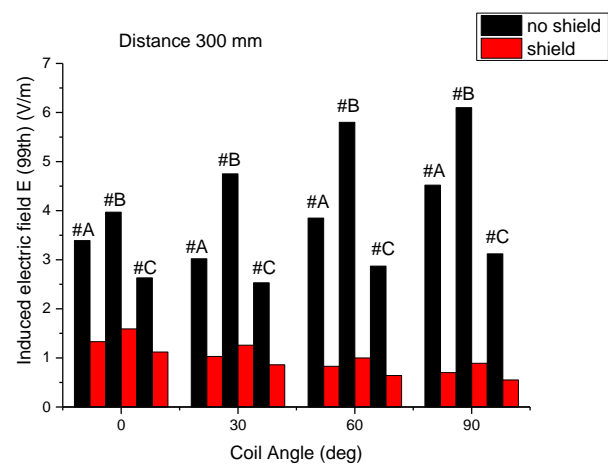


Fig. 2. - 99th percentile values of the maximum induced electric field in the operator body, computed with the coil at a distance equal to 30 cm from the body axis. The three positions #A, #B and #C, specified in Fig. 1 and the four angular positions have been considered.

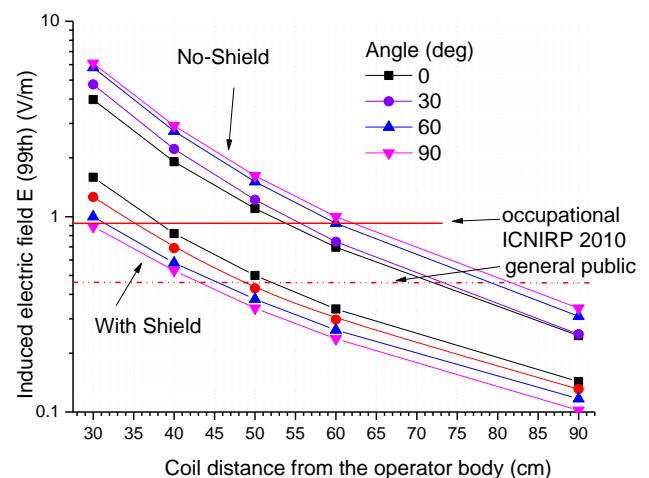


Fig. 3. 99th percentile values of the maximum induced electric field in the operator body, computed with the coil at different distances from the body axis. Case #B with and without shield.

TABLE II
99TH PERCENTILE OF THE INDUCED ELECTRIC FIELD

Dist. (cm)	Angle (deg)	Case #A (V/m)	Case #B (V/m) ^a	Case #C (V/m)
60	0	0.656/ 0.315	0.697/ 0.337	0.599/ 0.288
60	30	0.586/ 0.276	0.744/ 0.297	0.479/ 0.248
60	60	0.715/ 0.243	0.924/ 0.263	0.499/ 0.216
60	90	0.836/ 0.216	1.00/ 0.237	0.579/ 0.189

^a Unshielded/shielded values of the 99th percentile of the induced electric field in the operator body. Maximum computed values.

most interesting situations. Table III shows, in case #B for a distance of 40 cm, the 99th percentile of the induced electric field in three cases: all tissues, CNS with 4 mm side voxels and CNS with 2 mm side voxels. As it can be seen, the use of 4 mm voxels leads to a slight conservative overestimation in the CNS (~5÷7%) in comparison with the results given by the 2 mm voxels. Fig. 5, which presents the peak values computed with the 2 mm voxels, shows that the largest electric field is not found in the CNS, but in other tissues.

The distance between operator body and coil deserves one additional comment. It must be noted that, in the present work, we assume that the distance operator-coil is the distance

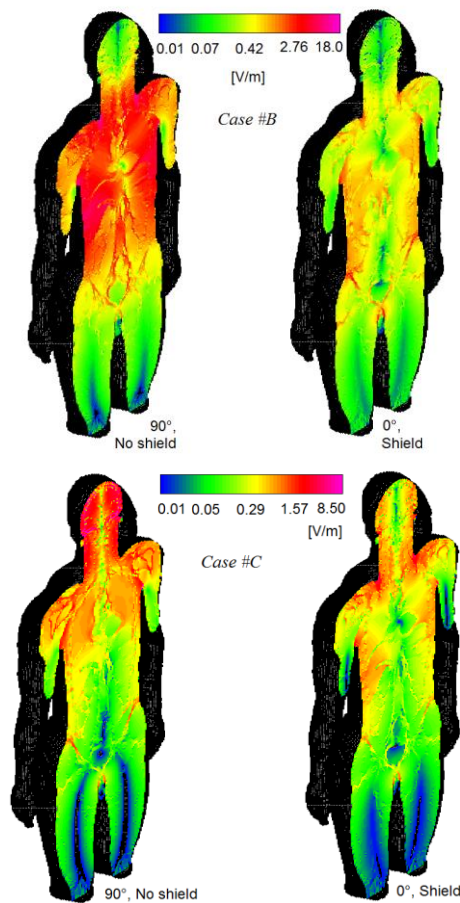


Fig. 4. Peak values of the maximum induced electric field in the operator body, for the cases #B and #C. The cases without shield are considered with the coil at 90°. The cases with shield are considered with the coil angle 0°. The distance between the coil and the operator body is 30 cm.

between the coil center and the body axis, where the body axis is the vertical straight line placed in the central position with respect to the parallelepiped circumscribing the body endpoints. For instance in the #C case, the body axis will be placed in the central position with respect to the tip of the nose and, on the other side, the extreme of the gluteus. Obviously, the previous consideration hold only for the “Duke” model, but an analysis that covers other somatotypes is of interest for the continuation of this study.

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TABLE III
99TH PERCENTILE OF THE INDUCED ELECTRIC FIELD

Shield	Angle (deg)	Voxel 4mm All tissues (V/m)	Voxel 4mm Only CNS (V/m)	Voxel 2mm Only CNS (V/m)
yes	0	0.82	0.187	0.178
no	0	1.91	0.574	0.548
yes	90	0.53	0.143	0.136
no	90	2.92	0.409	0.383

Unshielded/shielded values. Case #B, distance 40 cm.

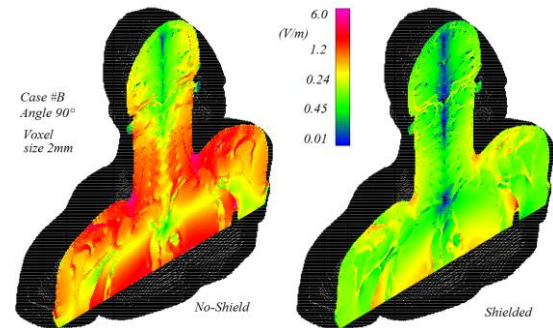


Fig. 5. Peak values of the maximum induced electric field in the operator body, for the case #B. The cases with and without shield are considered with the coil at 90°. Distance between the coil and the operator body is 40 cm. Voxel size: 2mm.

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