Biomagnetics

Safety Assessment of H-Coil for Nursing Staff in Deep Transcranial Magnetic Stimulation

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Abstract—This work investigates the exposure experienced by the nursing staff executing deep transcranial magnetic stimulations (TMS) using H-coil. The safety assessment was implemented by employing the H-coil and realistic human model. The 144 relative positions of the H-coil with respect to the TMS operator body were considered, including the distance and vertical height. Dependence of the magnetic flux density and induced electric fields in the human model were obtained by using the impedance method. Results were compared with the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines. Regarding the occupational exposure, safe distances of 120 and 100 cm are derived from the ICNIRP reference level (RL) and basic restriction (BR), respectively. At the distance of 100 cm, the exposure level does not exceed the ICNIRP BR, and although the exposure level exceeds the RL, continued exposure is allowed. The findings suggest that nursing staff should stand at least 100 cm apart from the H-coil.

Index Terms—Biomagnetics, occupational exposure, deep transcranial magnetic stimulation, H-coil, impedance method.

I. INTRODUCTION

Transcranial magnetic stimulation (**TMS**) is a technique for noninvasive stimulation of the human brain. Magnetic fields are produced by passing a strong current through an electromagnetic coil placed upon the scalp that in turn induce electric field and eddy currents in the underlying cortical tissue, thereby producing a localized axonal depolarization [Barker 1985, Ueno 1988]. Stimulation of deeper brain structures by TMS plays a role in the study of reward and motivation mechanisms, which will benefit treatment for several diseases, such as Parkinson's disease, addiction, epilepsy, etc., that are related to the neuropsychiatric conditions in deep brain regions [Bersani 2013].

Standard TMS is applied with an electromagnetic coil called a round, or figure-of-eight coil, which induces stimulation in cortical regions mainly just superficially under the windings of the coil. To stimulate deep brain tissues, the H-coil was developed for deep TMS (**dTMS**) [Yoth 2002, 2007, Lu 2017].

Exposure of the human body to time-varying magnetic fields results in the induction of internal body currents that may potentially cause health problems. The International Commission on Non-Ionizing Radiation Protection (**ICNIRP**) has set international guidelines for limiting human exposure to electromagnetic fields [ICNIRP 2010]. ICNIRP defines restriction on the electric fields induced within the tissue [basic restriction (**BR**)] and on the environmental fields [reference level (**RL**)]. The ICNIRP BRs and RLs at different frequencies are based on the biological thresholds of human tissues, i.e., avoiding flash phenomena in the retina or avoiding pain caused by stimulation of the peripheral nervous system. For the cases that applied field strengths above the ICNIRP limits, the effect of exposure on cellular parameters, such as changes in cell growth or viability, was found [Wang 2013, Barabáš 2015].

Although TMS is aimed at patient exposure, the nursing staff using these devices is easily exposed to magnetic pulses. Previous literature has investigated the compliance of conventional round and figure-of-eight coils with the ICNIRP guidelines [Karlström 2007, Lu 2010, Bottauscio 2016]. The purpose of this study is to present dosimetry analysis for nursing staff exposed to magnetic pulses from H-coil in dTMS applications.

II. METHODS

The H-coil for patient treatment is shown in Fig. 1. The H-coil is composed of a base portion running tangential to the scalp and return portions removed from the head. The coil, with complicated winding patterns and larger dimensions, is designed to generate the electric field in a specific brain region at a depth of 4–6 cm. The pulse current with an amplitude of 5000 A and a working frequency of 2381 Hz was fed into the coil in this study.

The exposure of H-coil for nursing staff is shown in Fig. 2(a) and (b). The coil is set in front of the operator. The relative position between the H-coil and the nursing staff is described by three parameters, i.e., ***d, L***, and ***h***. In front: The distance between the H-coil and the body model was set as ***d***, varying from 50 to 120 cm. In the side: The distance between the H-coil and the body model is set as ***L***, varying from –70 to 30 cm. The height of H-coil is defined as ***h***, varying from 95 to 145 cm.

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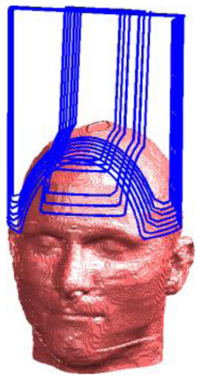
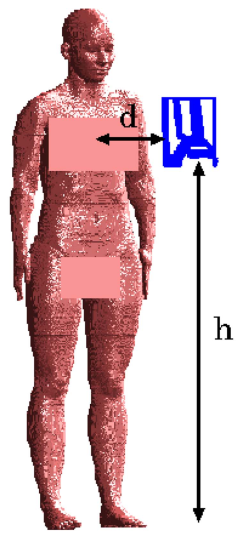
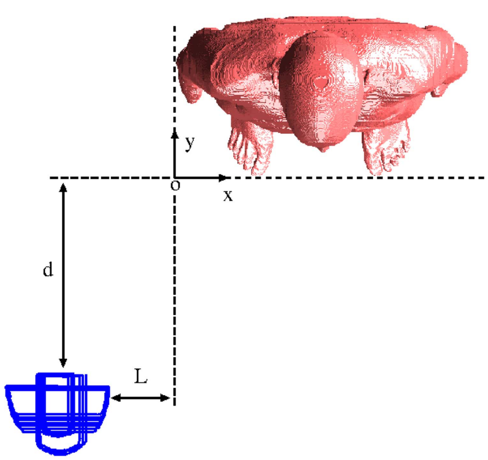


Fig. 1. H-coil placed on the patient's head.



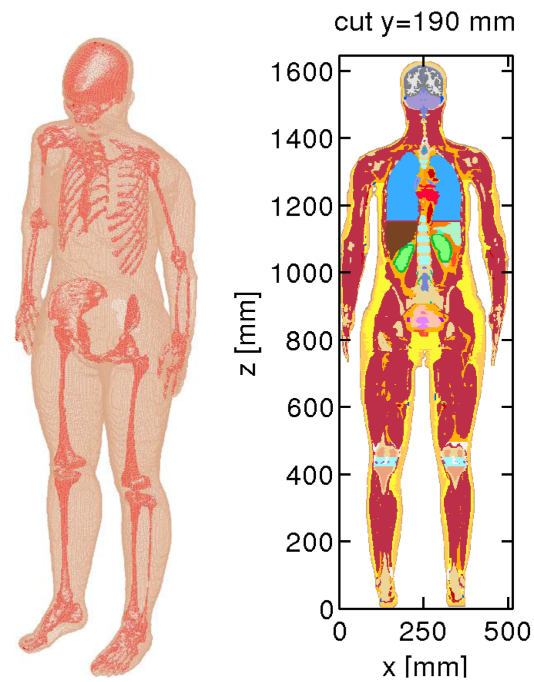
(a)



(b)

Fig. 2. H-coil with body model of nursing staff. (a) Front view. (b) Top view.

The body model of nursing staff is shown in Fig. 3. This model was obtained from the Virtual Family Project (**VFP**) [Christ 2010]. The VFP models are a set of detailed high-resolution anatomical models created from magnetic resonance image data of healthy volunteers. The nursing staff model was generated from MRI data of a 26-year-old female adult, comprising 77 separated tissues. The model is described using a uniform 3-D Cartesian grid and is composed of small cubic voxels. The size of each voxel is 1 mm × 1 mm × 1 mm. There are 230 million voxels in the computational space.



(a) (b)

Fig. 3. Body model of nursing staff. (a) Transparency of bone and skull. (b) Tissue slice at coronal plane of $y = 190$ mm.

TABLE 1. Tissue conductivities at $f = 2381$ Hz.

Tissue	σ (S/m)	Tissue	σ (S/m)
Artery	7.00e-01	Hypothalam	5.26e-01
Blood.Vessel	3.10e-01	Mandible	2.03e-02
Cartilage	1.75e-01	Marrow-bone	2.44e-03
Cerebellum	1.24e-01	Muscle	3.31e-01
CSF	2.00e+00	Midbrain	4.65e-01
Eye-cornea	4.25e-01	Nerve	3.04e-02
Eye- humor	1.50e+00	Pineal-body	5.26e-01
FAT	2.32e-02	Pons	4.65e-01
Gray matter	1.04e-01	Skull	2.03e-02
Hippocampus	1.04e-01	Thalamus	1.04e-01
Hypophysis	5.26e-01	White Matter	6.44e-02

The time variation of the applied magnetic field causes induced currents in the body through Faraday's induction mechanism. The magnetic flux density was calculated using Biot–Savart's law. The induced current was calculated using the impedance method [Orcutt 1988], and the induced electric fields were calculated using Ohm's law. The electrical properties of body tissues were modeled using the four Cole–Cole method [Cole 1941] and obtained by fitting to experimental measurements [Gabriel 1996]. The tissue conductivities for part of the tissues are shown in Table 1.

For the working frequency of 2381 Hz, the ICNIRP RL and BR for occupational exposure are 126 μT and 800 mV/m, respectively (Tables 3 and 4 of the ICNIRP guidelines [ICNIRP 2010]).

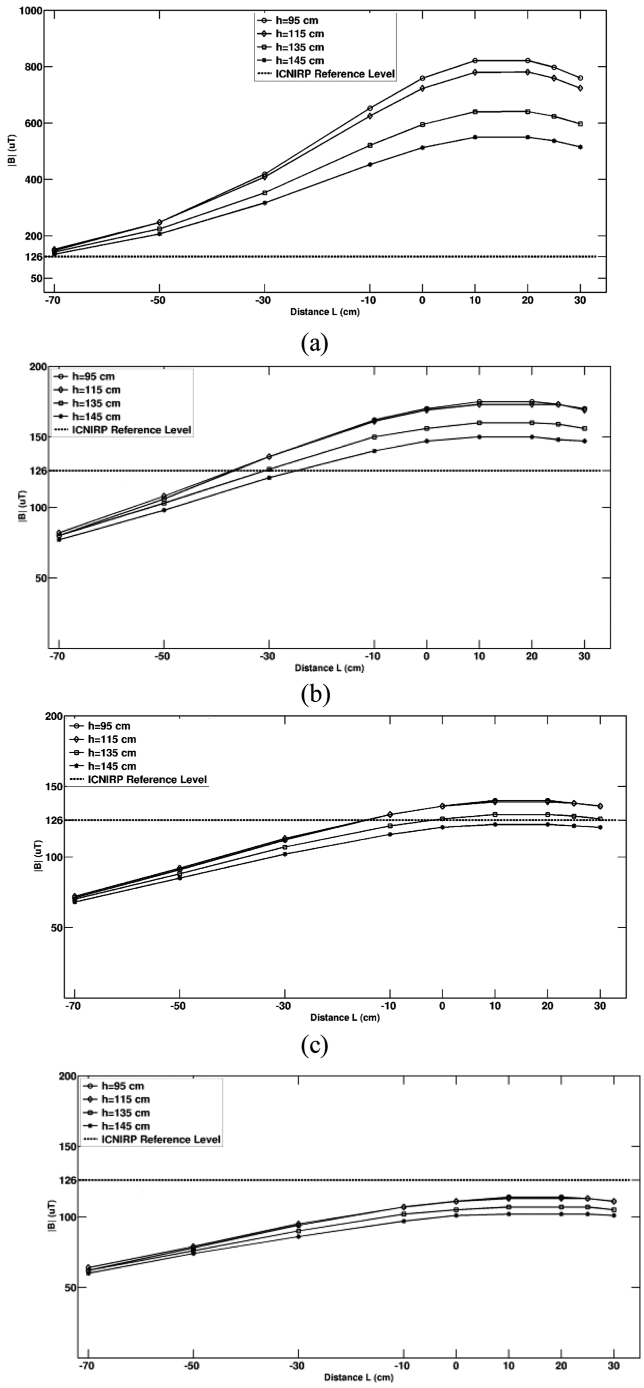


Fig. 4. Calculated magnetic flux density (B-field) versus distance $\boldsymbol{d}$ with varied $\boldsymbol{L}$ and $\boldsymbol{h}$. (a) $\boldsymbol{d} = 50$ cm, (b) $\boldsymbol{d} = 100$ cm, (c) $\boldsymbol{d} = 110$ cm, and (a) $\boldsymbol{d} = 120$ cm. The ICNIRP RL of 126 μT is shown for comparison (dot dashed line).

III. RESULTS AND DISCUSSIONS

The exposure level of the magnetic flux density (B-field) in the human model was calculated by spatially averaging the magnetic flux density over the entire model. Fig. 4(a)–(d) shows the dependence of the B-field on the distance between the coil and body model with $\boldsymbol{d} = 50$ cm, 100 cm, 110 cm, and 120 cm, respectively. In each of four figures, the coil height $\boldsymbol{h}$ was set as 95 cm, 115 cm, 135 cm, and 145 cm, respectively. And the coil position $\boldsymbol{L}$ along the x-axis was varied from –70 to 30 cm (see Fig. 2).

It can be seen that the exposure level completely exceeded the RL of 126 μT for $\boldsymbol{d} = 50$ cm [see Fig. 4(a)], partially exceeded the limit for $\boldsymbol{d} = 100$ cm [see Fig. 4(b)] and 110 cm [see Fig. 4(c)], and completely below the limit for the distance of $\boldsymbol{d} = 120$ cm [see Fig. 4(d)]. It suggests that the exposure level of the B-field was always below the ICNIRP RL of 126 μT when the distance between coil and the nursing staff was set 120 cm.

As the coil moves close to the body model along the x-axis ($\boldsymbol{L}$ varies), the exposure level was increased, and the maximum exposure level was presented when the coil was placed in front of the body model.

Regarding to the dependence of the exposure level of the B-field on the coil height, there is no big difference between the $\boldsymbol{h} = 95$ cm and $\boldsymbol{h} = 115$ cm. However, the exposure level decreased with an increase in coil height $\boldsymbol{h}$ from 115 to 145 cm.

The distributions of the B-field on the cross section (the coronal plane of $y = 190$ mm) of the human model for different coil positions are illustrated in Fig. 5. For all cases, the coil position along the x-axis was fixed with $\boldsymbol{L} = 10$ cm, i.e., the coil was placed in front of the body model.

The distribution of the B-field is uniform in body tissues. However, with increasing coil height $\boldsymbol{h}$ from 95 to 135 cm, the B-field in brain tissues was obviously increased [see Fig. 5(a) and (b)]. With the distance between the coil and the body model increasing from

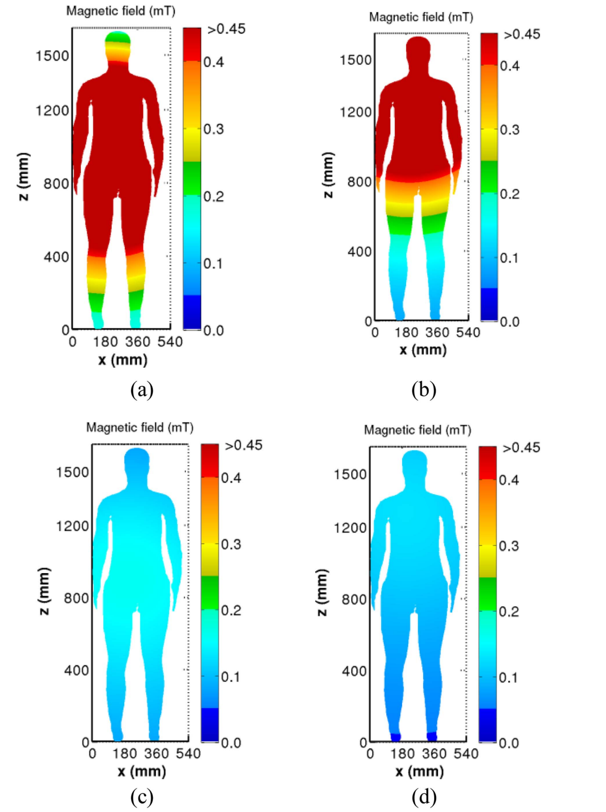


Fig. 5. Distribution of B-field (mT) in the coronal slice of $y = 190$ mm for varied coil positions. (a) $\boldsymbol{d} = 50$ cm, $\boldsymbol{h} = 95$cm, (b) $\boldsymbol{d} = 50$ cm, $\boldsymbol{h} = 135$ cm, (c) $\boldsymbol{d} = 120$ cm, $\boldsymbol{h} = 95$ cm, and (a) $\boldsymbol{d} = 120$ cm, $\boldsymbol{h} = 135$ cm. The coil was fixed at in front of the body model.

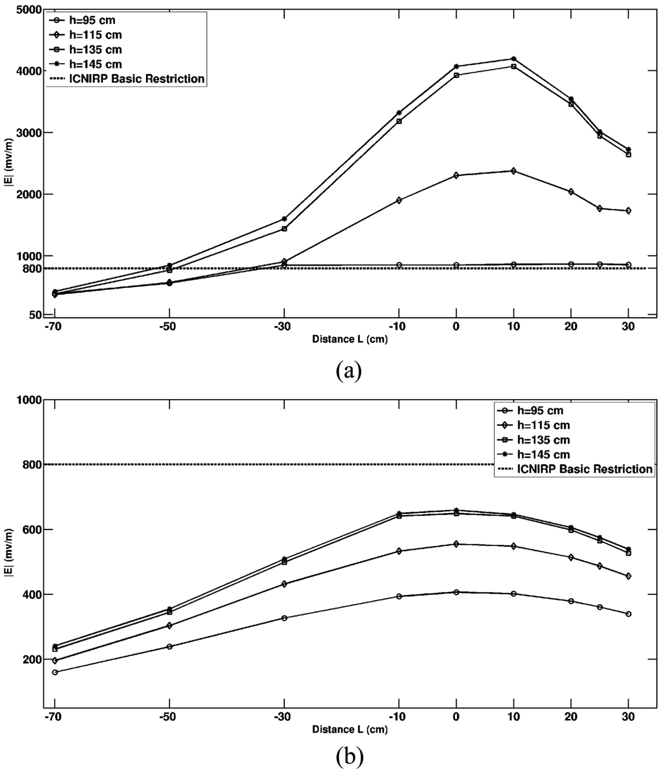


Fig. 6. Calculated induced electric field (E-field) versus distance $\boldsymbol{d}$ between the coil and body model. (a) $\boldsymbol{d} = 50$ cm and (b) $\boldsymbol{d} = 100$ cm. The ICNIRP BR of 800 mV/m is shown for comparison (dot dashed line).

$\boldsymbol{d} = 50$ cm to $\boldsymbol{d} = 120$ cm, the B-field in body tissues was decreased greatly.

To investigate the compliance of the H-coil with the ICNIRP BR, the induced electric field (E-field) in the central nervous system (**CNS**) was calculated. The maximum values of induced electric fields in CNS tissues were averaged over small contiguous tissue with a volume of 2 mm × 2 mm × 2 mm (E_{avg}).

Fig. 6(a) and (b) shows the dependence of E_{avg} on the distance between the coil and body model with $\boldsymbol{d} = 50$ cm and 100 cm, respectively. As in Fig. 4, the coil height $\boldsymbol{h}$ was set as 95, 115, 135, and 145 cm, respectively. And the coil position $\boldsymbol{L}$ along the x-axis was varied from –70 to 30 cm (see Fig. 2).

It can be seen that the exposure level fully exceeded the BR of 0.8 V/m for $\boldsymbol{d} = 50$ cm [see Fig. 6(a)], while the exposure level was completely below the limit for the distance of $\boldsymbol{d} = 100$ cm [see Fig. 6(b)].

Regarding to the dependence of the exposure level of E_{avg} on the coil height $\boldsymbol{h}$, the exposure level increased with an increase in coil height $\boldsymbol{h}$ from 95 to 145 cm. The maximum exposure level was presented when the coil was placed in front of the body model.

The distributions of the E-field on the cross section (the coronal plane of $y = 190$ mm) of the human model for different coil positions are illustrated in Fig. 7. For all cases, the coil position along the x-axis was fixed with $\boldsymbol{L} = 10$ cm, i.e., the coil was placed in front of the body model.

The distribution of the E-field is nonuniform in body tissues. As we expected, the stronger induced fields are presented in the tissues near H-coil at a distance of 50 cm, such as in the head, shoulders, and chest,

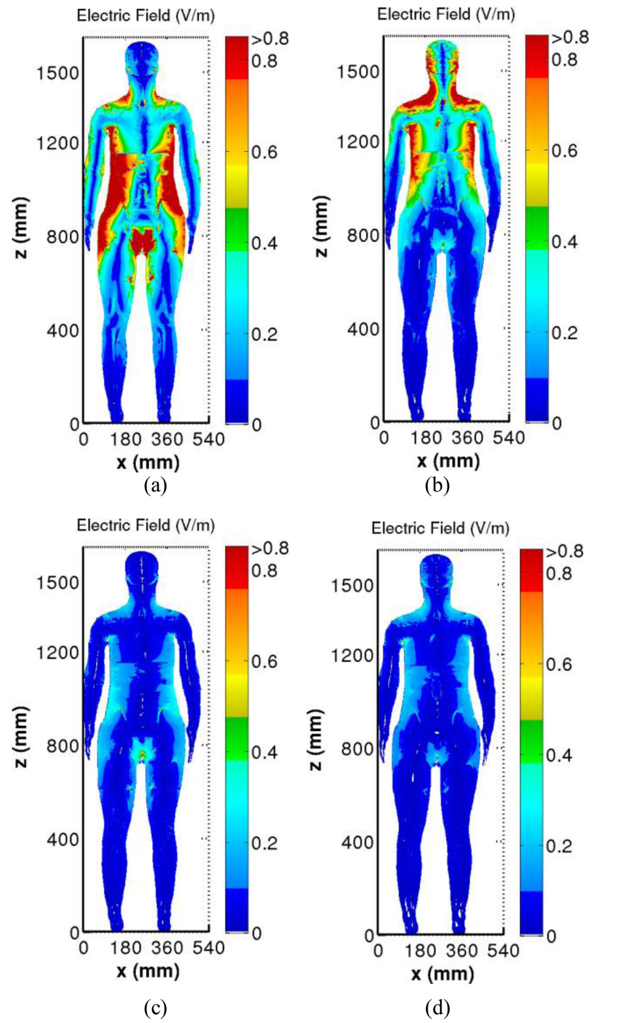


Fig. 7. Distribution of E-field (V/m) in the coronal slice of $y = 190$ mm for varied coil positions. (a) $\boldsymbol{d} = 50$ cm, $\boldsymbol{h} = 95$ cm, (b) $\boldsymbol{d} = 50$ cm, $\boldsymbol{h} = 135$ cm, (c) $\boldsymbol{d} = 120$ cm, $\boldsymbol{h} = 95$ cm, and (d) $\boldsymbol{d} = 120$ cm, $\boldsymbol{h} = 135$ cm. The coil was fixed in front of the body model.

etc. However, with increasing coil height $\boldsymbol{h}$ from 95 to 135 cm, the E-field in brain tissues was obviously increased [see Fig. 7(a) and (b)]. With the distance between the coil and the body model increasing from $\boldsymbol{d} = 50$ cm to $\boldsymbol{d} = 120$ cm, the E-field in body tissues was decreased greatly.

From the aforementioned results, one can find that the induced electric fields in CNS are less than the ICNIRP BR at a distance of 100 cm, while the exposure level of B-field is less than the ICNIRP RL at a distance of 120 cm. It suggests, that at a distance of 100 cm, the exposure level does not exceed the ICNIRP BR, although the exposure level exceeds the RL, continued exposure is allowed.

The nursing staff working with patient treatments using an H-coil can become exposed to magnetic field levels exceeding ICNIRP restrictions. According to the preliminary results in this study, the nursing staff should stand apart from the H-coil at least 100 cm.

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