Calculating the Electric Fields in the Human Brain by Deep Transcranial Magnetic Stimulation

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***Abstract*—Stimulation of deeper brain structures by transcranial magnetic stimulation (TMS) may be beneficial in the treatment of several neurological and psychiatric disorders. This paper presents numerical simulation of deep transcranial magnetic stimulation (dTMS) by considering double cone, H- and Halo coils. Three-dimensional distributions of the induced electric fields in realistic head model by dTMS coils were calculated by impedance method and the results were compared with that of standard figure-of-eight coil. Simulation results show that double cone and H-coils have significantly deep field penetration at the expense of induced higher and wider spread electrical fields in superficial cortical regions. The combination of Halo coil with a conventional circular coil produce deeply penetrating electric field the same as double cone and H-coils, but the stimulation in superficial brain tissues are much lower.**

I. Introduction

Transcranial magnetic stimulation (TMS) is a technique for noninvasive stimulation of the human brain. Stimulation is produced by generating a brief, transient high intensity magnetic field by passing a brief, transient electric current through a magnetic coil placed upon the scalp. The induced electrical currents in the underlying cortical tissue produce a localized axonal depolarization [1][2][3]. As a noninvasive method to stimulate brain, TMS has attracted considerable interests as an important tool for studying the functional organization of the human brain as well as a therapeutic tool to improve psychiatric diseases.

Although TMS treatment for depression with a common target in the dorsolateral prefrontal cortex has improved over the last years [4], current TMS methodologies do not yet yield the desired results, especially for major depressive disorder which is a highly prevalent and disabling condition associated with significant morbidity and mortality. Many studies indicate that reward circuit is the focus in the study of depression [5][6]. There is a reason to assume that activation of deeper prefrontal and limbic regions may increase the antidepressant effect. The promising targets for dTMS can be the subgenual anterior cingulate cortex and the nucleus accumbens which lie at depths of approximately 6 and 7 cm, respectively, or the orbitofrontal, medial frontal cortices, and the frontal pole which lie at depths of 3 to 4 cm and have strong connectivity to anterior cingulate cortex.

To stimulate deeper neuronal regions such as reward-related pathways directly, much higher stimulation intensities are needed, as the electric field decreases rapidly as a function of tissue depth. However, even if stimulation intensities could be highly increased at the source, the use of standard TMS coils (such as round or figure-of-eight coils) at such high stimulation intensities does not allow safe stimulation and can lead to undesirable side effects. These limitations have led to the development of novel coil designs suitable for dTMS, which allows direct stimulation of much larger and deeper brain regions by significant reduction of the decay rate. In the past decade, there are several coil configurations potentially suitable for dTMS: double cone, H- and Halo coils [7][8][9].

II. Coil Designs for Deep Transcranial Magnetic Stimulation

Three coil types for dTMS have been numerically designed as shown in Fig. 1, where Fig. 1(a)-(c) show the double cone coil, H-coil and Halo coil which are placed on the surface of the head model. For comparison, Fig. 1(d) shows the modelled figure-of-eight coil.

The double cone coil was composed with two large circular coils with an fixed angle (95 deg) between them. The inner and outer radii of the circular wings are 70 mm and 20 mm, respectively. The number of the wire turns in each wing is 10. The H-coil with complicated winding was composed of a base portion and return portions. The coil is designed to minimize the unintended stimulation of portions of the brain, while reducing the accumulation of the surface charges. The Halo coil with 5 turns has inner and outer radii of 138 and 150 mm, respectively. It is operated simultaneously with a typical circular coil of mean diameter 90 mm and 14 turns located 100 mm above the Halo coil. For comparison, We have also modeled the figure-of-eight coil. The inner and outer radii of the circular wings are 10 mm and 50 mm, respectively. The number of the wire turns in each wing is 10. The same pulse currents with amplitude of I=7.7 kA and working frequency 3.6 kHz was fed into each of the four coils.

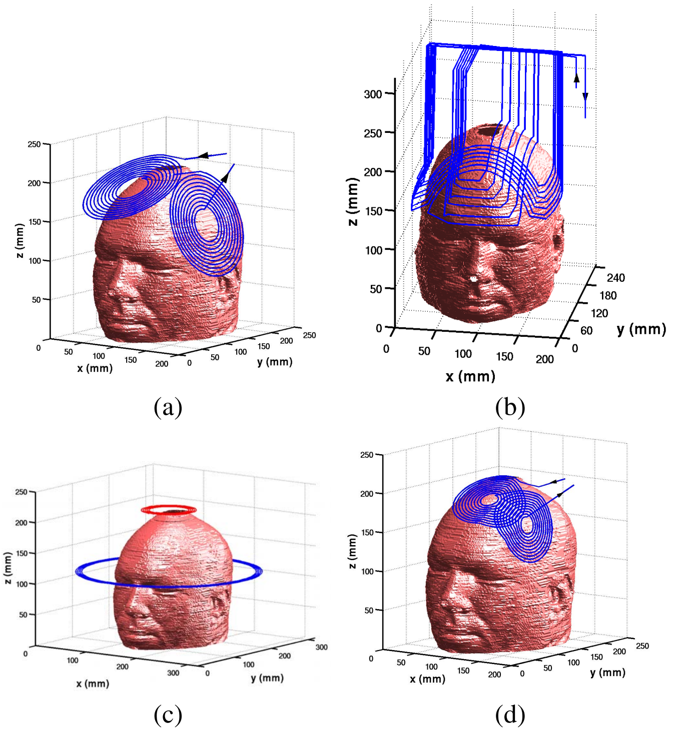

Fig. 1. Coil types for dTMS. (a) double cone coil, (b) H-coil, (c) Halo coil and (d) figure-of-eight coil.

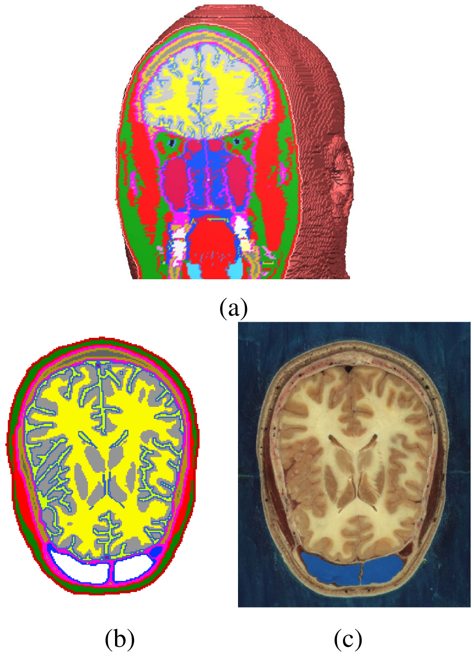

Fig. 2. Realistic head model. (a) Brooks model in 3D, (b) 2D Slice from Brooks model, (c) Anatomical slice image from VHP.

III. Impedance Method

The human head model is described using a uniform 3D Cartesian grid and is composed of small cubic voxels. The size of each voxel is 1mm $\times$ 1mm $\times$ 1mm. Assuming that, in each voxel, the electric conductivities are isotropic and constant in all directions, the model is represented as a 3-D network of impedances. The magnetic fields are calculated using Biot-Savart's law, the induced currents are calculated using the impedance method [10], and the induced electric fields are calculated using Ohm's Law. The impedance method has been found to be highly efficient as a numerical procedure for calculations of induced current densities and/or electric fields in tissue-classified anatomically based models [11][12][13].

IV. Human Head Model and Tissue Conductivity

In this study, we employed a 3D realistic human head model with 1 mm resolution as shown in Fig. 2. It was obtained from Brooks Air Force Laboratory (BAFL), USA. The head model which has 24 different tissues is based on anatomical slices from a male cadaver (1.8 m tall and 105 kg weight) originally from the Visible Human Project(VHP).

The electrical properties obtained from BAFL are modeled using the 4-Cole-Cole model [14]. In this model, the biological tissues subject to an electric field with angular frequency is modelled by relaxation theory and tissue properties can be obtained by fitting to experimental measurements [15]. The tissue conductivities used in the present calculations are shown in Table I.

TABLE I. TISSUE CONDUCTIVITIES AT f=3.6 kHz

Tissue	Conductivity $\sigma[S/m]$	Tissue	Conductivity $\sigma[S/m]$
Blood	7.00e-01	Lymph	5.27e-01
Blood vessel	3.11e-01	Mucous memb.	1.04e-03
Body fluid	1.50e-00	Cereb.spin.fluid	2.00e+00
Bone(cancellous)	8.21e-02	Nerve or spine	3.23e-02
Bone(cortical)	2.03e-02	Meninges	3.85e-01
Bone(marrow)	8.51e-02	Gray matter	1.07e-01
Cartilage	1.75e-01	White matter	6.56e-02
Fat	2.34e-02	Cerebellum	1.27e-01
Muscle	3.34e-01	Eye(cornea)	4.28e-01
Skin(dermis)	2.01e-04	Eye(lens)	3.33e-01
Tooth	2.03e-02	Eye(scle-wall)	5.08e-01
Glands	5.27e-01	Eye(aque.humo)	1.50e+00

V. Results and Discussions

Fig. 3 shows the field intensity in depth of 9.7 cm along lateral-medial line in the axial slice for double cone, H-, Halo and the figure-of-eight coils. Here we specifically focus on the depth of 9.7 cm because the Halo coil was positioned 9.7 cm below the top of the head. The lateral-medial axis lines as illustrated in the coronal (Fig. 3(a)) and axial (Fig. 3(b)) images were located in the coronal slice of y=7.6 cm which is relevant for the stimulation of dorsolateral prefrontal cortex for the treatment of depression.

Fig. 3(c) demonstrated that the maximum induced electric field along this line was presented in skull left side for all types of coils. H-coil produces higher fields in skull at both left and right side. Double cone coil produces very strong electric fields (more than 300 V/m) in skull tissues, such as in bone cortical, bone marrow, bone cancello, muscle and fat etc. If we focus on the induced electric fields in brain tissues (80

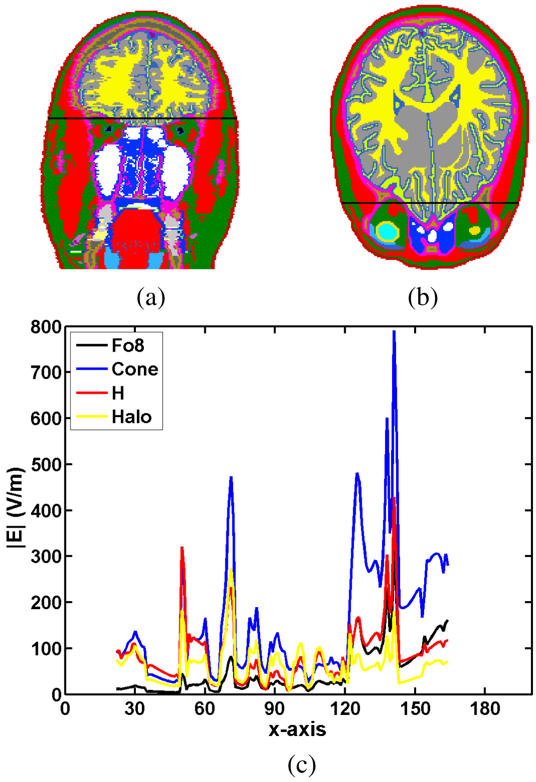

Fig. 3. Electric fields decay along lateral-medial line in the coronal plane. (a) lateral-medial line in coronal plane at y=76 mm, (b) lateral-medial line in axial plane at z= 114 mm, (c) Electrical field intensity along the lateral-medial line.

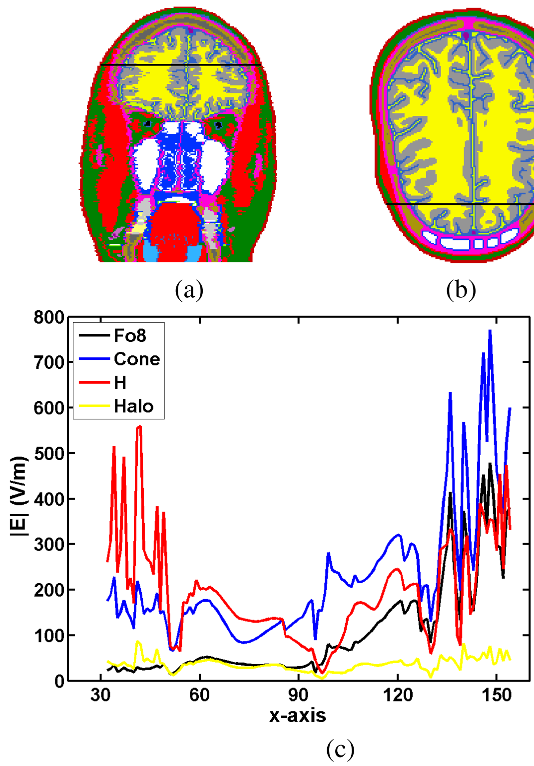

Fig. 4. Electric fields decay along lateral-medial line in the the coronal plane. (a) lateral-medial line in coronal plane at y=76 mm, (b) lateral-medial line in axial plane at z= 151 mm, (c) Electrical field intensity along the lateral-medial line.

mm $<$ x $<$ 120mm in Fig. 3(c)), we found both double cone and Halo coils can still produce the fields higher than 100 V/m the stimulation threshold. But for H- and figure-of-eight coils, stimulation would not occur as fields are much lower in brain tissues in the depth of 9.7 cm.

Fig. 4 shows the field intensity along lateral-medial line in the axial slice 6 cm below the top of the head and in the coronal slice of y=7.6 cm. From Fig. 4, we know that the figure-of-8 and Halo coils would not be sufficient to produce stimulation in brain tissues in depth of 6 cm, as the induced fields by both coils are less than 100 V/m. Both double cone and H-coils induce markedly greater fields compared to those in Fig. 3. For H-coil, it produces higher electric fields (up to 300 V/m in brain tissues and 600 V/m in skull) on both the left and the right side along this line. Which means this version of H-coil have been designed to stimulate bilaterally structures in prefrontal cortex.

The distributions of the induced electric fields in the positions of 4 cm and 8 cm below the top of the head are shown in Figs. 5 and 6, respectively. In order to show the results more clearly, nonlinear colorbars are employed in these figures. The color palette is linear up to stimulation threshold 100 V/m and then constant (dark red) above threshold. It is observed that all three dTMS coils i.e. double cone, H-, and Halo coil can induce electric fields beyond 100 V/m in deep brain regions with depth up to 8 cm. But the effective stimulation area or volume (electric fields exceeding 100 V/m) in superficial cortical regions by double cone and H-coils are much higher than that of figure-of-eight coil. The Halo coil combined with a conventional round coil carrying current with opposite direction induce a strong fields in deep brain regions with less fields in superficial cortical tissues.

VI. Conclusion

In this paper, the impedance method was used to calculate the induced electric fields in realistic head model by employing double cone, H-, Halo coils. Results were compared with that of figure-of-eight coil. It was found that deeper electric field penetration is obtained by double cone and H-coils, which inevitable induce higher and wider spread electrical fields in superficial cortical regions. The Halo coil working with a circular coil carrying currents in opposite directions realize deeper field penetration through the field cancellation principle. Stimulation by double cone or H-coils is painful since the two coils produce much higher fields in superficial cortical areas and facial muscles. The double cone coil would cause even greater pain and perhaps other side-effects. Stimulation by Halo coil should be less pain since the induced electric fields in superficial cortical regions are lower. Halo-circular coil assembly provides a flexible way

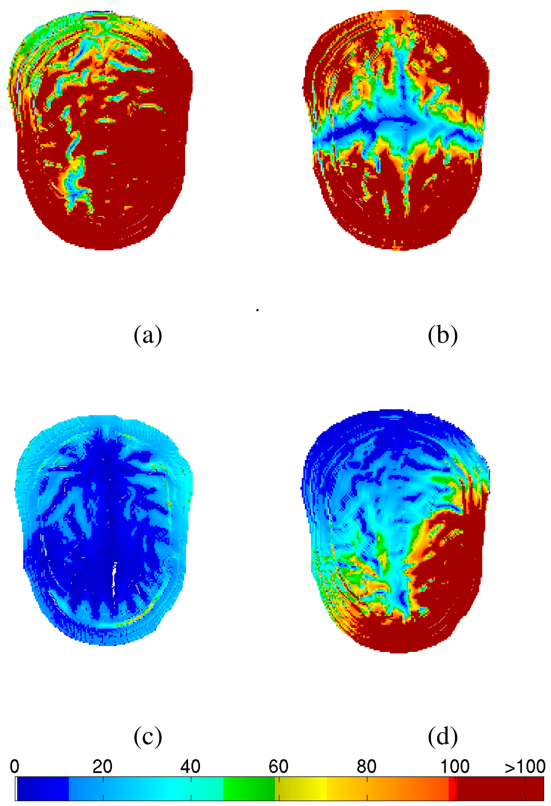

Fig. 5. Electric field distributions in an axial slice of 4 cm below the top of the head. (a) Double cone coil, (b) H-coil, (c) Halo-coil and (d) figure-of-eight coil.

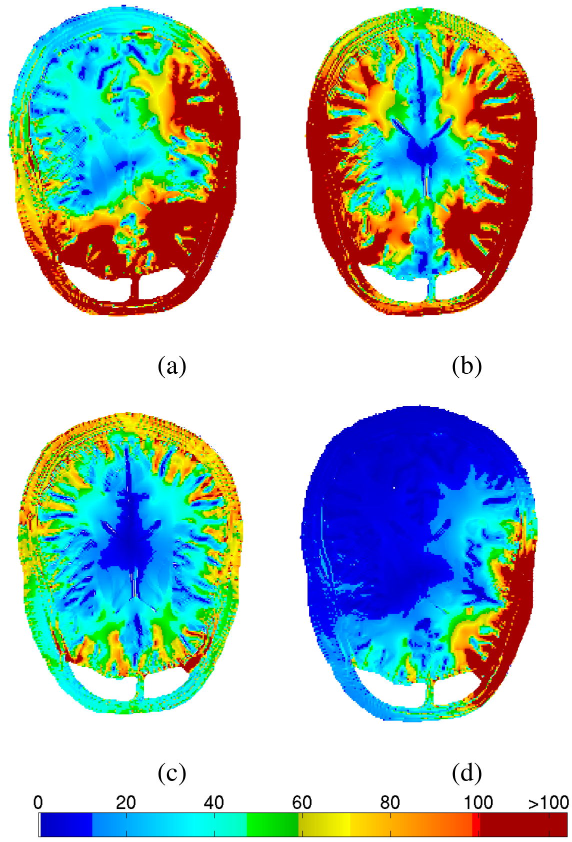

Fig. 6. Electric field distributions in an axial slice of 8 cm below the top of the head. (a) Double cone coil, (b) H-coil, (c) Halo-coil and (d) figure-of-eight coil.

to stimulate deep brain structures.

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