Dependence of Electromagnetic Fields in Human Brain on Coil Bending Angle in Transcranial Magnetic Stimulation

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Abstract

This paper presents numerical simulation of transcranial magnetic stimulation by employing figure-of-eight coil (fo8) with bending wings. Various fo8 coils with different bending angles were numerically designed. Three-dimensional distributions of the magnetic fields and induced electric fields in realistic head model were calculated by impedance method. Results were compared with those obtained from standard fo8 coil. Results show that either stimulation depth or focality is easily adjusted by changing the bending angle of coil wings. The fo8 coil with flexible folding wings can be served for providing controllable stimulation depth and focality in TMS applications.

1. Introduction

Transcranial magnetic stimulation (TMS) is a noninvasive technique to stimulate the brain. In TMS, stimulation coils located near the scalp produce magnetic fields that in turn induce electric fields and eddy-currents in the conductive brain tissues. When the spatial gradient of the electric field aligns with a nerve fiber, an action potential is generated. TMS has hold significant promise as a tool for cognitive neuroscience and the treatment of neurological disorders [1] .

The first TMS system used a circular coil due to its simple geometry and ease of construction[2]. However, the circular coil induces a non-focal ring-shaped electric field. The significant improvement of TMS focality has been realized by the introduction of the figure-of-eight coil [3][4]. In the past two decades, the search for even more focal TMS coils continues, novel coils such as cloverleaf, slinky, eccentric coils have been developed [5][6][7]. In the mean time, there have been great efforts to increase the depth of stimulation with the new coil configures, such as H-, and Halo-coils etc [8][9].

It is well know the fo8 configuration consists of a pair of adjacent circular loops with current flow in opposite directions, producing a relatively focal electric field maximum under the center of the coil where the two loops meet. There has been relatively little information published on the spatial variation of the induced electric fields produced by fo8 TMS coil with bending angle except for the only study by Tsuyama et al. [10]. In the present study, we have investigated the magnetic fields and induced electric fields in realistic head model by employing fo8 coils with varied bending angles. In this study, the coil wings were bent away from the scalp which is different from the bending pattern in [10]. The purpose of this work is to investigate the possibility for realizing the controllable stimulation depth and focality by employing fo8 coil with flexible folding wings.

2. Numerical Methods

The 3-D human head model employed in this work was obtained from Brooks Air Force Laboratory (BAFL), USA. The model, which has 24 different tissues, was based on anatomical slices from a male cadaver originally from the Visible Human Project (VHP). Figure 1 shows the head model with fo8 coil whose wings have been bent for different cases. Figure 1(a) shows the standard fo8 coil, Figures 1(b)-(c) show the coils whose two wings were bent simultaneously with 20 degrees and 60 degrees, respectively, and Figure 1(d) shows the coil whose left wing was bent by an angle of 80 degrees, while the right wing was kept unchanged. The inner and outer radii of the circular wings are 25 mm and 37.5 mm, respectively. The number of the wire turns in each wing is 10. The pulse currents with amplitude of I=7.7 kA and working frequency 3.6 kHz was fed into each of the coils.

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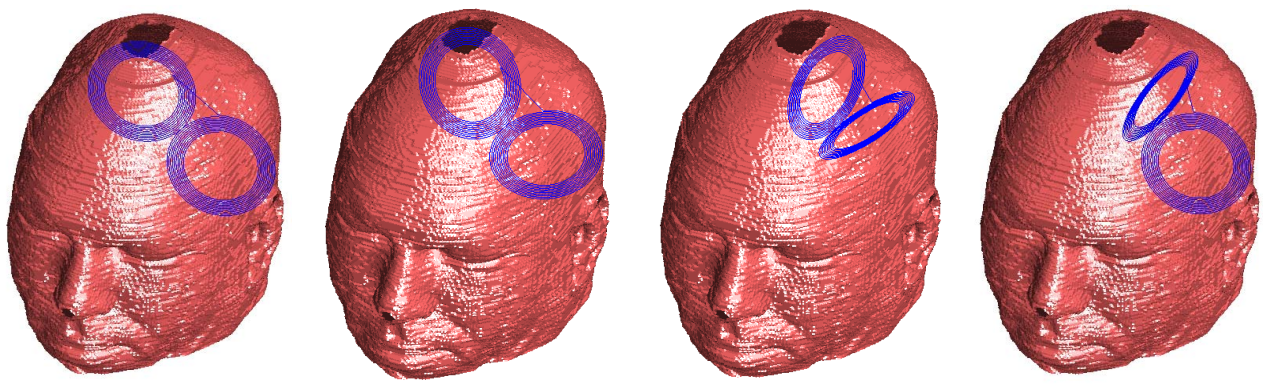
The time variation of the applied magnetic field causes induced currents in the head through Faraday induction mechanism. These currents can be calculated by using the impedance method[11][12]. In this method, the human head model is described using a uniform 3-D Cartesian grid and is composed of small cubic voxels. The size of each voxel is 1 mm x 1 mm x 1 mm. There are nearly nine million voxels in the computational space. 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 impedance. The application of Kirchhoff voltage law around each loop in this network generates a system of equations for the loop currents. These loops currents are driven by Faraday induction for the TMS applicator. The current density within the head model are then calculated from these loop currents, and the electric fields are in turn calculated using Ohm's Law. The electrical properties are modeled using the 4-Cole-Cole model [13]. 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 [14].



(a) (b) (c) (d)

Figure 1. Realistic head models with fo8 coils, (a) standard fo8 coil, (b) two wings were bent by 20 degrees, (c) two wings were bent by 60 degrees, and (d) only left wing was bent by 80 degrees.

3. Results and Discussions

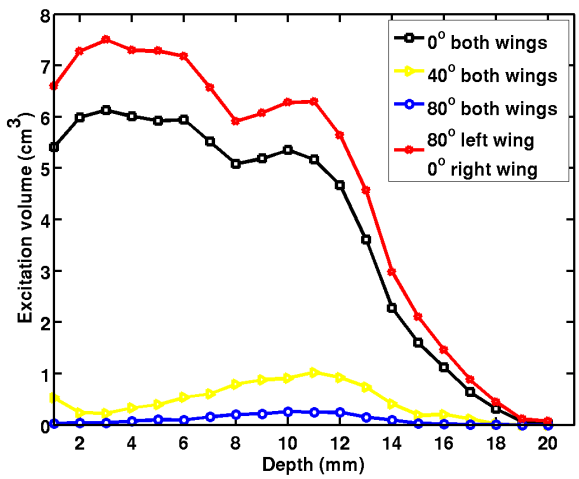
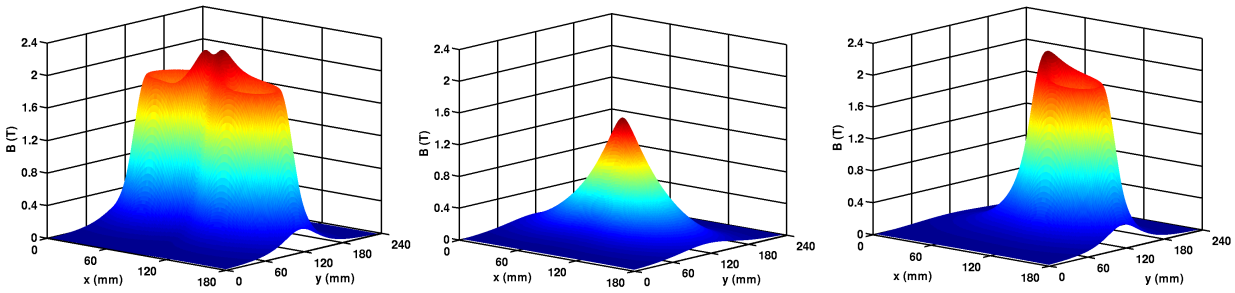


Figure 2. Dependence of excitation volume on the stimulation depth from the surface of the brain.

Figure 2 shows the relationship between the stimulation depth and the excitation volume in the brain for fo8 coil with different bending angles. The excitation volume consists of a group of voxels in which the magnitude of induced electric fields in each voxel is larger than the neural excitation threshold i.e. 150 V/m. From Figure 2, we know that the excitation volume decreases quickly as the bending angle increases if the two wings are bent simultaneously. While for the case that only one wing is bent as shown in Figure 1(d), the excitation volume increases and even larger than that of

standard fo8 coil. It means two orthogonally positioned circular coils produce larger electric fields. These characteristics are useful in practical applications because we can easily adjust the excitation volume through controlling the bending angle of fo8 coil, without replacing the coil with different sizes, or changing the output of power supplies.

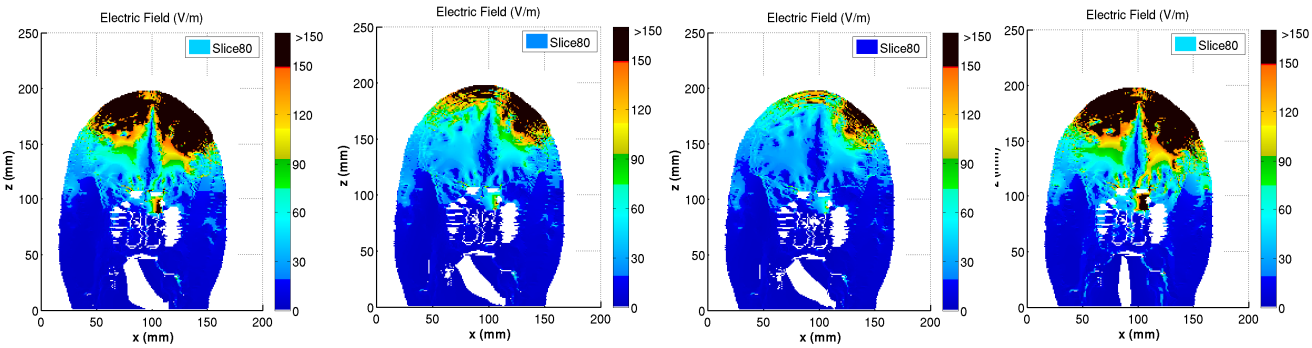
3D distributions of magnetic flux density (**B**) at the plane 7mm below the vertex of the head are shown in Figure. 3. Instead of the coil positions in Figure 1, the coils are all placed at the position 1mm above the vertex of the head for calculation of magnetic fields. It can be observed that the focality of magnetic fields can be improved by bending the coil wings (see comparison between Figure 3a for standard fo8 coil and Figure 3(b) for coil bending by an angle of 40 degrees). As the left wing was bent almost perpendicular to right wing as shown in Figure 1(d), the distribution of magnetic fields are similar to that of circular coil, except the peak magnetic flux density is presented (see Figure 3(c)).



(a) (b) (c)

Figure 3. 3D distributions of the magnetic fields. (a) standard fo8 coil, (b) two wings were bent by 40 degrees simultaneously, and (c) only left wing was bent by 80 degrees.

Figure 4 shows the variation of the magnitude of the induced electric fields in a typical slice at y=80 mm layer (coronal) for traditional fo8 coil (a), two wings were bent by 40 degrees (b), two wing were bent by 80 degrees (c), and only left wing was bent by 80 degrees (d). It can be observed that the stimulation depth has been decreased with the improvement of focality as the bending angle increases simultaneously. Although the distribution of electric fields in Figure 4(d) is similar to that in Figure 4(a), the electric fields in Figure 4(d) are a little larger. It can be expected that the stimulation depth can be further improved if the left wing is bent by an angle of 90 degrees.



(a) (b) (c) (d)

Figure 4. Distributions of induced electric fields in coronal plane at y=80 mm slice. (a) standard fo8 coil, (b) two wings were bent by 40 degrees simultaneously, (c) two wings were bent by 80 degrees simultaneously, and (d) only left wing was bent by 80 degrees.

4. Conclusions

We have presented the numerical results for the magnetic fields and the induced electric fields in realistic head model by employing figure-of-eight coil with varied bending angles. The stimulation depth decreases with increased focality as the coil wings were bent simultaneously. If two wings of fo8 coil are orthogonally positioned, the new coil

produces larger electromagnetic fields in the head than that by standard fo8 coil. The fo8 coil with folding wings provides a new way for TMS with adjustable stimulation depth and focality, without replacing the coils with different sizes, or changing the output of power supplies. In the future, we intend to investigate the dependence of penetration depth and focality on multiple fo8 coils with varied bending angles to realize the focused stimulation in deep brain regions

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