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Deep Transcranial Magnetic Stimulation with Improved Focality Using Figure-of-Eight and Halo Coils

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Abstract

The stimulation of deeper brain structures by transcranial magnetic stimulation (TMS) plays a role in the study of reward and motivation mechanisms, which may be beneficial to the treatment of several neurological and psychiatric disorders. In this work, the Halo coil working with a conventional figure-of-eight (Fo8) coil (Halo–Fo8 assembly coil (HFA coil) with varied bending angle of Fo8 coil wing for deep TMS (dTMS) is numerically designed. 3-D distributions of magnetic flux density, induced electric field in an anatomically based realistic head model were numerically calculated by the impedance method. It was found the HFA coil with varied bending angle of Fo8 coil wing can be employed to realize the dTMS with controllable stimulation depth and focality.

1. Introduction

Transcranial magnetic stimulation (TMS) is a technique to stimulate the brain noninvasively. 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. TMS has become a major tool in brain research and the treatment of various neurological disorders [1].

Recently, interests in stimulating deeper cortical, subcortical, and limbic areas have arisen and have become an active research topic in TMS, because several studies show that the activation of deeper prefrontal and limbic regions may increase the antidepressant effect [2-3].

TMS with round [4] and Figure-o8 [5] coils have been widely used in practical applications. However, they are restricted to stimulate the superficial cortical targets due to the rapid attenuation in depth of the electric field. Only very high intensities would allow functional stimulation of deep brain regions and such intensities would lead to painful scalp stimulation. Furthermore, the risk of seizure is increased. These limitations have led to the development of novel coil designs suitable for deep TMS (dTMS), such as double-cone coil [6], H-coil [7], and Halo-coil [8]. The Halo coil, a large circular coil being placed around the head, was developed for stimulating the brain in depth. It was found the Halo coil working with a conventional Fo8 coil at the top of the head can increase the fields at depth in the brain. However, the stimulation focality becomes poor [9]. In the present study, we investigated to improve the stimulation focality of HFA coil by employing Fo8 coils with varied bending angles of coil wings, so that the HFA coil can be employed to realize the controllable dTMS with reasonable focality.

2. Method

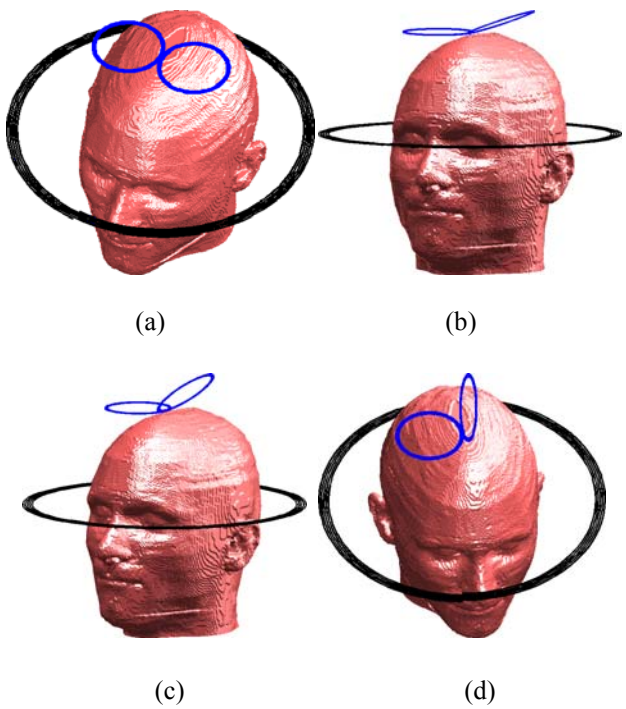


Figure 1. Realistic head model with stimulation coils. (a) HFA coil. Right wing of Fo8 coil was bent by 20 degree (b), 40 degree (c) and 80 degree (d).

Fig. 1 shows an overview of the coil configurations. The standard HFA coil is shown in Fig. 1(a). The Fo8 coil was located 3 mm above the vertex of the head, and the Halo coil was positioned 97 mm below the vertex of the

head. The inner and outer radii of the circular wings of Fo8 coil are 64 mm and 70 mm, respectively. The number of the wire turns in each wing is 10. The Halo coil with 5 turns has inner and outer radii of 138 and 150 mm, respectively. The pulse currents with amplitude of I=5.0 kA and working frequency of 2381 Hz were fed into each of the coils.

The realistic head model was obtained from a man model (Duke, 34-year-old male) developed by Virtual Family project [10]. The head model consists of 36 different kinds of tissues, including several important deep brain regions, such as thalamus, hippocampus, pons, etc. The head model is composed of 10 million cubic voxels with resolution of 1 mm.

The time variation of the applied magnetic field causes induced currents in the head 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 [11], and the induced electric fields were calculated using Ohm's Law.

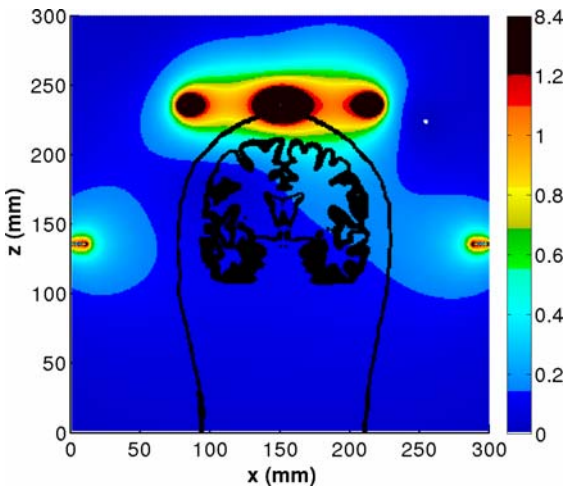
The electrical properties for realistic head model were modeled using the four Cole–Cole models [12]. In this model, the biological tissues subject to an electric field with angular frequency are modeled by relaxation theory, and tissue properties can be obtained by fitting to experimental measurements [13]. The tissue conductivities for part of the head tissues are shown in Table I.

Table I. Tissue Conductivities (σ) at *f*=2381 Hz.

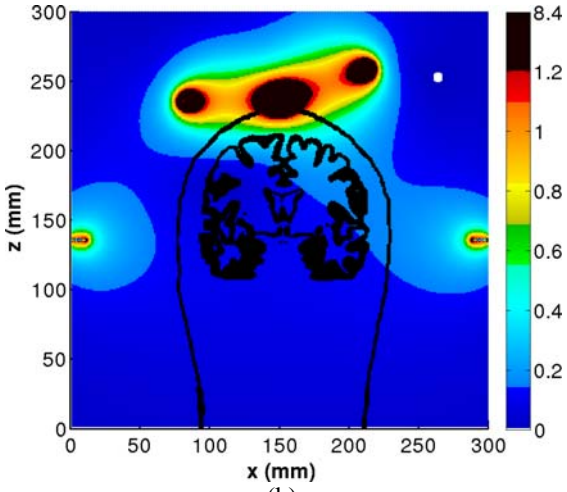
Tissue	σ (S/m)	Tissue	σ (S/m)
Artery	7.00e-01	Hypothalam	5.26e-01
Blood.Vessel	3.10e-01	Mandible	2.03e-02
Cartilage	1.75e-01	Marrow-bone	2.44e-03
Cerebellum	1.24e-01	Muscle	3.31e-01
CSF	2.00e+00	Midbrain	4.65e-01
Eye-cornea	4.25e-01	Nerve	3.04e-02
Eye- humor	1.50e+00	Pineal-body	5.26e-01
FAT	2.32e-02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

3. Results and discussions

Fig. 2(a)–(d) show the distribution of magnetic flux density (B-field) at coronal slice of y = 120 mm for HFA coil with different bending angles of right wing of Fo8 coil. To show the field distribution in head tissues, the contour outlines of scalp and gray matter (GM) were also included in each of the figures. It was observed that the maximum value of B-field is presented in the coil surface and decay quickly with distance from the coils. It was also found the distribution of the B-field in brain tissues was increased in brain tissues at the right side. The distribution of the B-field in brain tissues was decreased as the right wing of Fo8 coil was bended from 0 degree to 80 degree. It suggests the increased field penetration depth was obtained in the right hemisphere when the HFA coil operates, while the stimulation focality can be improved by bending the Fo8 coil wing away from the head model.



(a)



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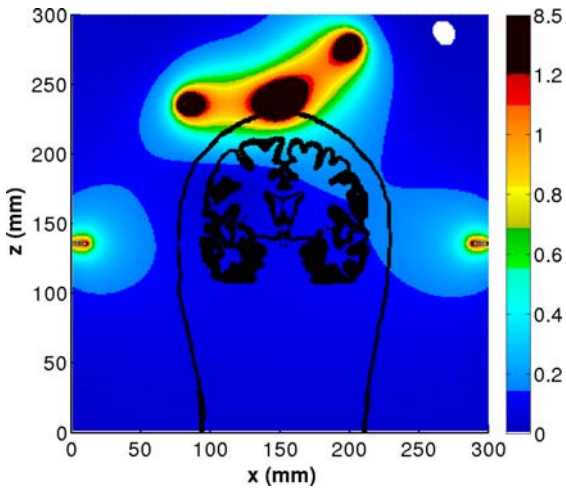
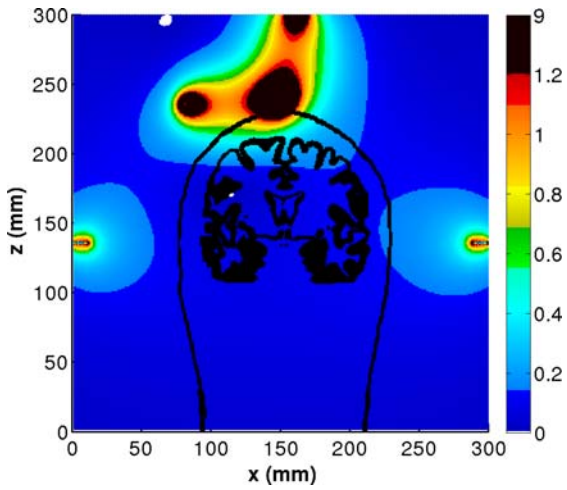
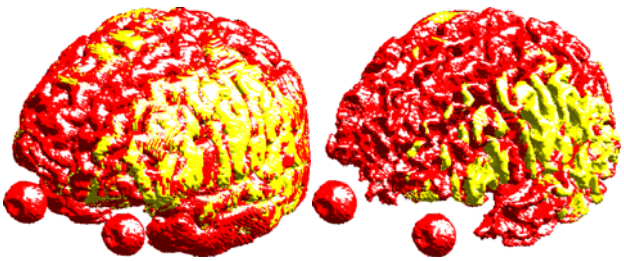


(c)

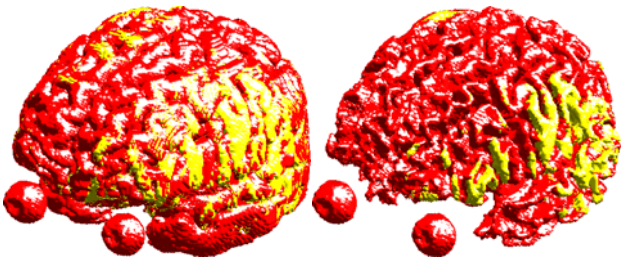


(d)

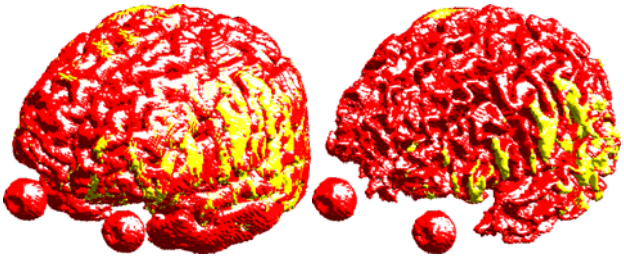
Figure 2. Distribution of B-field (Tesla) with the contour outline of scalp and GM in the coronal slice of y=120 mm. (a) standard HFA coil. Right wing of Fo8 coil was bent by 20 degree (b), 40 degree (c), and 80 degree (d).



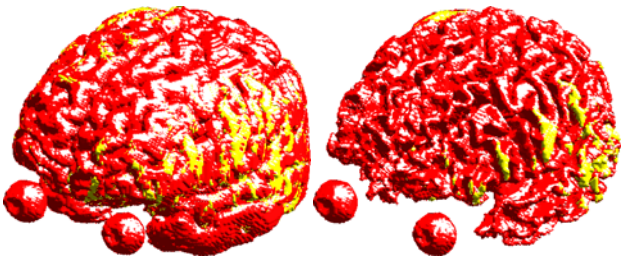
(a) (b)



(c) (d)



(e) (f)



(g) (h)

Figure 3. Electric field distributions on the cortical surfaces. Top row: HFA coil, (a) GM and (b) WM. 2nd row: right wing of Fo8 coil was bent by 20 degree, (c) GM and (d) WM. 3rd row: right wing was bent by 40 degree, (e) GM and (f) WM. Bottom row: right wing was bent by 80 degree, (g) GM and (h) WM. Red color: GM and WM surfaces. Yellow color: E-field with |E| > 100 V/m.

Fig. 3 shows the comparison of the electric field distribution on the surfaces of gray matter (GM) and white matter (WM) for HFA coil with different bending angles of Fo8 coil wing. The GM and WM surfaces were represented by red color, while the magnitude of electric field higher than 100 V/m (neuron excitation threshold) was represented by yellow color. It can be clearly found the induced electric fields on the surfaces of GM and WM were reduced (i.e. improved focality) when the right wing of Fo8 coil was bended with different angles.

From the above results it can be concluded that the HFA coil enables the stimulation of the brain at greater depth than, is currently achievable with the standard Fo8 coil. By properly bending the right wing of Fo8 coil with an angle away from the head model, the HFA coil can be employed for dTMS with controllable stimulation depth and with reasonable focality.

Acknowledgements

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