

The Optimal Design of Magnetic Coil in Transcranial Magnetic Stimulation

Guizhi Xu, Yong Chen, Shuo Yang, Mingshi Wang and Weili Yan

Abstract—Transcranial magnetic stimulation (TMS) is a new tool for the study of the human brain and for neurological therapeutics. Magnetic coil design is very important in the TMS technique. Precise spatial localization of stimulation sites is the key of efficient functional magnetic stimulations. This paper develops circular coils, figure-of-8 coils and coil array elements in order to realize a transcranial magnetic stimulator, and analyses the coil properties. The results show that different coils have different focus.

I. INTRODUCTION

THE use of non-invasive neuroimaging has increased explosively in recent years. Details of the functioning of the human brain are revealed by measuring electromagnetic fields outside the head or metabolic and hemodynamic changes using electroencephalography (EEG), magnetoencephalography (MEG), positron emission tomography (PET), nearinfrared spectroscopy (NIRS) or functional magnetic resonance imaging (fMRI). Transcranial magnetic stimulation (TMS) is a new tool for the study of the human brain and for neurological therapeutics. Brain stimulation with TMS is achieved from the outside of the head using pulses of electromagnetic field that induce an electric field activating nearby excitable neural elements in the brain. When used over the motor cortex, TMS produces a motor-evoked potential in the muscles innervated by the corticospinal tract, allowing central motor conduction time to be measured. TMS can transiently excite or inhibit neural activity, and probe regional brain excitability and intracortical circuits. TMS has numerous applications in the study, diagnosis and therapy of the brain. TMS can either excite the cortex or disturb its function. The observed excitatory effects are normally muscle twitches or phosphenes, whereas in the “lesion” mode TMS can transiently suppress perception or interfere with task performance. Repeated use of TMS with

rapid trains of stimuli can produce long-lasting therapeutic effects in the treatment of depression, Parkinson's disease, and pain states.

Magnetic coil design is one of the most important aspects of the TMS technique for its application. Recent advances in Magnetic coil configuration have improved the focality (the ability for a coil to stimulate at a small area of tissue) significantly. The planar “butterfly” coil was the first major improvement over the conventional planar circular coil, followed recently by the planar “four-leaf” coil. Recently, the three dimensional (3-D) design has shown even greater promise. Precise spatial localization of stimulation sites is the key of efficient functional magnetic stimulations. This paper involves the development of more sophisticated coil designs in TMS. As a general guide line of Magnetic Coils (MC) design, the procedure of MC development for TMS applications should include the followings: 1) identifying the problem; 2) locating the nerves of interest; 3) determining the area of stimulation; 4) estimating the depth of penetration; 5) optimizing the MC configuration; 6) constructing the MC; and 7) testing the performance of the MC both electromagnetically and physiologically [1].

II. THE BASIC PRINCIPLES IN TMS

Despite the widespread and successful application of TMS, it is not possible to predict precisely the territory that is affected. Addressing this problem requires knowledge of the spatial distribution of the electric field induced within the head and the mechanism of interaction between the induced electric field and neural tissue [2]. Neurons can be excited by externally applied time-varying electromagnetic fields. In TMS, excitation is achieved by driving intense pulses of current $I(t)$ through a coil located above the head. The source of activation is the electric field E induced in the tissue, obtained from Faraday's law:

$$\nabla \times E = -\frac{\partial B}{\partial t}, \quad (1)$$

where B is the magnetic field produced by the coil, given by the Biot Savart law:

$$B(r, t) = \frac{\mu_0}{4\pi} I(t) \oint_C \frac{dI(r') \times (r' - r)}{|r - r'|^3}. \quad (2)$$

Manuscript received April 30, 2005. This work was supported by the Natural Science Foundation of Hebei Province under Grant No.E2004000054.

Guizhi Xu is with Department of Precision Instrument, Tianjin University, Tianjin 300072, China. She is also with the Key Laboratory of Electromagnetic Field and Electrical Apparatus Reliability of Hebei Province, Hebei University of Technology, Tianjin 300130, China (phone: +86-022-60204405; e-mail: gzxu@hebut.edu.cn).

Mingshi Wang is with Department of Precision Instrument, Tianjin University, Tianjin 300072, China.

Chen Yong, Shuo Yang and Weili Yan are with the Key Laboratory of Electromagnetic Field and Electrical Apparatus Reliability of Hebei Province, Hebei University of Technology, Tianjin 300130, China.

The integration is performed with the vector $d\mathbf{l}$ along the coil windings C . μ_0 is the permeability of free space which is the same as the permeability in head tissues, such as white matter, gray matter, etc. The pulses of current are generated with a circuit containing a discharge capacitor connected with the coil in series by a thyristor. With the capacitor first charged to 1kV, the gating of the thyristor into the conducting state will cause the discharging of the capacitor through the coil. The resulting current waveform is typically a damped sinusoidal pulse that lasts about 160 μ s and has a peak value of 1803.53A.

III. THE INDUCED ELECTRICAL FIELD

Generally, the shape of the electric field induced in the tissue depends on 1) the shape of the induction coil, 2) the location and orientation of the coil with respect to the tissue, and 3) the electrical conductivity structure of the tissue. The total electric field in the tissue is the sum of primary and secondary electric fields, the primary field E_1 being induced by the changing magnetic field $B(t)$ from the coil, as stated by (1) and (2). In conductors, E_1 causes a flow of current

$$J = \sigma E_1, \quad (3)$$

σ is the conductivity. Any conductivity changes along the path of the current cause nonuniformity of electric charges, and give rise to an electrostatic potential ϕ , the negative gradient of which is the secondary field:

$$E_2 = -\nabla\phi, \quad (4)$$

Expressing B in term of the vector potential A , i.e.,

$$B = \nabla \times A. \quad (5)$$

The total E is

$$E = E_1 + E_2 = -\frac{\partial A}{\partial t} - \nabla\phi. \quad (6)$$

The potential ϕ obeys Laplace's equation,

$$\nabla^2\phi = 0. \quad (7)$$

This has been solved for the unbounded space and for simple conductor shapes such as the semi-infinite space, spheres, and infinite-length cylinders. Other shapes and inhomogeneities have been modeled numerically.

IV. THE OPTIMAL DESIGN OF MAGNETIC STIMULATION COIL

A. Circular coils

There are four coil configurations shown in Fig.1, and their geometric parameters are shown in Table I.

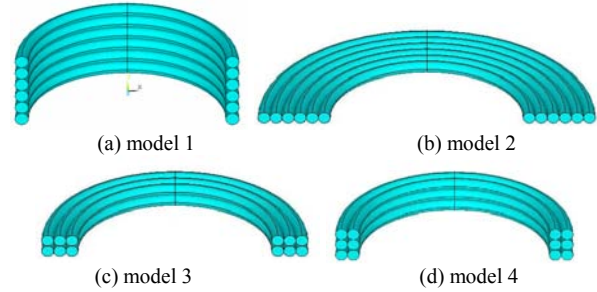


Fig. 1. The cross section of the four circular coils

The RLC circuit is shown in Fig.2. C is capacitor for charging and discharging. L is the magnetic coil. R is the resistance. U_1 is the excited source. The current in the coil L

TABLE I
THE GEOMETRIC PARAMETERS OF THE MAGNETIC STIMULATION COILS

Capacitance	Voltage	Diameter of wire	Inductance	Inner radius	Turns
130 μ F	1000V	0.0025m	20 μ H	0.02m	6

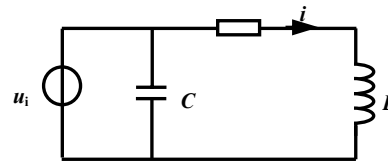


Fig. 2. The RLC circuit in TMS

is given by:

$$i = e^{at} \frac{U_0}{bL} \sin(bt), \quad (8)$$

where

$$a = -\frac{R}{2L}, \quad b = \frac{\sqrt{4LC - R^2C^2}}{2LC}.$$

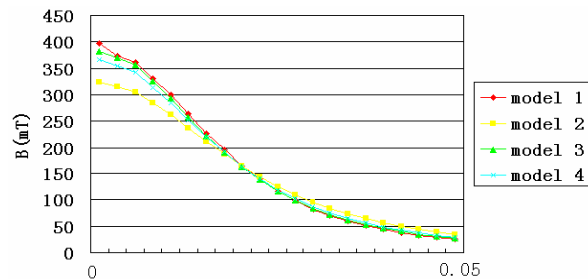


Fig.3. Axial distribution of magnetic flux density

Fig.3 shows the magnitude of the magnetic flux density at 5cm in the direction of the axis. When the axial distance is less than 0.025m, models 1, 3 and 4 have bigger intensification of magnetic field. But when the axial distance is more than 0.025m, model 2 has bigger intensification of magnetic field than the others.

Fig.4 shows the magnitude of the magnetic flux density at radial 5cm on the surface at 3mm above the coil. The focus ability of model 1 is the worst, and the others is better than model 1.

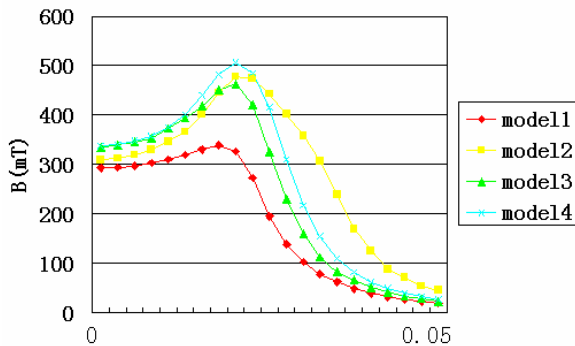


Fig.4. Radial distribution of magnetic flux density

B. Figure-of-8 Coils

The parameters of the figure-of-8 coils are the same as Table I.

In Fig.5 (a), (b) and (c), the interval of axis of the two coils is $D/4$, $2D/4$, $3D/4$ respectively. D is the outer-diameter of coil; in (d), the two coils are no interval and not in the same plane; in (e), the two coils are no interval and in the same plane. In Fig.8, (a), (b), (c), (d), (e) have the same means in Fig.5. Fig.6 and Fig.9 are the radial distributions of magnetic flux density of types of model 1 and model 2 with the currents in the same direction respectively. Fig.7 and Fig.10 are the radial distributions with the currents in the reverse direction.

The mutual coupling could induce currents at adjacent coils, which could influence the spatial localization of the stimulation when the coil array has a high magnetic coupling configuration. However, the coupling effect can be

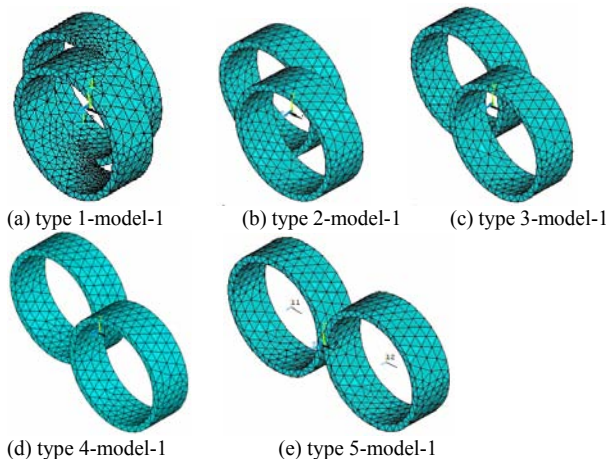


Fig.5. Figure-of-8 coil configurations

compensated by proper control of the charge voltages [3]. When the figure-of-8 coils have the current of the same direction, different type has different focality. The type 2-model-2 has the max numerical value and better focality. At other positions, magnetic field which produced by figure-of-8 coils are not uniform; when the figure-of-8 coils have the current of the reverse direction, the type 5-model-1

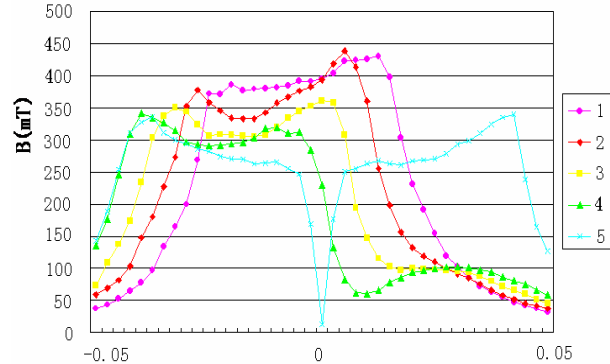


Fig.6. Radial distribution of magnetic flux density 3mm below the coils in the types of model 1. The currents are both anticlockwise.

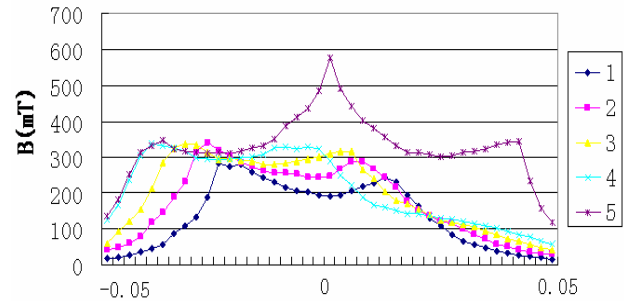


Fig.7. Radial distribution of magnetic flux density 3mm below the coils in the types of model 1. The current in one of the coil is anticlockwise and the other is clockwise.

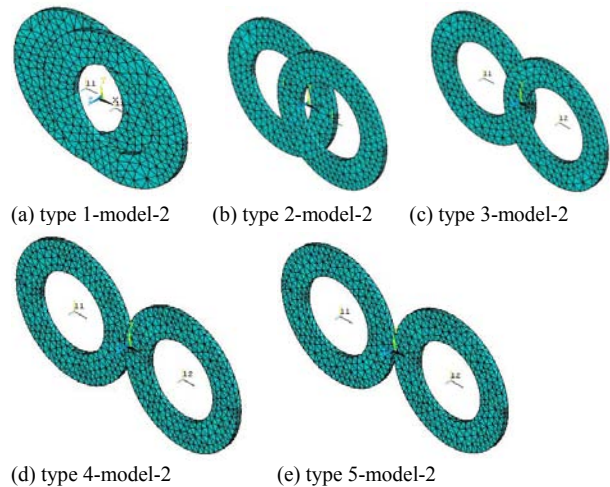


Fig.8. Figure-of-8 coil configurations

has the best focality, and type 1-model-1 and type 5-model-1 have two focuses, so we should consider the position of the coils. If controlling the radius of the coil properly, the precision of focus should be able to reach millimeter, which is very useful in TMS; and the figure-of-8 coils of model 2 can produce several focuses, it can stimulate several targets

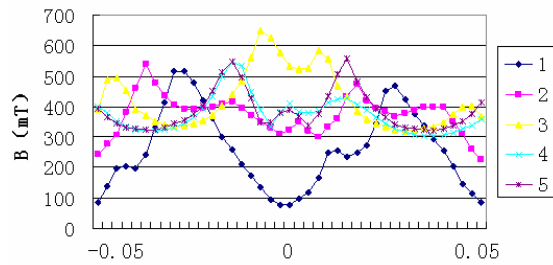


Fig.10. Radial distribution of magnetic flux density at 3mm below the coils in the types of model 2. The current in one of the coil is anticlockwise and the other is clockwise

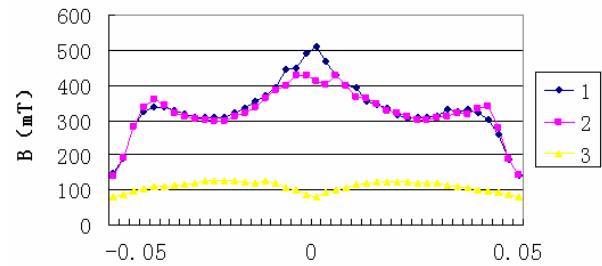


Fig.12. Radial distribution of three coil array elements at 3mm below the coils.

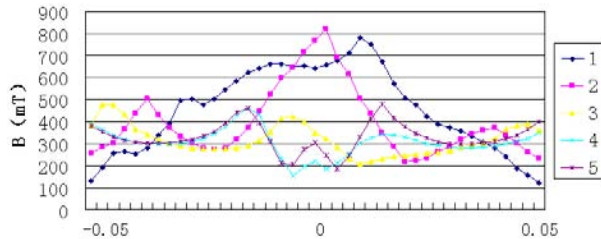


Fig.9. Radial distribution of magnetic flux density at 3mm below the coils in the types of model 2. The currents are both anticlockwise

at the same time, which are very useful in coils array elements.

C. Coil array element

To perform efficient TMS or to localize stimulation sites more precisely in brain studies, multichannel magnetic stimulations are desired. By using multicoils with which separate driving channels are connected, the stimulation site can be moved without any physical movements of the coils and the spatial localization in the stimulation can be achieved more precisely than by a conventional single coil-based system.

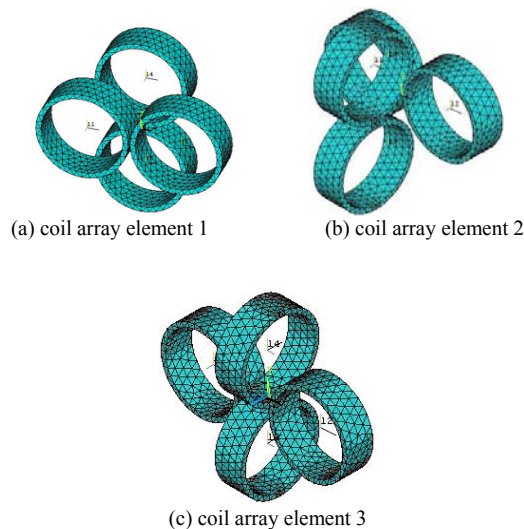


Fig.11. The coil array elements composed by two figure-of-8 coils

Fig.11 shows three kinds of coil array element constructions. Two figure-of-8 coils are difference in the direction. That is, one is with anticlockwise and the other with clockwise.

From Fig.12, the conclusions are the following: array element 1 and array element 2 have better focus; array element 3 can produce a magnetic field which has symmetrical intension and deep stimulating distance; the array element has better ability of focus than circular loop coil. If the current direction in a coil array element is controlled properly, they can produce several focuses, and also can produce many kinds of magnetic fields, which is useful in TMS.

V. CONCLUSION AND DISCUSSION

In this paper, the focality and stimulation depth of four circular models, five types of 8-shaped coils and three array elements have been discussed. The performance of model 2 is better than the others. The current direction has little effect on the stimulation depth. When the current directions in two coils are both anticlockwise, the 8-shaped coils can produce several focuses. The array element has better ability of focus than circular loop coil and figure-of-8 coils. Those are a well basis for our further work. In the next work, we will make our great efforts to analyze multichannel magnetic stimulation coils array.

REFERENCES

- [1] Vernon Weh-Hau Lin, Ian N. Hsiao, and Vijay Dhaka, "Magnetic Coil Design Considerations for Functional Magnetic Stimulation" *IEEE Trans. Biomed. Eng.*, vol. 47, no. 5, pp.600-610, May. 2000
- [2] Pedro C. Miranda, Mark Hallett, and Peter J. Basser, "The Electric Field Induced in the Brain by Magnetic Stimulation: A 3-D Finite-Element Analysis of the Effect of Tissue Heterogeneity and Anisotropy," *IEEE Trans. Biomed. Eng.*, vol. 50, no. 9, pp. 1074-1085, Sep. 2003.
- [3] Byung H. Han, In K. Chun, Sang C. Lee, and Soo Y. Lee, Member, Multichannel Magnetic Stimulation System "Design Considering Mutual Couplings Among the Stimulation Coils," *IEEE Trans. Biomed. Eng.*, vol. 51, no. 5, pp. 812-817, May. 2004.