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A Design of Array Transcranial Magnetic Stimulation Coil System

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***Abstract*—**This research proposed a new design of helmet-shaped array transcranial magnetic stimulation coil system. It was constructed using several sagittal directional wires and several coronal directional wires. By varying the current direction and strength on each wire, this array coil system could be constructed into the circular coil and figure-eight coil of different size. Also, this proposed coil system can flexibly not only change the stimulation location, range, type and strength, but also change the shape and the channel number of coil dynamically.

***Keywords*—**TMS, circular coils, figure-eight coil, array coil

I. INTRODUCTION

ALL human behaviours are controlled and propelled by the complex interactions between different regions of the brain. The information present in spatially different regions is processed at various times. In order to study how different regions of brain process information and how they interact with each other, there is a need of in-depth study of both spatial component (focused on the actual processing of information in various brain region) and time component (focused on the time point of information processing) of the brain. Currently, the non-invasive methods to observe information processing include functional magnetic resonance imaging (fMRI), electroencephalogram (EEG), magnetoencephalography (MEG) and transcranial magnetic stimulation (TMS). Although fMRI, EEG and MEG are used to detect signals from the brain, they are limited to collecting brain signals passively, and not actively. Thus these methods cannot be utilized to artificially control the information processing in the brain. Due to the accelerating development in this field, passive capture of brain signals can no longer satisfy the level of the current neurological studies; there is a demand for controlled experiments to actively stimulate and observe how the brain interact and process information, as this new approach will become the forefront of neurological studies. TMS is the only current non-invasive methods to exert stimulus to the brain, and its uniqueness has caught the attention of many scientists.

TMS uses electromagnetic induction to generate an electric current across the scalp and skull without physical contact. A plastic-enclosed coil of wire is held next to the skull and when activated, produces a magnetic field oriented orthogonally to the plane of the coil. The magnetic field passes unimpeded through the skin and skull, inducing an oppositely directed current in the brain that activates nearby nerve cells in much the same way as currents applied directly to the cortical surface.

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Such induced currents will cause the depolarization or hyperpolarization of the neurons in the brain [1], [2]. As a non-invasive and effective method to making reversible lesions in the human brain, TMS can investigate not only the spatial but also the temporal characteristic of brain activation.

Currently, most TMS coils can be classified as circular coil or figure-eight coil as shown in Fig. 1 [1]. As shown in Fig. 1, the circular coil can generate a wider magnetic field (Fig.1.a), while the figure-eight coil can generate a more localized magnetic field (Fig.1.b) [3].

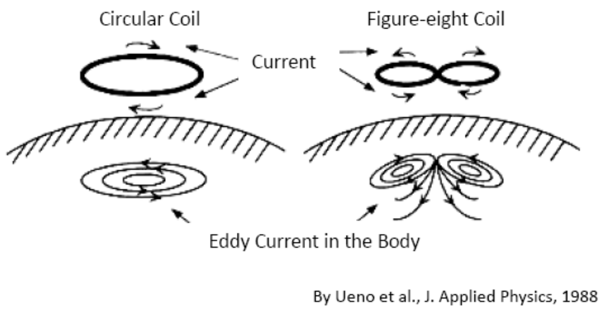

Fig. 1 The traditional design of TMS coils. (a). Circular coil; (b). Figure-eight coil

In order to study the brain activity in a whole-head range, researchers need to investigate brain activity over whole head at multiply locations. Since fMRI and positron emission tomography (PET) scan the whole head in each small voxels, and EEG and MEG are whole-head array designed, those approaches have been widely used in investigating the whole-head brain activity. However, as the unique approach which can modify the activity of brain, now TMS can only be applied over a fixed location during one experiment.

Some researchers tried to use multiple TMS coils to achieve quasi whole-head array stimulation [4]-[11] (Fig. 2). However, their designs still remained in arranging multiple single coils over the skull. Because of the limitations of shape of the coils themselves and the interval between the coil elements, those designs cannot achieve high-resolution configuration of coils. To ensure the accurate positioning of coils over the skull, and the relative positions among individual coils, operator need to locate those coils one by one accurately. Such difficulty to control relative displacement of each coil makes it nearly impossible to repetitively experimental stimulation on the exact same location. Moreover, each single coil requires a separate control unit, thus multichannel system will inevitably lead to complicated control problem. Since past quasi whole-head array TMS coil designs have low resolution configuration, hard to position and control, those designs have not been widely used in the study the dynamic brain activity.

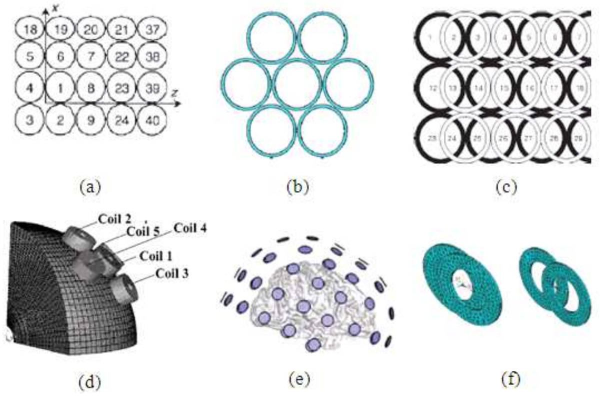

Fig. 2 Past quasi whole-head array TMS coil system. (a). Ref. [4-6]. (b). Ref.[7]. (c). Ref.[8]. (d). Ref.[9]. (e). Ref.[10]. (f). Ref. [11]

To the best of our knowledge, a true whole-head array TMS coil system, in which multiple coils are fixed together and has high-resolution configuration, has yet to be developed. In this study, we tried to propose a new design of whole-head helmet-shaped array TMS coil to overcome the disadvantages of the past researchers. In this study, we attempt to develop a true whole-head array TMS coil system. The coil system can allow the researcher to stimulate multiple brain areas in a single experiment. In addition, it can easily design stimulus pattern spatially and temporally (time: stimulus time; space: stimulus position). Researchers can use the proposed TMS system to study temporal-spatial feature of information processing of the brain. Such researches can aid our current understanding of behavior of the brain as well as neurological or psychiatric pathology.

II. Methods

A. Design

The main component of any TMS system is the coil used to induce the current stimulation inside a brain region.

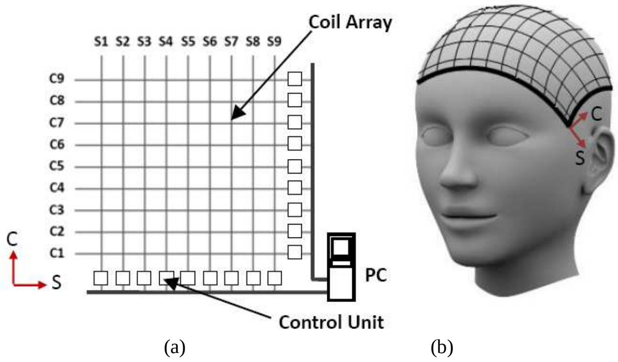

Fig. 3 The outline of the proposed helmet-shaped array coil. (a). Proposed coil system is constructed by a set of coronal and sagittal directions wires. (b). Proposed coil system arranges along the surface of the skull. S: sagittal axis; C: coronal axis

In the proposed system, a helmet-shaped array coil as shown in Fig.3 will be developed. The coil system consists of set perpendicular wires, *S* direction and *C* direction correspond to the sagittal axis and coronal axis, respectively. Wires in the *S* and *C* directions are physically cross to each other but electrically insulated. Each wire is connected with a separate control unit, which can control the current direction and strength.

By varying the current direction on each wire, we can configure the proposed coil system into the circular coil or figure-eight coil of different sizes (Fig.4 and Fig.5). Fig.4 illustrates two configured circular coils of different sizes. Let current strength $S2=I$, $S3=-I$, $C7=I$, $C8=-I$, and setting the current strength of the other wires to zero, this proposed array coil can configure a small circular coil at the top-left corner. While, if let $S4=I$, $S8=-I$, $C2=I$, $C6=-I$, and setting the current strength of the other wires to zero, this proposed array coil can configure a large circular coil at the bottom-right corner.

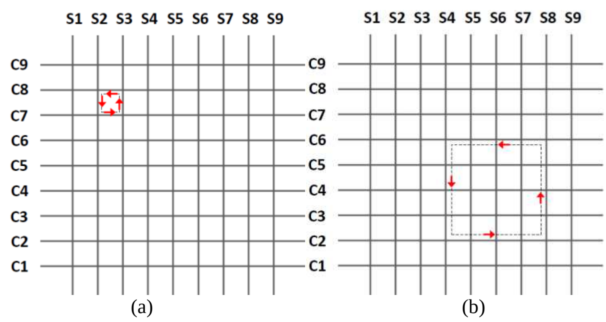

Fig. 4 The proposed coil system can generate circular coils for different sizes. (a). A small circular coil is configured by controlling the currents in wires of S2-S3-C7-C8. (b). A large circular coil is configured by controlling the currents in wires of S4-S8-C2-C6

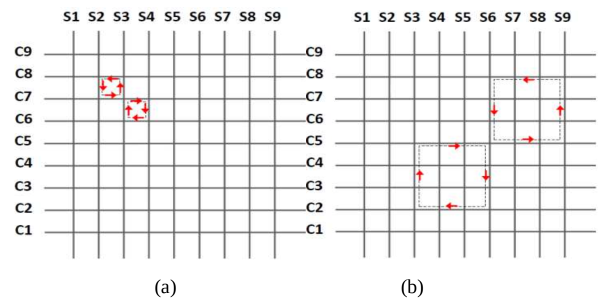

Fig. 5 The proposed coil system can generate figure-eight coils for different sizes. (a). A small figure-eight coil is configured by controlling the currents in wires of S2-S3-S4-C6-C7-C8. (b). A large figure-eight coil is configured by controlling the currents in wires of S3-S6-S9-C2-C5-C8

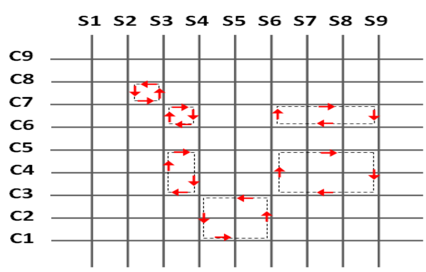

Fig. 6 The proposed coil system can generate multi-channel coils in different size and type

Fig. 5 shows figure-eight coils of different sizes can be configured. Let current strength *S2=I*, *S3=-I*, *S4=I*, *C6=-I*, *C7=I*, *C8=-I*, and setting the current strength of the other wires to zero, this proposed array coil can configure a small figure-eight coil at the top-left corner. Let current strength *S3=-I*, *S6=I*, *S9=-I*, *C2=-I*, *C5=I*, *C8=-I*, and setting the current strength of the other wires to zero, this proposed array coil can configure a big figure-eight coil at the bottom-right corner. Such design provides maximum flexibility in that the location and range of stimulation on the brain surface can be modified depending on experimental requirement. Based on the circular coil and figure-eight coil, this proposed coil system can generate multi-channel coils (Fig. 6), there are three different type coils in the coil array: Let current strength *S2=I*, *S3=-I*, *S4=I*, *C6=-I*, *C7=I*, *C8=-I*, and setting the current strength of the other wires to zero, this proposed array coil can configure a standard figure-eight coil at the top-left corner; Let current strength *S6=-I*, *S9=I*, *C6=-I*, *C7=I*, and setting the current strength of the other wires to zero, this proposed array coil can configure a planar circular coil at the top-right corner; Let current strength *S3=-I*, *S4=I*, *S6=-I*, *S9=I*, *C1=I*, *C3=I*, *C5=-I*, and setting the current strength of the other wires to zero, this proposed array coil can configure a double figure-eight coil at the bottom of the coil array, respectively. Moreover, by varying the current strength, the stimulation strength of the TMS coil can be adjusted. By pre-programming the control units, this proposed coil system can flexibly change the stimulation location, range, type and strength during the experiment. Also the shape and the channel number of coil can be flexibly changed.

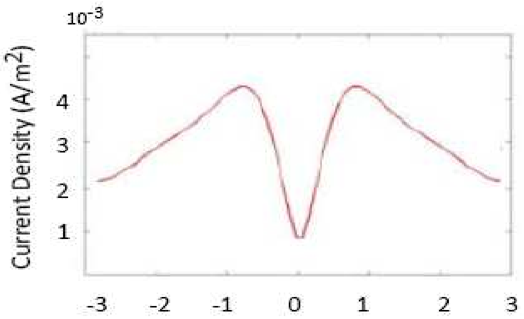

Fig. 7 Induced current density distributions of the circular coil

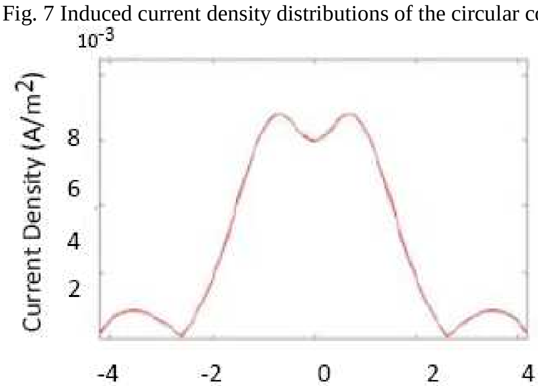

Fig. 8 Induced current density distributions of the figure-eight coil

B. Simulation

In order to verify the feasibility of our proposed design, the current density distributions of the circular and figure-eight coils were simulated with Matlab (MathWorks, R2008a). Simulation was performed using a rigorous three- dimensional (3D) impedance method [12].

III. Results

Using this impedance method, the induced current strengths generated by the circular coil and the figure-eight coil are shown in Fig.7 and Fig.8. Fig.7 shows the current density distribution of the circular coil. Fig.8 shows the current density distribution of the figure-eight coil. Based on the simulation results, it is clear that the distributions of current density of circular coil and figure-eight coil are consistent with the theoretical values. Thus, the correctness and validity of this proposal are confirmed.

IV. Discussion

This proposed design has some distinct advantages as following:

Firstly, the proposed array coil system has great advantage in variability. By varying the current direction and strength on each wire; we can configure this array coil into circular and figure-eight coil of different sizes.

Secondly, the array coil system also minimizes the relative movement compared to past proposed quasi array coils design [4]-[6]. In the past quasi array coil design [4]-[6], the position of each single coil element need to be set separately, and the relative displacement among the coils may cause offset of the magnetic field. The proposed array coil system has a fixed shape, which can eliminate the relative displacement among individual coils.

The third advantage of this proposed coil system is this system can maximize the flexibility of stimulation locations and ranges according to the specific experimental conditions. In addition, by preprogrammed various stimulation patterns and range within the control unit, it can alter the stimulation pattern and range during the experiment.

The fourth advantage of this proposed coil system is this system can greatly reduce the control unit. For the past quasi N-by-N coil array, it needs N*N control units; while for our proposed design, for an N-by-N coil array, the number of control units is only 2*(N+1). Such design will especially simplify the complex control system of large coil array system.

Acknowledgment

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