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Study on Performance Evaluation System for Transcranial Magnetic Stimulation Devices

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Abstract—**Transcranial magnetic stimulation devices have been widely used for clinic and research purposes and their performance such as stimulation strength, depth and focality are of great concern from various studies. However, there is no specific evaluation index nowadays. TMS devices could only be appraised qualitatively with accurate parameters, thus, a preliminary evaluation work for TMS devices is proposed in this paper. Practical indexes are proposed in order to give a clear image of the TMS device performance. This work may provide a design guideline for TMS device, performance evaluation and comparison as well.**

I. INTRODUCTION

Transcranial magnetic stimulation (TMS) is a kind of non-invasive bio-stimulation technique, which changes the action potential of the cortical cell with an induced current in the cerebral cortex by a time-varying magnetic field provided from a pulse current flowing in a stimulation coil, thus affecting the brain metabolism and electrical activity of nerves. Comparing with conventional electrical stimulation, TMS, which has a broad application prospect, is easier to achieve deeper brain region without causing the shock of brain motor area and pain [2]. TMS is a potential measure treat depression, Parkinson's disease and other neurological diseases [3-4].

In a typical TMS device, a stimulation coil is connected to a pulse generation circuit. When a pulsed current flow through the coil, time-varying magnetic field will be generated, which penetrates the scalp and skull, and induces a time-vary electrical field in cortex stimulating brain tissues. The magnetic field distribution is determined by the structure of coil, and its magnitude depends on the magnitude and the frequency of the current. In the sense of stimulation effectiveness, the TMS system should achieve enough electrical field strength in the target tissue with limited action area in order not to affect the non-target tissues. This requirement infers two important indexes: stimulation strength, the electrical field induced in the target tissue and stimulation focality, which describes the effective stimulation area.

Except for stimulation strength and focality, stimulation depth and efficiency are important as well. Stimulation depth indicates the maximum depth where the induced electrical field may cause neuron's excitation. Obviously, it depends on the magnitude of pulse current and coil structure. Efficiency indicates how much energy is acquired to achieve the same stimulation strength at the same stimulation position. But efficiency is not much concerned in practice.

Although quite amount of work [5-8] has been done to investigate the stimulation effect both from TMS devices and biological-effect aspects, there has no unified evaluation criterion for TMS devices, which is of great importance to assess the stimulation effect quantitively instead of vague expression such as 'better' or 'worse'. In this paper, preliminary work has been done to propose several indexes which can be used as design guidelines for TMS devices and performance comparison as well.

II. THE PRINCIPLE OF TMS

A. Biological Mechanism

Human brain is a complex nervous system, composed of neurons and glial cells. Neuron is the main functional units receiving external stimulation and processing information through electrical signals, which closely related to ion channels in the synapses [9]. Neuron in stimulation is described as mammal nerve fibers Hodgkin-Huxley model as shown in Fig.1, where C_M is membrane capacitance, E is the electrical potential outside, and E_{Na}, E_K, E_l and R_{Na}, R_K, R_l are the original potential and resistance of different ion channels, while R_{Na}, R_K are variable resistance that related to E. When neuron is placed in an electric field larger than its threshold, R_{Na}, R_K will decrease sharply, and the current in Na^+ and K^+ ion channels increase, then a nerve impulse is generated so as to achieve the stimulation.

In addition, studies showed that neurons respond to applied electric fields differently with different frequencies [10-11]. The higher frequency the field is with, the higher threshold neurons will have. Fig.2 shows the relationship between cell threshold and the frequency of the excitation electric field [10-11]. Apparently, though the magnitude of electric field gets higher when frequency increases, the threshold increases at the same time. From the figure, it is seen that the threshold is easier to achieve for the induced electric field with lower frequency, but more tissues including healthy cells may be affected as well in this case. Therefore, the frequency of current pulse should be decided carefully.

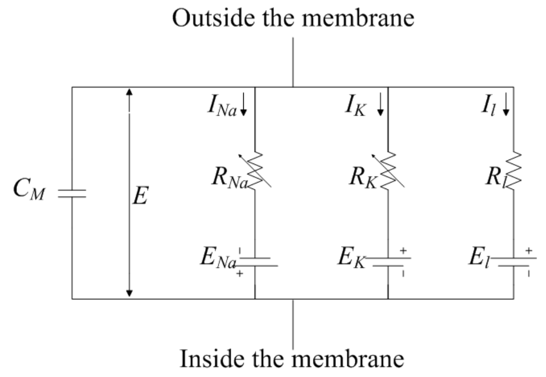

Fig.1 Hodgkin-Huxley model of mammal nerve fibers

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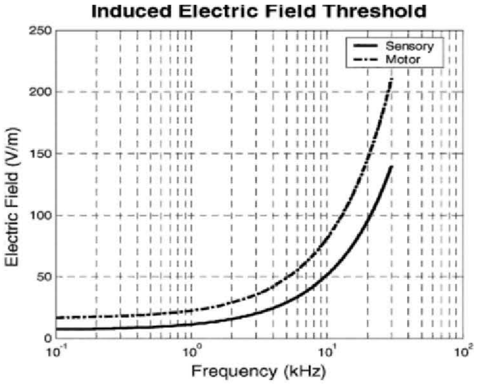

Fig.2 Relationship between induced electric field threshold and its frequency

B. *TMS Devices*

TMS device is commonly composed of pulse current generation circuit and stimulation coil.

The schematic circuit to generate the pulse current for the TMS system is shown in Fig.3. A sinusoidal pulse current is produced by discharging the capacitor *C* to the inductor *L* (coil inductance) when closing the thyristor. The current waveform depends on the charged voltage on the capacitor and the electrical parameters of the discharging circuit.

The typical sinusoidal current pulse shows in Fig.4 can be determined by

$$I_L(t) = \frac{U_0}{\omega L} e^{-\delta t} \sin(\omega t) \tag{1}$$

Where, ω is the frequency of the *LC* circuit. Thus, the amplitude and frequency of the current can be adjusted accordingly. In the aforementioned equation, *L* is the inductance of the stimulation coil and its value is subject to coil structure. Various types of stimulation coils have been designed but only circular and butterfly coils are widely used in clinical nowadays. While other types like slinky and double-butterfly coil are still in testing. The magnetic flux density in the free space generated by the coil current is determined by Biot-Savart law as

$$\vec{B} = \frac{\mu}{4\pi} \oint_{l'} \frac{\boldsymbol{J}(r^{'}) \times \boldsymbol{e}_R}{R^2} \tag{2}$$

Neglecting the resistance in discharged circuit, the current in the coil will be in a sinusoidal form as

$$J = J_m \cdot \sin \omega t \tag{3}$$

Where J_m is the peak of the current, and the electrical field generated in space is therefore determined by

$$\vec{E} = -\frac{\mu}{4\pi} \omega \cos \omega t \int_{l'} \frac{J_m(r')}{R} d\vec{l}' \tag{4}.$$

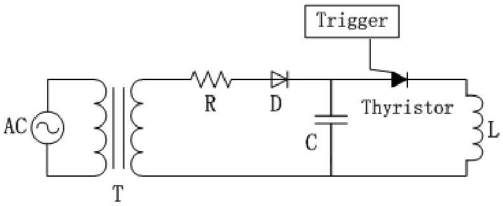

Fig.3 The schematic diagram of the circuit producing the current pulse

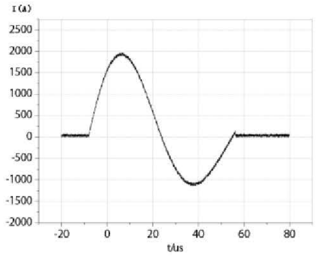

Fig.4 The typical waveform of generated current pulse.

III. PERFORMANCE EVALUATION OF TMS DEVICES

An effective TMS device is supposed to meet the following basic requirements: the induced electric field generated could exceed neuron threshold, and it is focused on target area to reduce side effect on non-target tissue. Due to the complexity and diversity the neurons, it's very difficult to set up a uniform standard for each patients, therefore in this paper, we tried to evaluate its effect on from device's side. The detailed discussion is as follows.

A. *Evaluation of Pulse Current Generating Circuit*

It is obvious that the pulse current waveform will determine the induced electric field which directly influences the stimulation effect. Thus the amplitude, frequency and repetition rate of the generated pulse current are selected as the major indexes to evaluate the circuit performance. The current amplitude is determined by the charged voltage and circuit parameters. The frequency of current is determined by the self-resonance frequency of the discharge circuit and the repetition rate is determined by the charging time constant and the switch frequency.

Thus, TMS pulse current generating circuit can be evaluated using the maximum current magnitude I_m, the current frequency f_s, and the maximum repetition rate f_r.

B. *Evaluation of stimulation strength*

In clinic, the stimulation strength is adjusted by the MT level (motor threshold) of the patient. However, only the value of maximum magnetic flux density will be given to customers for most of the TMS products so far. Since the magnetic field is different at different position and the electrical field is the only cause for neuron excitation, it is not proper to evaluate using maximum magnetic flux density.

In most cases, the stimulation target of TMS is cortex, which is about 15mm deep under head epidermis of adults. For a broader sense, the stimulation strength at a depth of 20mm (E_{20mm}) can be defined as an evaluation index to describe the maximum electric field can be generated on the plane 20mm beneath stimulation coil. Output energy can also be evaluated using the index of E_{20mm}, since the energy is a function of electric field.

In addition, E_{20mm} is proportional to the Ampere turns of the stimulation coil and the frequency of the current, therefore it can be normalized to another index E_a, the magnitude of the electric field produced by per unit current with per unit frequency and number of turns in the stimulation coil (in this paper, this p.u. is defined as 1kA, 1kHz, 1 turn. Of course, it can be defined in other ways.). In this sense, E_a is mostly related to the coil structure showing the ability of TMS converting current to electric field.

C. Evaluation of Stimulation Depth

Stimulation depth expresses the penetration ability of the electric field. The stimulation depth H can be defined as the depth that an effective stimulation can reach. In other words, it denotes the maximum distance beneath the coil that the electric field can exceed neuron excitation threshold. Studies have shown that the threshold approximately meets the equation (5) and the variables are defined in TABLE.I [10-11]:

$$E = \beta \cdot (1 + 2\gamma f) \tag{5}$$

Therefore, the maximum stimulation depth can be predicted by analytical or numerical simulations.

D. Evaluation of Focality

In order to minimize the side effect on healthy tissues, electric field generated by TMS device ought to be focused into small area. The stimulation is more beneficial and safe with better focality.

In previous studies, the focality of the stimulation coil is evaluated by the half power region (HPR) of the electrical field [12], in which the magnitude of the induced electric field is greater than 1/√2 (3dB decay point) of its maximum magnitude (see Fig.5). Since the electric field strength decreases with the distance to the coil plane, HPR will increase with stimulation depth and the electric field decreases on the contrary. To evaluate the focality, an attenuation coefficient η is introduced in advance [13]:

$$\eta = \frac{E_m - E_h}{E_m} \tag{6}$$

where E_h is the maximum electric field at a certain depth h, E_m is the maximum electric field on scalp (defined as h=2mm). η is always small when h is small. The focality function F is thus proposed as a function of HPR area S_h at depth h with attnuation factor η:

$$F(h) = \eta \cdot S_h = \frac{E_m - E_h}{E_m} \cdot S_h \tag{7}$$

TABLE.I Neural magnetic stimulation response parameters

	Rheonbase β		Chronaxie γ	
	Median (V/m)	Std. dev (V/m)	Median (μs)	Std.dev (μs)
sensory	6.75	2.06	329	78.4
motor	16	6.1	203	78.5

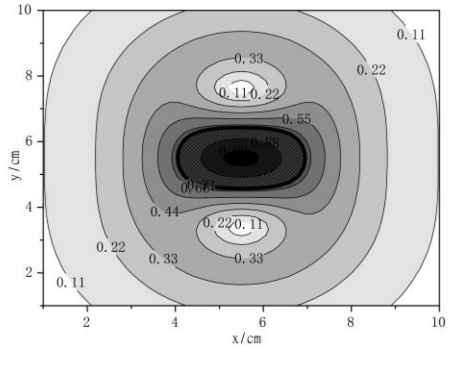

Fig.5 Schematic diagram of HPR (area surrounded by thick black line)

Focality of a TMS device is better when F is smaller, and the focality on cortex F(20mm) is especially concerned. In most cases, scalp, skull and cerebrospinal fluid are not affected by electric field, so parameter h_b indicating the best stimulation depth is defined as the depth that F ($h \geqslant$20mm) attains the minimum value. Generally h_b=20mm because F increases when h increases. But it can be larger with special methods adopted, such as placing several coils at designed position.

E. TMS evaluation system

In summary, considering the major performance concerned, a comprehensive evaluation for a TMS device is possible to be conducted by taking account of the indexes listed in TABLE.II.

It is noted that, among these parameters, F and E_a only depend on stimulatin coil structure and can be taken as a comparsion base for different coil designs.

IV. APPLICATION OF THE PROPOSED EVALUATION SYSTEM

This evaluation system can be used to evaluate whole TMS device, or circuit and coil separately. Examples are given in following section.

A. Evaluation of TMS devices

Two TMS devices are evaluated at this section: a popular TMS device Rapid^2 [14], and a tested device by our laboratory [15]. Technical parameters of two are shown below.

Rapid^2 can provide a peak current of 7kA. The 7-turn butterfly coil diameter is 70mm and inductance of 16.35μH. According to Rapid^2's coil structure and circuit feature, the current frequency is calculated to be 2.5 kHz. The thresholds of sensory and motor neurons are 17.85V/m and 32.24V/m respectively.

The induced electric field magnitude E_{max} and focality F versus depth h of two devices are estimated by finite element analysis (see Fig.6). The evaluation for these two devices is

TABLE.II Parameters of TMS devices evaluation system

Evaluating object	Major parameters	Description
Circuit	I_m	Maximum current of circuit
	f_s	Current frequency
	f_r	Maximum repetition rate
Stimulation strength	E_{20mm}	Maximum electric field at h=20mm
	E_a	Nomalized stimulation strength
Stimulation depth	H	Maximum stimulation depth
	h_b	Best stimulation depth
Focality	F	$F(h) = \eta \cdot S_h = \frac{E_m - E_h}{E_m} \cdot S_h$

TABLE.III Evaluation of Rapid^2 and Laboratory designed device

Object	Index	Rapid^2	Tested device
Circuit	I_m	7kA	2kA
	f_s	2.5kHz	15kHz
	f_r	100Hz	100Hz
Stimulation strength	E_{20mm}	239.47V/m	154.78V/m
	E_a	1.95V/m	3.20V/m
Stimulation depth	H	Sensory: 93mm motor: 72mm	Sensory: 35mm motor: 26mm
	h_b	20mm	20mm
focality	F（20mm）	12.3cm^2	7.89cm^2

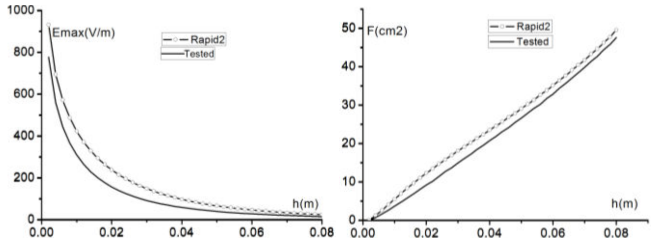

Fig.6 E_{max} and F versus depth h of two devices

listed in Table III. It is shown that Rapid^2 has better performance in E_{20mm}, H and h_b, while the tested device has better focality and E_a. Rapid^2 maintains high electric field magnitude at cortex; its maximum stimulation position is relatively deeper. On the other hand, the tested device performs well in F and E_a, expressing that its coil design is better.

B. *Evaluation of Stimulation coils*

In this section, the performance of some typical coil types, including circular coil, butterfly coil and double butterfly coil [15], are compared using the proposed indexes E_a and F. For convenience, the diameters of these three coils are set the same of 70mm, the number of turns is one. For the double butterfly coil, the outer diameter is 70mm as well, and the inner coil diameter is 35mm (see Fig.7).

The simulation result is shown in TABLE.IV. It is observed that the double-butterfly coil is the best for producing the largest E_a and the smallest F. It should be noted that these two indexes are independent to the current generation circuit and the patients under treatment.

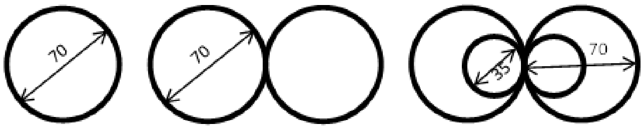

Fig.7 Schematic diagrams of different coils (circular coil, butterfly coil and double butterfly coil).

TABLE.IV Evaluation of coils

	Circular	Butterfly	Double-butterfly
E_a	0.977V/m	1.95V/m	3.20V/m
$F(20mm)$	$68.7\ \text{cm}^2$	$12.3\ \text{cm}^2$	7.89cm^2

V. CONCLUSION

An evaluation system with explicit physical meaning is presented to assess TMS devices. This evaluation system takes into consideration of both the pulse current generation circuit and the stimulation coils. Several practical indexes are proposed to support the evaluation system and attempts are carried out to build up a unified standard for TMS products. It may be helpful for the research and development of the TMS devices in the future. However, a complete evaluation involves not only the indexes mentioned above but also other factors such as volume, price, safety, stability and etc. More detailed and extension work is under progress.

REFERENCES

[1] A. T. Barker, R. Jalinous, and I. L. Freeston. “Non-invasive magnetic stimulation of human motor cortex”, *Lancet*, 1985, no. 1: 1106-1107.

[2] Nitsche MA, Cohen LG, Wassermann EM, et al. “Transcranial direct current stimulation: state of the art”. *Brain Stimulation*, vol.1, no.3, pp.206-223, 2008.

[3] Kirkcaldie MTK, Pridmore SA, Pascual-Leone A. “Transcranial magnetic stimulation as therapy for depression and other disorders”, *Australian and New Zealand journal of psychiatry*, vol.31, no.2, pp.264-272,1997.

[4] Cantello R, Tarletti R, Civardi C. “Transcranial magnetic stimulation and Parkinson's disease”, *Brain research reviews*, vol.38, no.3, pp.309-327,2002.

[5] AL-Mutawaly, Hubert de Bruin, et al. “Magnetic nerve stimulation: field focality and depth of penetration”, in *23rd Annu. Int. conf. of IEEE. Engineering in Medicine and Biology Society*, vol.1, pp.877-880,2001.

[6] Salvador R, Miranda P, Roth Y,Zangen A, “High-Permeability Core Coils for Transcranial Magnetic Stimulation of Deep Brain Regions”,in *29th Annu.EMBS Conf. Engineering in Medicine and Biology Society*, pp.6652-6655,2007.

[7] Kent D, Charles M, “Magnetic Stimulation Coil and Circuit Design”, *IEEE Trans.Biomedical Engineering*, vol.47, no.11, pp.1493-1499, 2000.

[8] P Willianms, P Marketos, et al. “New Designs for Deep Brain Transcranial Magnetic Stimulation”, *IEEE Trans.Magnetics*, vol.48, no.3, pp.1171-1178, 2012.

[9] A.L Hodgkin, A.F Huxley, “A quantitative description of membrane current and its application to conduction and excitation innerve,’’ *J. Physiol.*, vol. 117, pp. 500-544, 1952.

[10] Bourland J, Nyenhuis J, Noe W, et al. “Motor and sensory strength-duration curves for MRI gradient fields”, in *Proc.Int. Soc.Magnetic Resonance in Medicine 4th Scientific Meeting and Exhibit*, pp.1724, 1996.

[11] Davey K, Riehl M. “Designing transcranial magnetic stimulation systems”, *IEEE Trans.Magnetics*, vol.41, no.3, pp.1142-1148,2005.

[12] Qingyao Ai, Jiangtao Li, et al. “A new transcranial magnetic stimulation coil design to improve the focality”, in *3rd Int. Conf. on BMEI*, pp1391-1395, 2010.

[13] Lina Pu, Tao Yin, “Study on the coil parameter optimization method improving induced electricn focality in cranial magnetic stimulation”, *Biomedical Engineering*, vol.27, no.2, pp74-78,2008.

[14] http://www.magstim.com/products-and-applications, (accessed April 14, 2013).

[15] Jiangtao Li, Zheng Liang, “Double Butterfly Coil for Transcranial Magnetic Stimulation Aiming at Improving Focality”, *IEEE Trans.Magnetics*, vol48, no.11, pp3509-3012, 2012.