Simulation and Optimization of Transcranial Magnetic Stimulation Coil Structure

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Abstract

Transcranial magnetic stimulation is widely used in the field of neurological treatment for its non-invasive and painless effects. The figure-8 coil is a widely used stimulation coil because of its simple production and good focusing. In this paper, the induced electric field distribution of four different figure-8 coils, such as circular, triangular, square and pentagonal, is analyzed under the condition of equal coil length. The results show that the triangular coil has better electric field focusing in the target area. The circular coil field value is better in tangential distribution, and the production is simpler. The research results has certain engineering value in medical applications.

Keywords

Transcranial magnetic stimulation, figure-8 coil, focusing, induced electric field.

1. Introduction

Transcranial Magnetic Stimulation (TMS) is based on the principle of electromagnetic induction. The time-varying magnetic field is generated by the coil, and a time-varying electric field is generated in the brain to depolarize or hyperpolarize the neurons[1]. The purpose of neuronal inhibition or excitement. Transcranial magnetic stimulation is mainly composed of stimulation coil and pulse circuit. The pulse circuit generates time-varying current to stimulate the coil. Low-frequency stimulation excites neurons, and high-frequency stimulation suppresses neurons. It is widely used in depression, Parkinson's disease and nerve Sexual tinnitus, etc. treatment of neurological diseases[2-4]. The coil structure design has always been the focus of magnetic stimulation in recent years. The geometric structure, size and number of turns of the coil are important factors affecting the field distribution. Earlier magnetic stimulators were designed by Barker[5]. in 1985 on a single-circle coil. In 1988, Ueno[6] used 8-shaped coils as stimulation coils to improve field focus and was widely used in medical environments. Later, many scholars designed and improved various coil structures to improve electric field focusing, such as Slinky and improved coils [7, 8], and increased window panels[9].

In this paper, the field distribution characteristics of circular coil, triangular coil, square coil and pentagon coil are analyzed under the condition of equal coil length, which provides reference for coil structure design in medical applications.

2. Basic Theory of Transcranial Magnetic Stimulation

Transcranial magnetic stimulation is based on the principle of electromagnetic induction. The time-varying current is generated in the coil to induce a time-varying magnetic field around the coil. The time-varying magnetic field generates an induced current in the brain, and reaches the nerve threshold to achieve the purpose of making the neuron active.

The magnetic induction $\vec{B}$ generated by the coil is derived from Biot-Savart Law:

$$\vec{B} = \int_l d\vec{B} = \frac{\mu_0}{4\pi}\int_l \frac{Id\vec{l} \times \vec{R}}{R^3} \tag{1}$$

Where μ_0 =4π×10^{-7} H/m is the vacuum permeability, and I is the current in the loop, which is the position vector of the current element to any point P in space.

The induced electric field $\vec{E}$ generated by the coil can be derived from Faraday's Law of electromagnetic induction:

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{2}$$

In order to better characterize the distribution performance of the electromagnetic field generated by the coil, the Half Power Region (HPR) is usually used to quantify the degree of focus, which is usually the area where the field value is greater than 1/√2[10]:

$$E \geq \frac{E_{max}}{\sqrt{2}} \tag{3}$$

The smaller the HPR value, the better the field focus. At the same time, the Half Width Region (HWR) is defined, which is the width of the field point when the field extremum is attenuated to 1/√2, as shown in Fig. 1.

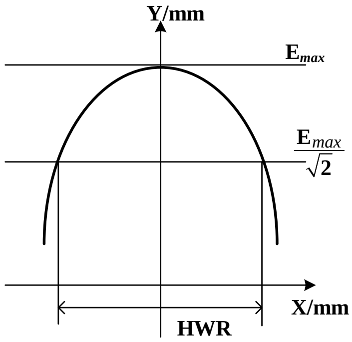


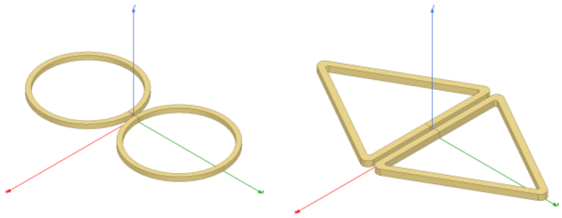
Fig. 1 Schematic diagram of the half width region (HWR)

3. Coil Structure Design and Performance Analysis

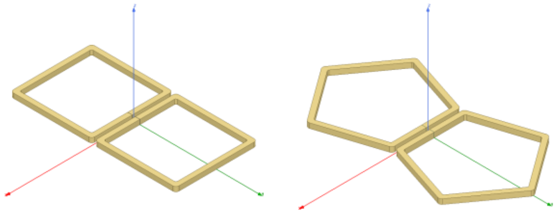
In this paper, four kinds of coils are designed as single turns, which are placed tangent to two equivalent structure coils. The specific parameters are shown in Table 1, and the structural model is shown in Fig. 2. The stimulation current I=30 A, the frequency f =10 kHz, and the target area length and width is 100 mm×100 mm at 30 mm below the coil. To characterize the electric field distribution characteristics of the target area, draw a tangential line X(y=0，z=-30) and the radial line Y(x=0，z=-30), and the half widths HWR_X and HWR_Y are analyzed. At the same time, along the Z axis, an axial line Z(x = 0, y = 0) from the origin to 50 mm below the coil is analyzed, and the field distribution is analyzed to characterize the axial attenuation.

Table 1 Figure-8 coil structure parameters

coil	Circular	Triangular	Squar	Pentagonal
Diameter(length) r/mm	30	62.8	47.2	37.6
Wire diameter h/mm	3	3	3	3



Circular coil Triangular coil



(c) Square coil (d) Pentagonal coil

Fig. 2 Coil structure model

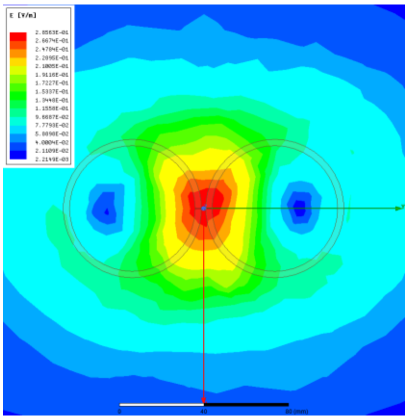


Fig. 3 Induced electric field distribution of circular coil

Fig. 3 is a diagram of the induced electric field distribution of the circular coil in the target plane. The electric field is focused at the tangent of the two coils. The field distribution of the other three coils is similar to the circular shape. We analyze the performance of each coil by analyzing the HPR of the target plane and the HWR value of the test line.

Fig. 4 shows the HPR distribution of the different structures of the coil and the HWR of the test lines X and Y. It can be seen from the figure that the half-power value of the triangular coil is relatively small, indicating that the field focusing of the structure is better; The difference in the HPR ratio of the shape, square and pentagon coil is small, indicating that the field distribution is related to the length of the tangent portion of the coil. The circular coil has a smaller HWRX, the other three coils are relatively larger, and the four coils HWRY are substantially equal, indicating that the coil structure has a greater influence on the tangential field distribution.

Fig. 5 shows the axial field distribution of the coil, which shows that the axial attenuation trend of the coil is basically the same, but the circular coil field value is stronger, followed by the pentagon, quadrilateral and triangle.

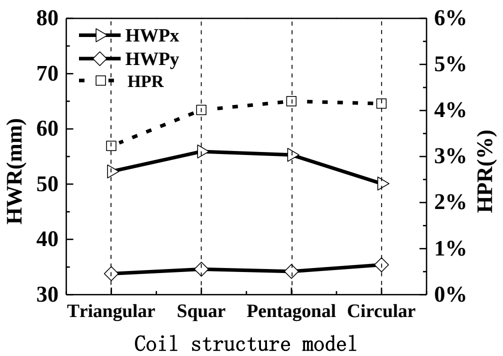


Fig. 4 Half power region (HPR) and half width region (HWR) distribution of each coil

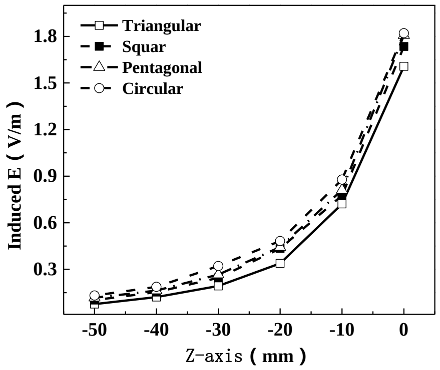


Fig. 5 Induced electric field distribution of axial Z

4. Conclusion

In this paper, the performance analysis of four different structural stimulation coils is carried out. The results show that the triangular coils have better focusing, but the field extremum is smaller; the circular coil tangential distribution HWR is smaller, and the radial distribution of the four coils is smaller. The coil structure design can consider the effect of reducing the tangential distribution to improve the focusing performance; the coils are exponentially attenuated along the axial field value, the circular coil field value is larger, and the triangular coil field value is smaller. Increasing the amplitude of the stimulation current when using a triangular coil can reduce the stimulation of the non-target area. The circular coil has an advantage in axial focusing, and the circular coil is more advantageous in consideration of the manufacturing procedure. This result has practical significance for the clinical application of the stimulation coil.

Acknowledgements

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