INVESTIGATION OF A NEW COIL DESIGN FOR MAGNETIC STIMULATION

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Abstract: Michael Faraday, was first to describe the Electromagnetic induction, producing a current in a conductive object by using a moving or time-varying magnetic field, and it is probably the most relevant experimental observation for the magnetic stimulation [6]. With it, a new research direction appeared, which has its hallmark in the modern science. This study investigates new quadruple coils for magnetic stimulation which is proposed in the study [9], trying to calculate approximately the induced magnetic and electrical fields strengths, and comparing them with those of the traditional coil, in order to establish the benefits or disadvantages of the new design.

Introduction

Typical Magnetic nerve stimulation consists of two parts: high current pulse generator producing about 5KA discharge current or more, and a stimulating coil producing magnetic pulses. The field strengths can vary between 1 to 2.5 tesla. Nowadays commercial coils, which can produce even 4 tesla are available. Pulse duration can be 1 ms, or lower.

The current flowing through the coil generates the necessary magnetic pulse which induces current in the conductive human body, if the induced current has sufficient amplitude and duration it will stimulate the neuromuscular tissue in the same way as with conventional electrical stimulation.

A large capacitor is used as an energy storage up to a desired maximum level, then the energy is transmitted to the coil by closing the circuit and allowing the current to flow into the coil. The thyristor is the switch used to close the circuit, because it can deal with large currents in few microseconds.

The most important factor in the nerve magnetic stimulation is the maximization of the peak coil energy, which can range from 500J to 10kJ stored in the capacitor and transferred to the coil in around 100ns, this rapid rate of energy transfer is necessary to achieve a rapid rise in the magnetic field strength. The resulting induced current is about 1-20mA/cm^2, which is close to the value used in conventional electrical stimulation.

The stimulation characteristics of the magnetic pulse, such as depth of penetration, strength and accuracy, depend on the rise time of the magnetic pulse peak, the magnetic energy transferred to the coil, and spatial distribution of the field. They are All governed by the electrical characteristics of the magnetic stimulator, the stimulating coil. The spatial distribution of the induced electric field depends on the coil's geometry and the anatomy of the region where the induced current flows [1] [2].

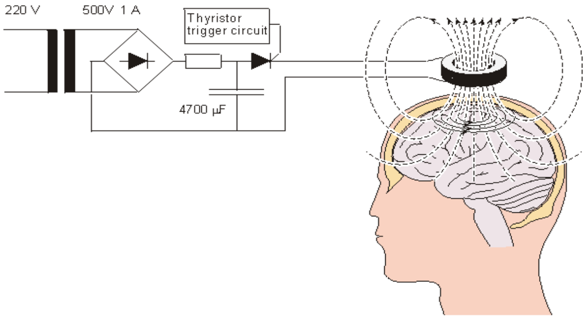

Figure 1: Illustration of a simple magnetic stimulation circuit [1]

Materials and Methods

There are some important notes about the magnetic stimulation.

In the round coils, the induced tissue current is zero or near zero at the central axis of the coil and increases to a maximum in a ring approximately under the mean diameter of the stimulation coil. Therefore, the stimulation is most likely to occur at the winding, not under the center of the coil.

Butterfly coils use two windings placed side by side. The main advantage of this model over the circular coil is that the induced tissue current is at its maximum directly under the center, where the two windings meet.

This is explained by the activating function, which has its maximum value at the points where the stimulation occurs. Activating function is the spatial derivative of the electrical field along the target tissue, which can be cellular fiber or muscular cylindrical cell. Where the activating function has negative peak, the stimulation is more likely to happen at that point, because it encourages the depolarization of the stimulated tissue, while the positive peak decreases the probability of stimulation, due to the hyperpolarization effect on the tissue and cellular membrane.

Magnetic stimulation types

There are three main types of magnetic stimulators [6]:

Conventional Recharger: it gives pulses with the time intervals of 1-5 seconds. It has high output capacity while all the energy dissipates after each magnetic pulse.

Rapid Rate: has a medium output power at repetition rate of 10-30 Hz, it must be noted that rapid-rate trains of fire armor pulses applied cortically have been shown to be capable of inducing seizures.

Pulse train: In this type, we apply a few pulses as a train pulse with a minimum of 1 ms between stimuli, then we give the tissue time to relax.

There are also three types of magnetic field output form [6]:

Monophasic: It is more accurate than biphasic, lower noise and causes lower heat, but in this mode of magnetic stimulation a bilateral cortical responses is not easy to obtain.

Biphasic: A pulse of two different polarities is applied. This mode is better to get the bilateral cortical responses, but with higher noise, and less accuracy.

Polyphasic: This mode is efficient for the bilateral cortical stimulation, but it causes the highest noise and heat and it is less accurate.

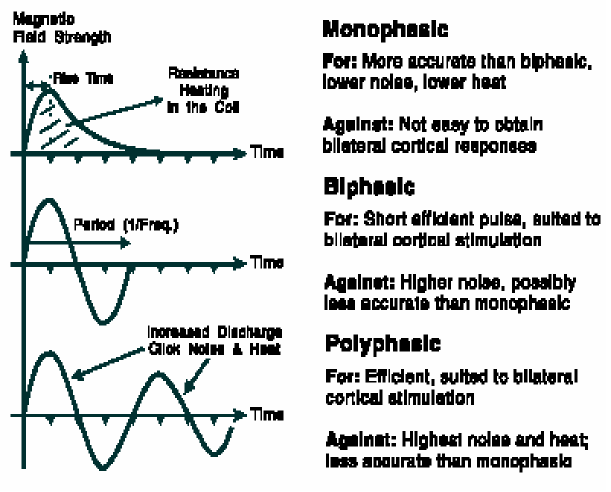

Figure 2: Three types of magnetic stimulation output [6].

Typical coils for magnetic stimulation nowadays are circular and have radius between 100-150 (mm). The component of the induced magnetic field which is perpendicular on the coil's surface is the component that penetrates through the tissue and has the stimulation effect.

The coil inductance

When constructing any efficient coil we have to check the practical properties and consideration of the coil. Let us make a look on a simple inductor that consists of one loop of conducting wire. The voltage across the inductor can be given by the next equation:

$$V/L = di/dt \tag{1}$$

L is inductance of the coil, and i is the current that passes through it.

The inductance is the property of the coil that describes the inductor, exhibits an opposition to the changes in the current flowing through it, and is measured in Henrys.

It is clear from the last equation that the rate of changing current in the coil is proportional to $1/L$, meaning that the decreasing of the coil inductance will increase the rate of the changing in the current, which will affect the changing rate of the magnetic field induced by the coil.

Almost all magnetic stimulation studies yield the same result that the efficiency of the stimulating increases by increasing the growing rate of the magnetic field, and allowing the field to reach it maximum value in a short time. This can be achieved by making the inductance smaller. The inductance of an inductor depends on its physical dimension and construction, and it is a very important factor when constructing the stimulator. The inductance equation becomes more complicated when the design becomes complicated, in our comparison we consider that the changing rate of the magnetic field is the same in both cases.

Comparison study

This paper investigates a quadruple coil design, which consists of four round small coils next to each other, looking like two butterfly coils placed next to each other. The activation function was calculated in previous study [1] for this design, and found to be similar to the butterfly coil, which means that the excitation happens at the center of the coil arrangement.

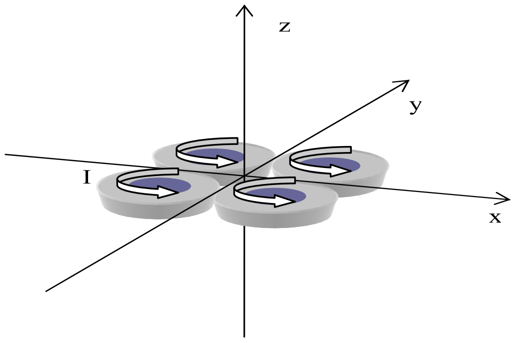

Figure 3: An illustration of the quadruple coils arrangement and the surface that encloses the magnetic field is at the center and between the four coils.

To calculate the electrical and magnetic field for a typical round coil and the new quadruple coil, it is important to find a surface that encloses all magnetic field lines which participate in the stimulation. It is well known that when the magnetic field lines cut an arbitrary surface Σ and that surface is surrounded by boundary Γ , then the transformation between the area integral of the magnetic field over the surface and the line integral of the electrical fields over it's boundary is given by the following equation:

$$\oint_{\Gamma} \vec{E}d\vec{l} = -\frac{d}{dt}\iint_{\Sigma} \vec{B}d\vec{s} \tag{2}$$

This means that in a time unit, the variation of the magnetic field through a closed surface is equal to the electrical field circulation around the boundary of that surface. The calculations are made approximately, where the real values are expected to be smaller, Considering Bmax is the maximum value of the magnetic field, and τ is the rising time for the magnetic field to reach it's maximum value.

In the case of the round conventional coil, the surface that encloses all the magnetic field lines is the loop's surface, and the boundary is the circle that has the coil's average diameter. The equation for this coil will be written as the following.

$$2\pi rE = \pi r^2 B_{\max}/\tau \tag{3}$$

r is the radius of coil and τ is the growing time of the magnetic field.

In the case of quadruple coils, we assume that the magnetic field penetrates through symmetric surface, which has the shaped of the space left at the center between the four coils. It's boundary is equal to a circular boundary of one of the four coils, which has a radius d. mean while this surface is no longer circular, it is smaller, and it's area is calculated as:

$$S = d^2(4-\pi) \tag{4}$$

While the surface of a regular circle with a radius r is equal to πr^2.

The electrical and magnetic field's equation for this arrangement is given by the following:

$$2\pi dE_q = (4-\pi)d^2 B_{q\max}/\tau \tag{5}$$

Eq, $Bqmax$ refer to the calculated electrical and magnetic field for the quadruple coil.

The current passes through the coils wires in a chosen direction to ensure that the magnetic field lines will be concentrated in the central area, and that all the perpendicular components of the magnetic field vectors on the surface will have the same direction.

The magnetic field exerts pressure on bodies, which can be described by the following Equation.

$$P = \frac{1}{2}\varepsilon E^2 + \frac{1}{2}B^2 \tag{6}$$

The direction of the pressure is perpendicular on the surface. It is about 1.25 N/m^{-2} for the usual round coil.

Results

By comparing the equations for quadruple design and the traditional round coil, it was found that:

If we want to obtain from the quadruple coils the same electrical and magnetic fields values as we obtain from the round coil, then d will be 3.7 times bigger than r, if the average conventional coil that can provide about 2T have a diameter of 5cm, then the quadruple coil design will have 40 cm as diminutions.

If we want to obtain the same electrical field from both designs, and assume that d is equal with r, then the surface S calculated for the quadruple coil is 3.7 smaller than the surface of the round coil with the radius r, and $Bqmax$ is found to be 3.7 times bigger than the $Bmax$, which increases the pressure exerted by the magnetic field on the smaller surface S up to about 14 times than the pressure on the larger surface.

If we want to obtain from the quadruple coil and the round coil the same value of the electrical field E, which is important to achieve the stimulation and make d half of r, then the value of the induced magnetic field by the quadruple coil will be about 7 times bigger than the value of the magnetic field induced by the round coil. It could be about 10T, which is a very big value applied on even a smaller surface S.

Discussion

If we want the proposed design to produce the same effect of stimulation as the round coil, then the radius of one coil from the quadruple coils has to be about four times bigger than the round coil's radius, which leads us to obtain a huge unpractical and hard to use apparatus. Reducing the radius will not be efficient, because it will produce very large field enclosed in a very small area, it is even more unpractical. In addition, changing of the stimulation frequency may be useless, because the nerve fibers have a preferable value of stimulation frequencies according to their dimensions.

Conclusions

It appears that there are serious technical challenges to achieve the focal effect in the magnetic stimulation, there is a limit for the numbers of coils that can be set next to each other to produce the desired magnetic field. A triple round coils configuration can be examined in order to find if it can focus the induced magnetic field deep in the tissue. An inclination angle can be introduced to the design to investigate the effects of the new shape and the increasing of distance between the coil center and the tissue on the focusing problem of the stimulation.

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