A Stimulation of Neural Tissue by Pulse Magnetic Signals

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***Abstract* – In this paper a theoretical and experimental investigation on stimulation of neural tissue by pulse magnetic signals is described. The experimental investigation has been done using appropriate circuit. A comparison between direct electrical stimulation of neural tissue and stimulation of neural tissue by pulse magnetic signals is done with respective conclusions and recommendations. An optimisation of parameters of used pulse magnetic signals for stimulation is done, also.**

***Keywords* – Magnetic stimulation, neural tissue, pulse magnetic signals**

I. INTRODUCTION

It's well known that the origin of the biomagnetic field is the electric activity of biological tissue. This bioelectric activity produces an electric current in the volume conductor which induces the biomagnetic field. This correlation between the bioelectric and biomagnetic phenomena is, of course, not limited to the generation of the bioelectric andbiomagnetic fields by the same bioelectric sources. This correlation also arises in the stimulation of biological tissue.Magnetic stimulation is a method for stimulating excitable tissue with an electric current induced by an external time-varying magnetic field. It is important to note here that, as in the electric and magnetic detection of the bioelectric activity of excitable tissues, both the electric and the magnetic stimulation methods excite the membrane with electric current. The former does that directly, but the latter does it with the electric current which is induced within the volume conductor by the time-varying applied magnetic field. The reason for using a time-varying magnetic field to induce the stimulating current is, on the one hand, the different distribution of stimulating current and, on the other hand, the fact that the magnetic field penetrates unattenuated through such regions as the electrically insulating skull. This makes it possible to avoid a high density of stimulating current at the scalp in stimulating the central nervous system and thus avoid pain sensation. Also, no physical contact of the stimulating coil and the target tissue is required, unlike with electric stimulation.

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II. THE DESIGN OF STIMULATOR COILS

A magnetic stimulator includes a coil that is placed on the surface of the skin. To induce a current into the underlying tissue, a strong and rapidly changing magnetic field must be geneated by the coil. In practice, this is generated by first charging a large capacitor to a high voltage and then discharging it with a thyristor switch through a coil. The principle of a magnetic stimulator is illustrated in Fig.1. The magnitude of induced electromotive force (emf) - e is proportional to the rate of change of current, *dl/dt* and to the inductance of the coil *L*. The term *dl/dt* depends on the speed with which the capacitors are discharged; the latter is increased by use of a fast solid-state switch (i.e., fast thyristor) and minimal wiring length.Inductance L is determined by the geometry and constitutive property of the medium. The principal factors for the coil system are the shape of the coil, the number of turns on the coil, and the permeability of the core. For typical coils used in physiological magnetic stimulation, the inductance may be calculated from the following equations.

III. CURENT DISTRIBUTION IN MAGNETIC STIMULATION

The magnetic permeability of biological tissue is approximately that of a vacuum. Therefore the tissue does not have any noticeable effect on the magnetic field itself. The rapidly changing field of the magnetic impulse induces electric current in the tissue, which produces the stimulation. Owing to the reciprocity theorem, the current density distribution of a magnetic stimulator is the same as the sensitivity distribution of such a magnetic detector having a similar construction. It's necessary to note that in the lead field theory, the reciprocal energization equals the application of stimulating energy. The distribution of the current density in magnetic stimulation may be calculated using the method introduced by Malmivuo (1976) and later applied for the MEG (Malmivuo, 1980). Two cases of application of single coil and quadrupolar coil configuration are described below.

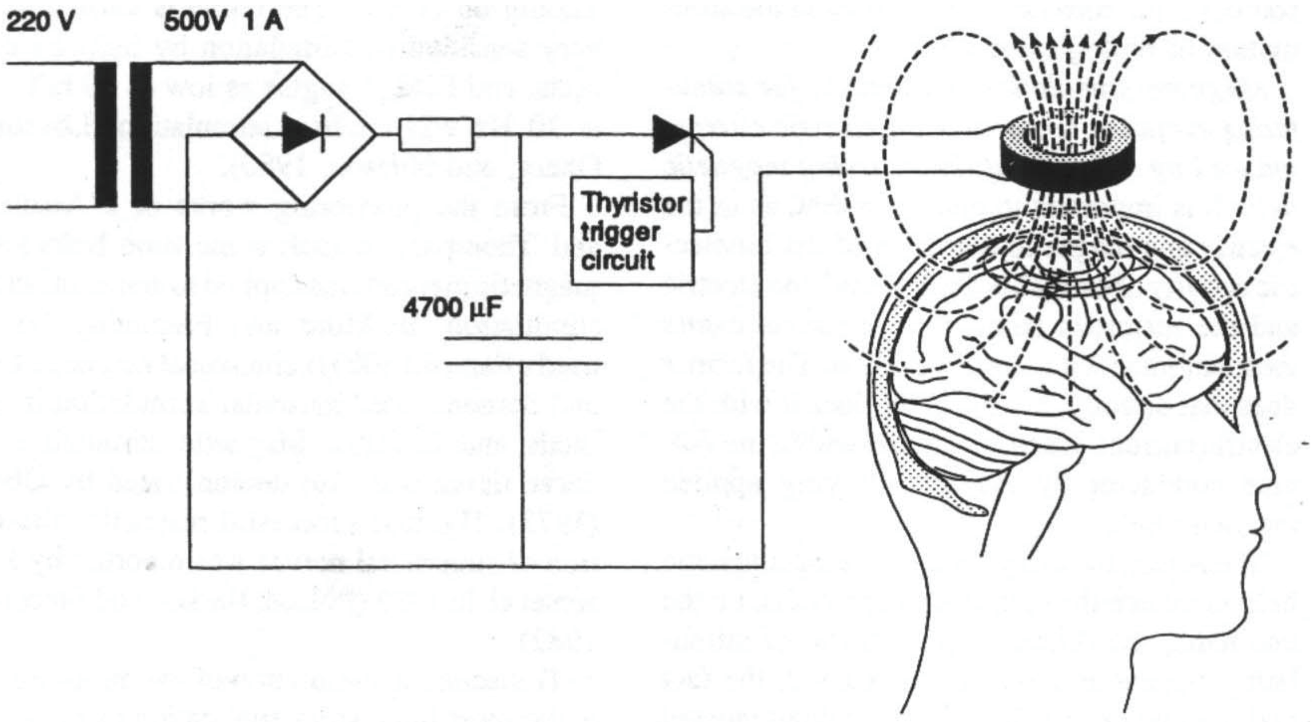

Fig.1 The principle of the magnetic stimulator

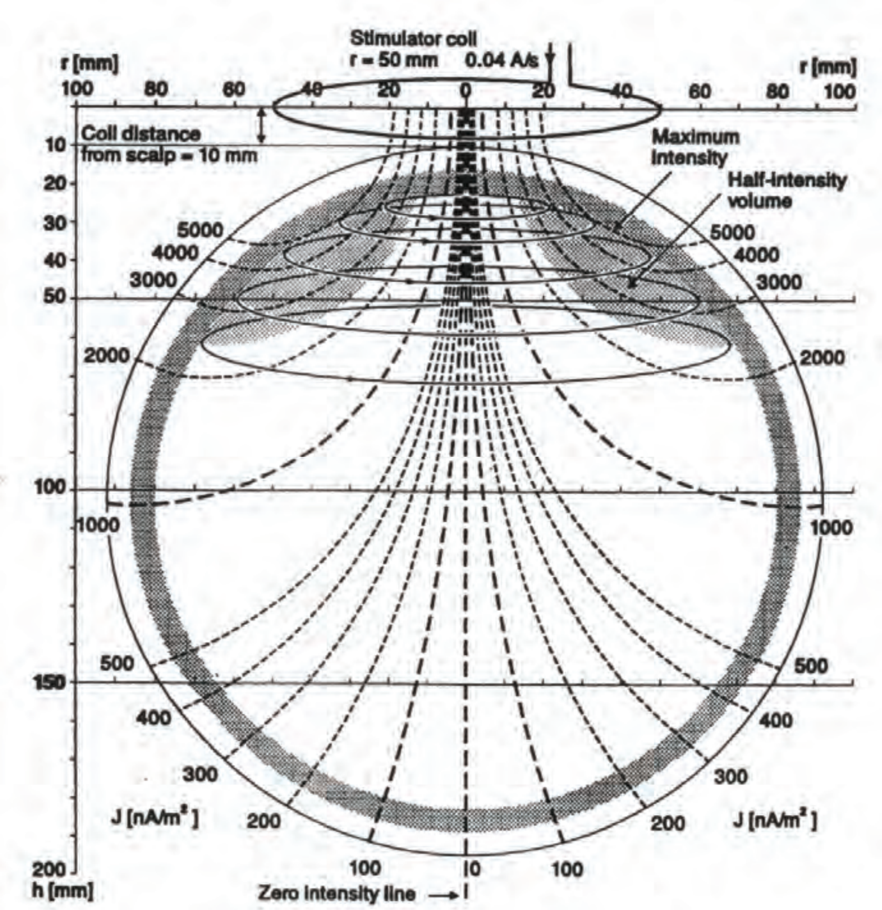

Fig.2.Isointensity lines and half-intensity volume for a stimulation coil with 50mm radius. The distance of the coil plane from the scalp is 10mm

A. Single Coil

The current distribution of a single coil, producing a dipolar field, is presented on fig.2, which illustrates the isointensity lines and half-intensity volume for a coil with a 50 mm radius. The concepts of isointensity line and half-intensity volume are reciprocal to the isosensitivity line and half-sensitivity volume. Because of cylindrical symmetry the isointensity lines coincide with the magnetic field lines.

B. Quadrupolar Coil Configuration

The coils can be equipped with cores of highly permeable material. One advantage of this arrangement is that the magnetic field that is produced is better focused in the desired location. Constructing the permeable core in the form of the letter V results in the establishment of a quadrupolar magnetic field source. With aquadrupolar magnetic field, the stimulating electric current field in the tissue has a linear instead of circular form. In some applications the result is more effective stimulation. On the other hand, a quadrupolar field decreases as a function of distance faster than that of a dipolar coil. Therefore, the dipolar coil is more effetive in stimulating objects that are located deeper within the tissue.

IV.STIMULUS PULSE

The experimental stimulator (Fig.1) has a capacitor construction equaling a capacitance of 4760 μF . This was charged to 90-260 V and then discharged by thyristor through the stimulating coil. The result was a magnetic field pulse of 0.1-0.2 T, 5 mm away from the coil. The length of the magnetic field pulse was of the order of 150-300 μs . The energy W which is required to stimulate tissue is proportional to the square of the corresponding magnetic induction B. According to Faraday's induction law, this magnetic field is in turn approximately proportional to the product of the electric field magnitude E and the pulse duration t.

$$W \propto B^2 \propto E^2 t^2 \tag{1}$$

where:

W is the energy required to stimulate tissue
B is the magnetic induction
E is the electric intensity
t is the pulse duration

The effectiveness of the stimulator with respect to energy transfer is proportional to the square root of the magnetic energy stored in the coil when the current in the coil reaches its maximum value. A simple model of a nerve fiber is to regard each node as a leaky capacitor that has to be charged. Measurements with electrical stimulation indicate that the time constant of this leaky capacitor is of the order of 150-300 μs . Therefore, for effective stimulation the current pulse into the node should be shorter than this. For a short pulse in the coil less energy is required, but obviously there is a lower limit too.

V. ACTIVATION OF EXCITABLE TISSUE BY TIME-VARYING MAGNETIC SIGNALS

The actual stimulation of excitable tissue by a time-varying magnetic field results from the flow of induced current across membranes. Without such flow a depolarization is not produced and excitation cannot result. Unfortunately, one cannot examine mis question in a general sense but rather must look at specific geometries and structures. To date this has been done only for a single nerve fiber in a uniform conducting medium with a stimulating coil whose plane is parallel to the fiber. In the model examined by Roth and Basser,
the nerve is assumed to be unmyelinated, infinite in extent, and lying in a uniform unbounded conducting medium, the membrane described by Hodgkin-Huxley equations. The transmemhrane voltage V_m is shown to satisfy the equation (2):

$$\lambda^2 \frac{\partial^2 V_m}{\partial x^2} - V_m = \tau \frac{\partial V_m}{\partial t} + \lambda^2 \frac{\partial E_x}{\partial x} \tag{2}$$

where:

V_m is transmembrane voltage
λ is the membrane space constant
τ is the membrane time constant
x is the orientation of the fiber
E_x is x- component of the magnetically induced electric intensity (proportional to the x component of induced current density)

It is interesting that it is the axial derivative of this field that is the driving force for an induced voltage. For a uniform system in which end effects can be ignored, excitation will arise near the site of maximum changing current and not maximum current itself. In the experimental investigation the coil lies in the xy plane with its center at $x = 0, y = 0$, while the fiber is parallel to the x axis and at $y = 2{,}5cm$ and $z = 1{,}0cm$. They consider a coil with radius of 2.5 cm wound from 30 turns of wire of 1.0 mm radius. The coil, located at a distance of 1.0 cm from the fiber, is a constituent of an RLC circuit; and the time variation is that resulting from a voltage step input. Assuming $C = 200\mu F$ and $R = 3\Omega$ an overdamped current waveform results. From the resulting stimulation it is found that excitation results at x = 2.0cm (or 2.0 cm, depending on the direction of the magnetic field) which corresponds to the position of maximum $\partial E_x / \partial x$. The threshold applied voltage for excitation is determined to be 30 V. (This results in a peak coil current of around 10A.) These design conditions could be readily realized.

Stimulators with short risetimes (< 60 μs) need only half the stored energy of those with longer risetimes (> 180 μs). The use of a variable field risetime also enables membrane time constant to be measured and this may contain useful diagnostic information.

VI. CONCLUSION

It's possible to do the next conclusions after theoretical and experimental investigations described above:

1.The magnetic stimulation can be applied to nervous stimulation either centrally or peripherally.

2.The main benefit of magnetic stimulation is that the stimulating current density is not concentrated at the skin, as in electric stimulation, but is more equally distributed within the tissue. This is true especially in transcranial magnetic stimulation of the brain, where the high electric resistivity of the skull does not have any effect on the distribution of the stimulating current.

3.Another benefit of the magnetic stimulation method is that the stimulator does not have direct skin contact. This is a benefit in the sterile operation theater environment.

4.It may be predicted that the magnetic stimulation can be applied particularly to the stimulation of cortical areas, because in electric stimulation it is difficult to produce concentrated stimulating current density distributions in the cortical region and to avoid high current densities on the scalp.

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