TRANSCRANIAL MAGNETIC STIMULATION OF THE CEREBRAL CORTEX

Kent Davey, Ph.D.
School of Electrical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0250

Kostas C. Kalaitzakis, Ph.D.
Electronic Engineering Department
Technical University of Crete
GR 73132 Chania, Greece

Charles Epstein, M.D.
Neurology, Emory University
1365 Clifton Road
Atlanta, Georgia 30322

ABSTRACT

Surgical resection of the epileptic focus is an effective treatment for otherwise uncontrollable epileptic seizures. Localization of cerebral function in the region of the epileptic focus is a mandatory part of the presurgical evaluation. Development of magnetic stimulation for evaluation of speech and memory is technically feasible and will lead to safer, more efficient, noninvasive evaluation of seizure surgery patients. Strategies for predicting an optimum excitation circuit and field configurations are discussed. The goal is to maximize the rate of change of the magnetic field for a minimum of 20 µs while not exceeding reasonable power requirements. The induced field level must be repeated at 15-20 Hz to maintain constant brain stimulation during the period of the test.

MAGNETIC STIMULATION OF CEREBRAL CORTEX

Transcranial electrical stimulation of the brain was developed by Merton and Morton in 1982. Transcranial electrical stimulation is precisely localized but painful. Magnetic brain stimulation (MBS) was introduced in 1985, and is relatively painless, but the induced cerebral currents are more difficult to localize. Thus far MBS has been used exclusively for evaluating motor pathways in brain and spinal cord. No significant complications of MBS have been described; nor are they expected, given previous experience with direct electrical stimulation of the cortex at surgery and with electroconvulsive therapy of depression. Present magnetic stimulators utilize a round coil approximately 4 inches in diameter. Coil currents of 6,000 A peak and 0.1 ms duration are delivered by capacitive discharge, producing changes in cerebral neuronal potentials over approximately 40 ms. Other coil shapes are being investigated for the possibility of producing a more precisely directed field. Noninvasive functional mapping will require delivery of a higher induced current to a more precisely defined area than is possible with the current first-generation stimulators. The key issue at hand is the change in magnetic field/unit time, since this governs the induced electrical current.

FIELD CONFIGURATION

It is thought that perhaps the best field configuration is one which would allow the field to penetrate into the head 4 cm with as small attenuation as possible over an area of 16 cm^2. The time rate of change of the magnetic field (dB/dt) must be at least 5×10^4 tesla/s for 10-20 µs. Stimulation at this induced field strength for a period longer than 20 µs is unnecessary and wasteful; the cells will either fire or not fire depending on whether the electric induced field level is sufficient. A key concern is the focusability of the magnetic field. Because the magnetic field levels are quite high, tests to date have not employed magnetizable media. In this case, one is limited basically to a standard dipole or quadrapole field with a characteristic $1/r^3$ or $1/r^4$ field decay and focusing over a halfplane quadrant or octant, respectively. Nickle cobalt cores do not saturate until about 2.5 tesla and can be used to greatly enhance focusing capability for the same current. The problem lies in how to utilize a focused field. Figure 1 is one attempt at forcing the field in a tightly focused pattern into the cranial region using shaded pole effects. The conducting ring in the gap inhibits flux penetration during the transient; proper shaping of the ring can yield an induced field which has a small spatial spread pattern.

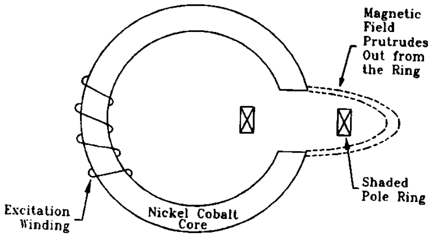

Figure 1. Excitation Coil which Employs the Shaded Pole Effect to Force the Magnetic Field of the Nickel Cobalt Core away from the Gap in a Tight Pattern

CIRCUIT DESIGN CONSIDERATIONS

The principle of operation of the magnetic stimulation device is shown in Fig. 2. The circuit consists of two main loops: the charging loop (I_c) and the discharging loop (I_L). At the beginning of each operating cycle, Switch 1 is closed, while Switch 2 is open. The capacitor is charged to the peak DC voltage provided by the Adjustable Power Supply. Then Switch 1 is opened and Switch 2 is closed. The capacitor C discharges quickly through the excitation coil L yielding a high dB/dt. When discharging is completed, Switch 2 is opened again and after a short delay, Switch 1 is closed again and the above procedure is repeated.

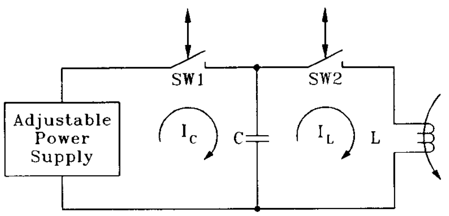

Figure 2. Simplified Diagram of the Magnetic Stimulation Device.

The following conflicting design aspects need to be considered in the selection of components:

1. The magnetic induction rate of change must be as high as possible. The induction rate is given by the relation $dB/dt = V_o/AN$, where B is the induction, V_o is the peak charging voltage, A the effective area of the coil, and N the coil turns. Thus, the charging voltage should be high, while coil area and turns have to be kept low. This argues for a low coil inductance L.
2. Larger inductance coils allow a concentration of the field. This is desirable since it focuses the stimulation region and realizes a large dB/dt with less current.
3. The duration time of the current pulse through the coil must not be lower than about 15-20 µs or it will not be able to fire the neurons. Thus, the product LC has a minimum lower limit.
4. The power consumption of the device is high and depends on the capacitor value C and the square of the charging voltage V_o. To maintain continuous stimulation, the process repetition frequency must be greater than 15 Hz. To keep the power consumption within reasonable limits, the values C and V_o have to be kept as low as possible.
5. The peak charging current and the peak discharging current must both be low enough to maintain the voltage limits of Switches 1 and 2. The same applies for the charging voltage.

A computer program modeling the circuit performance is used to estimate the proper values of the components of the circuit based on the above criteria. Figure 3 illustrates the block diagram of the implemented configuration. The high voltage power supply provides the charging voltage at its output. The charging circuit shapes the charging current and reduces the waste power to a minimum. Switch 1 conducts the charging current to the capacitor, while Switch 2 commutates the discharging current through the coil. The two electronic switches are controlled by a timing circuit, consisting of a free running multivibrator and a pulse sequencing circuit. The pulse related with Switch 1 remains "ON" about 80% of the repetition period (15-20 Hz). The control pulse for Switch 2 is narrow and appears when the Switch 1 pulse is in its "OFF" state. The sequential operation of the switches results in an effective reduction of the dissipated energy. The double lines in the figure denote the power flow, while the single lines denote the control signal flow.

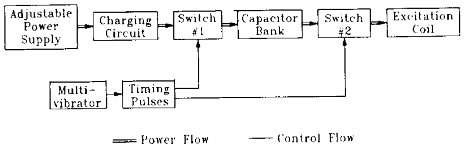

Figure 3. Block Diagram Illustrating the Operation of the Overall Configuration

The detailed electronic diagram of the proposed device is depicted in Fig. 4. A rectifying bridge converts the AC transformer (not shown) voltage to DC. A high power resistor connected in series with an appropriate coil shapes the waveform of the charging current to minimize wasted power. The high voltage transistor (BU500) serves as Switch 1. The diode across the capacitor prevents reverse charging of the capacitor due to the oscillation of the LC circuit. This further reduces the dissipated power. A thyristor (2N4377) in series with the coil serves as Switch 2.

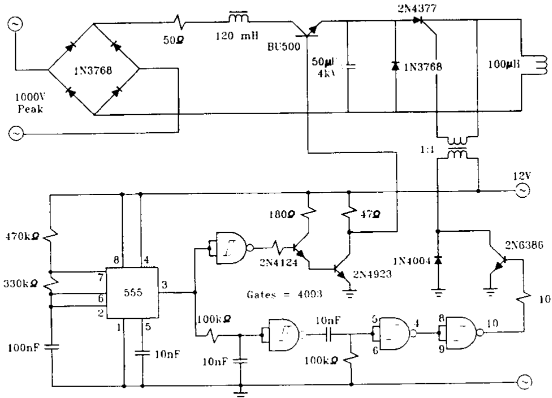

Figure 4. Detailed Electronic Diagram of the Experimental Configuration

The multivibrator is built around the integrated circuit 555, while the timing pulses are produced by four Schmitt triggered NAND gates (4093). The transistor stages boost the pulses' power to a level sufficient to drive the transistor and the thyristor. The 1:1 transformer isolates the low signal lower part of the circuit from the high power upper section.

With the values of the components set as marked in Fig. 4, the magnetic induction rate is 50,000 Teslas/µs, the current derivative duration time is 86 µs, the peak coil current reaches 900 A, the power dissipated on the charging resistor is 260 W, and the total consumed power is 640 W. The peak charging current remains below 11 A, and the operating frequency is set to 15 Hz. These ratings are satisfying for both the effective brain stimulation and good operation of its electronic components.