

# **BIOMAGNETISM:** **Applications & Theory**

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This paper is not presented in a refereed journal, but only as part of a conference proceeding. Nevertheless, it is believed this is the first presentation of the TMS (transcranial magnetic stimulation) idea.

FEASIBILITY OF A MAGNETIC STIMULATOR  
FOR THE BRAIN

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ABSTRACT

A design is presented for a non-invasive stimulator for a localized area of the cortex. This design overcomes several problems which would be present if attempting to stimulate by applying a current pulse directly through electrodes mounted on the scalp.

KEYWORDS

Non-invasive, magnetic stimulator, neural stimulation, induced current, current pulse.

INTRODUCTION

A non-invasive stimulator of the brain which is localized would have many clinical and research applications. For example, clinically it could be used to map functional sites before brain surgery, or to define a site of an epileptic focus by precipitating a discharge, where both procedures are now performed only on the exposed brain. In research it could be used to localize brain functions such as control of motor systems and motivational states, now only possible with implanted electrodes. Unfortunately, non-invasive stimulation of the cortex by passing a current pulse directly through scalp electrodes is not used on humans, because of three major problems. However, a magnetic stimulator, which is placed very near the scalp and induces a current pulse in the brain, should reduce some of these problems and could be successful. The purpose of this paper is to suggest a design of a magnetic stimulator, and theoretically show its feasibility. While a reduced experimental model has been used only for some electrical tests, a model which actually stimulates has not yet been built.

Two major problems in stimulating the cortex non-invasively with electrical current generally would be both the pain (electrical shock) and damage (mostly heat) in the tissues along the current path to the cortex; this is because in any method, using either scalp electrodes or a magnetic stimulator, the current density generally increases with approach from the cortex to the scalp surface. The special problem of damage to the target area itself has been largely solved by using an opposing pulse-pair (Lilly, 1954). In addition to the pain and heat problems, there is the third problem of current localization in the cortex; either with electrodes or magnetically, the current in the cortex cannot be "focussed" and the larger the cortical area of stimulation, the less useful is the stimulator. Because of these

three problems, non-invasive stimulation via scalp electrodes has been studied almost always in animals (Gualtierotti and Paterson, 1954). However, there have recently been experiments on the human head where the application of an extremely short high-voltage pulse appears to have produced some cortical stimulation without uncomfortable shock (Merton and Morton, 1980), although the stimulation was not well localized.

A magnetic stimulator is proposed here which would reduce both the heat and the localization problems. The stimulator would consist of a one-turn coil of small diameter but thick wire placed on the scalp over the cortical area to be stimulated. A pulse of large current would be passed through the coils; this would induce a localized pulsed current through the cortex. The heat problem would be alleviated because there would be almost no current induced in the high-resistivity regions (skin, skull). As shown by lead field studies (Cuffin and Cohen, 1979), the current induced magnetically would be more localized than that produced by surface electrodes. Although there has been a previous report on magnetically induced currents in the brain (Rentsch, 1966), this was for the purpose of electrosleep where a large coil was used over the human head, hence there was no cortical localization or attempt at alleviating the heat or pain.

#### GENERAL DESIGN

The idea here is to magnetically induce enough current density in the cortex for stimulation, with the current as localized as possible. These are opposing requirements; a large coil on the scalp would be most efficient for the former, while a small coil (or several small loops in opposition) would be efficient for the latter. Calculations show that a single, small coil should do the job, and the general design is shown in Fig. 1. Flux compressors have been utilized

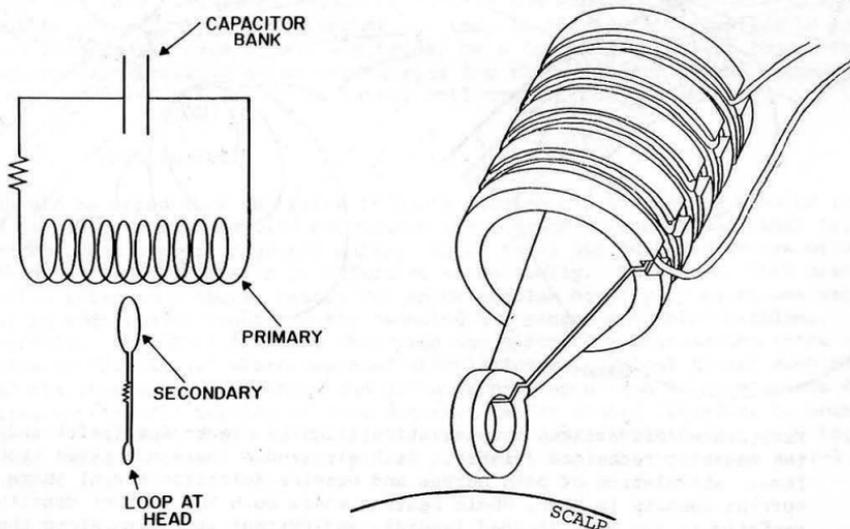


Fig. 1. Right: Sketch of the coil unit, called a flux-compressor. The entire unit is machined from one piece of metal. A low-current pulse in the primary, shown as 12 turns placed in four grooves, is efficiently converted into a high-current pulse in the one-turn loop (2 cm diameter) at the scalp. Left: Equivalent circuit of flux-compressor and power source, which is a capacitor bank.

previously at the Magnet Lab for high-field purposes, and their technology is well understood. The primary winding is on the outside, the secondary winding is the metal cylinder itself, and the load is the loop at the end. Therefore, this is a device for impedance matching the capacitor bank to the final loop, where only a low-current line need be used from the capacitor bank to the unit; this is important because the capacitor bank is bulky and hence will be located some distance from the subject. The way this design alleviates the heating problem, and produces localization, is shown in Fig. 2. For emphasis, the differences between electrode and magnetic current loops are here exaggerated. The two main points are that magnetically there is far less ohmic heating and there is far less spread of current in the cortex.

#### SOME DETAILED CALCULATIONS

It has been estimated (Fry, 1968) that the necessary charge density for cortical stimulation is  $Q = 0.064$  coulombs/m<sup>2</sup>; on several grounds this appears to be too conservative, and instead I chose  $Q = 0.030$  coulombs/m<sup>2</sup>. The charge transfer is assumed to take place during  $t = 100$   $\mu$ sec. Therefore, the current density  $J = Q/t = 3 \times 10^2$  amps/m<sup>2</sup>. Now the electric field amplitude  $E = J\rho$ , where the resistivity  $\rho = 1.5$  ohm-meter, therefore for stimulation  $E = 450$  volts/meter in the cortex. Assuming the stimulation takes place 1 cm below a loop of 2 cm radius,

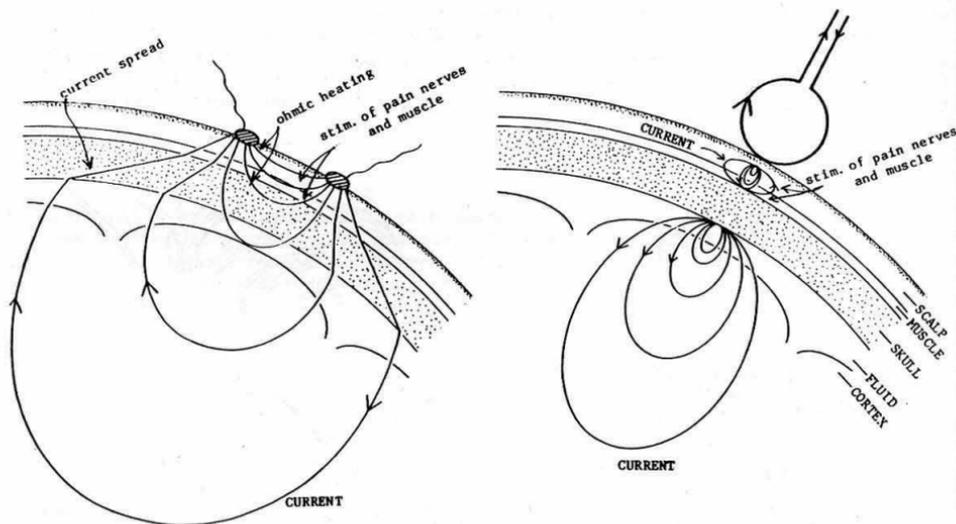


Fig. 2. Exaggerated differences between stimulation by electrodes (left) and by the magnetic technique (right). With electrodes there are three problems: stimulation of pain nerves and muscles (electric shock) where the current density is high, ohmic heating where both the current density and resistivity are high (shaded layers), and current spreading along the cortex due to the high resistivity of the skull. In the magnetic method, the pulsed magnetic field (not illustrated) induces a current in the low-resistivity areas. Because almost none of this current flows in the high resistivity layers (zero current is shown for emphasis), the heating problem is greatly reduced. Also, there is no current spreading because spherical shells do not magnetically affect each other.

this yields a rate of current change in the loop of  $di/dt = 2.8 \times 10^9$  amps/sec. Therefore the final current level after 100  $\mu$ sec is  $2.8 \times 10^5$  amps, and the magnetic field amplitude at the loop center is 9 Tesla. This current and field may appear to be high, but are certainly attainable when a capacitor bank is fired through a single small loop. This has routinely been done at the Magnet Lab in firing projectiles electromagnetically. However, the single-turn coil must be strong, hence designed and machined with care; Be-Cu is the alloy of choice. The entire design appears to be feasible.

Some verification of the flux-compressor design was obtained by performing some measurements with a "scrap" flux compressor, of reduced strength so that no actual stimulation was possible. Firing a capacitor bank through the coil and measuring the pulsed field in and around the loop showed that the electrical engineering principles were indeed sound; for example, essentially all the flux generated in the primary was transferred to pass through the loop.

#### SPATIAL LOCALIZATION

For our purposes here, we can define localization as the effective area of stimulation in the cortex, say bounded by the half-value of E. The improvement in localization of this magnetic design over electrodes can be seen by examining the lead fields in Cuffin and Cohen (1979). By the definition of lead fields, stated there, the lead field distribution is exactly the same as the distribution of the induced E, due to either electrodes or to coils which are parallel to the head. For the case here of a single erect (non-parallel) coil, the induced E can be estimated from the lead field of the closely related case of two opposing parallel coils. This should be compared to that of the single electrode; although two electrodes are actually used in stimulation, they are far enough apart (to avoid local effects) so that the lead field more resembles that of the single electrode. In this estimate, the area of stimulation of the loop is considerably smaller on the cortex than is the area of one electrode, by a factor of at least four. This advantage is maintained after corrections for the proximity of the second electrode and the increased spacing of an actual coil center from the scalp.

#### FINAL REMARKS

It should be noted that the first or shock problem can perhaps be handled in the same way as is suggested with electrodes (Merton and Morton, 1980); that is, by a stronger but shorter magnetic pulse. If it turns out to be effective with electrodes, then it should also be effective magnetically. Therefore, this design of magnetic stimulator should handle the shock problem equally to electrode stimulation, in addition to significantly reducing the second and third problems. Physiologically, it should be noted that with any electrical stimulation there is the problem of "kindling," where repeated stimulation of cortical tissue appears to lower its stimulation threshold and produces predisposition to spontaneous firing. Initial and careful testing of this magnetic device should therefore be done in laboratory animals, with collaboration of electrophysiologists, not only to evaluate the improvement in the three stated problems, but also to assess neural phenomena such as kindling.

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