Localized stimulation of neural tissues in the brain by means of a paired configuration of time-varying magnetic fields

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A method of localized stimulation of the human brain is proposed. The basic idea is to concentrate induced eddy currents locally in the vicinity of a target in the cortex by a pair of coils which are positioned outside the head so that time-varying magnetic fields pass through the head in the opposite directions around a target. The eddy currents induced at the target are expected to flow together, which results in an increased current flow at the target. Spatial distributions of induced eddy currents are calculated in cubical and spherical volume conductor models by a finite element method. The results show that the current vectors make themselves two vortexes which flow together at the target. The current density at the target makes a peak which is higher by 2–3 times than current densities at nontarget regions. The validity of the proposed method is demonstrated by experiments using frog nerve-muscle preparations.

INTRODUCTION

As part of diagnoses of neurological diseases, and as part of an investigation of the central nervous system, studies on magnetic stimulation of the human cortex have been recently reported.[1–8] Effects have been made to observe the presence or absence of responses of muscle action potentials to the stimulation of the motor cortex, and to measure conduction time, latency of the electromyographic (EMG) responses, and other parameters. Single coils are used for these purposes. Current pulses are passed through a single coil placed outside the head, and eddy currents induced in the head by the pulsed magnetic fields serve to stimulate the brain. However, the previously reported method can be dangerous, as it causes broad areas of the brain to be stimulated simultaneously.

In the present report, we propose a new method of magnetic brain stimulation which alleviates this shortcoming. By employing a pair of oppositely connected coils, the current densities induced in the target area of the brain can be raised. Numerical calculations for a three-dimensional model have shown that localized stimulation of the brain is possible. An experiment has also been demonstrated to verify this method using frog nerve-muscle preparations.

PRINCIPLE OF LOCALIZED STIMULATION

Figures 1 and 2 show the principle of localized stimulation of the brain. The basic idea is to concentrate induced eddy currents in the target area by a pair of time-varying magnetic fields. A pair of coils are positioned outside the head so that time-varying magnetic fields $B_1(t)$ and $B_2(t)$ pass through the head in the opposite directions around the target which should be stimulated. The induced eddy currents J_1 and J_2 are expected to flow together. This convergence of eddy currents acts to raise the current densities in the target area where depolarization of neural tissues can be caused. In practice, either air coils or coils with magnetic cores are used.

This method is an application of our previously proposed method for localized hyperthermia to magnetic brain stimulation.[9,10]

CALCULATED RESULTS

The human head is modeled by a spherical conductor of a dimension 12.0 units in diameter with a uniform conductivity. The surface of the sphere is represented by 58 planes, as shown in Fig. 3.

A pair of coils of a dimension 2.0 units in diameter are positioned outside the head at $X = 0.0$, $Y = \pm 2.0$, and $Z = 6.0$ units. These coils generate magnetic fields in the opposite directions when currents are applied to the coils in the opposite directions.

The distributions of eddy currents in the conductor can be calculated using a finite element method. The quasispherical conductor with 58 surface planes is divided into 5504 small elements of tetrahedron.

The calculated results are shown in Figs. 4 and 5. Figure 4 shows current distributions induced in cross sections at $Z = 5.125$ and 3.5 units. The current vectors make themselves two vortexes which flow together at the target between coils, thereby eddy currents are concentrated in the target area.

Figure 5 shows current distributions induced in X-Z cross section at $Y = 0.5$ units and in Y-Z cross section at $X = 2.5$ units. The current density decreases with the increase in depth from the surface. It is understood that the

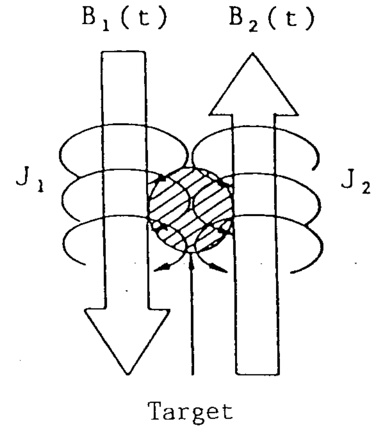

FIG. 1. Principle of localized stimulation. Magnetic fields $B_1(t)$ and $B_2(t)$ are applied in the opposite directions around the target area.

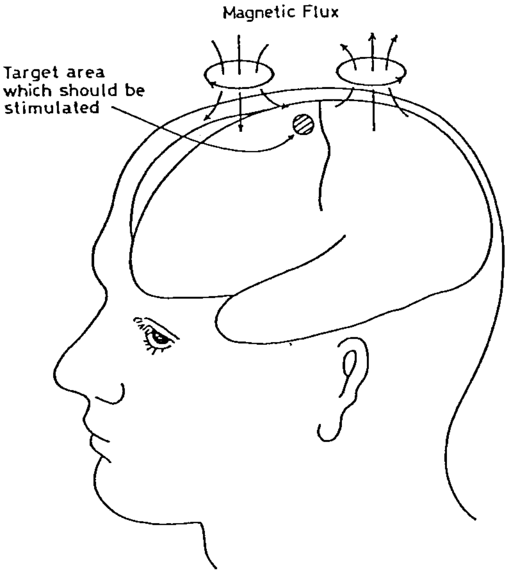

FIG. 2. Principle of localized stimulation of the cortex. A pair of coils are placed outside the head so that the magnetic fields pass through the head in the opposite directions around the target.

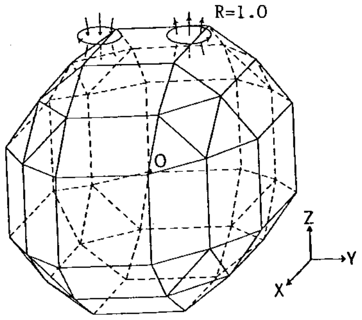

FIG. 3. A quasispherical volume conductor and paired-coil configuration. The surface of the sphere is scraped out into 58 planes.

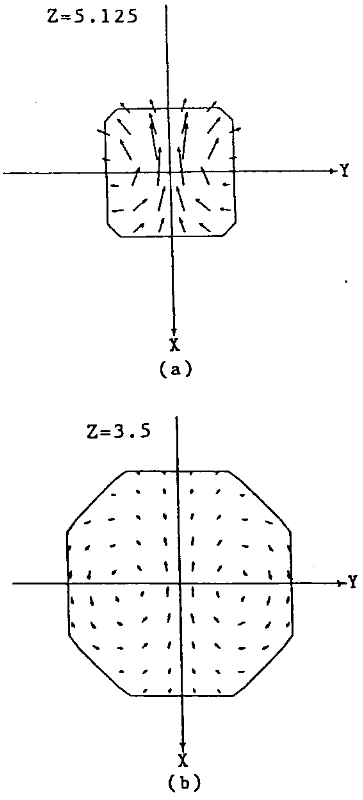

FIG. 4. Distributions of eddy currents in cross section on X-Y plane produced by a pair of one-turn coils.

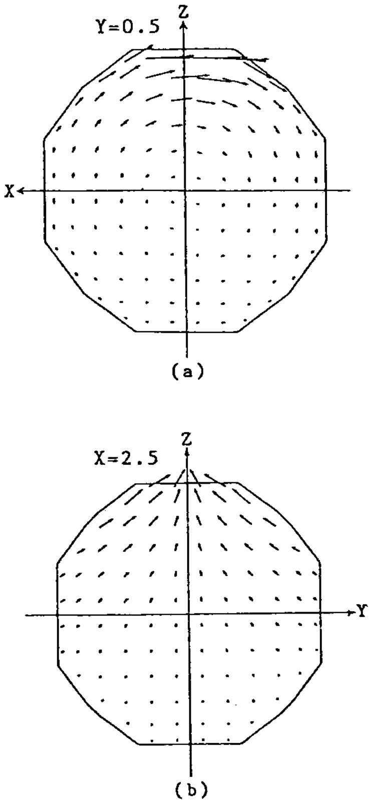

FIG. 5. Distributions of eddy currents in cross section on (a) X-Z plane and (b) Y-Z plane produced by a pair of one-turn coils.

current density is higher only at the target near the surface of the head.

The effect of distance between coils on the current density induced at the target is also investigated.

For simplicity, a cubical model of a dimension 10.0 units on a side with a uniform conductivity is used for this study.

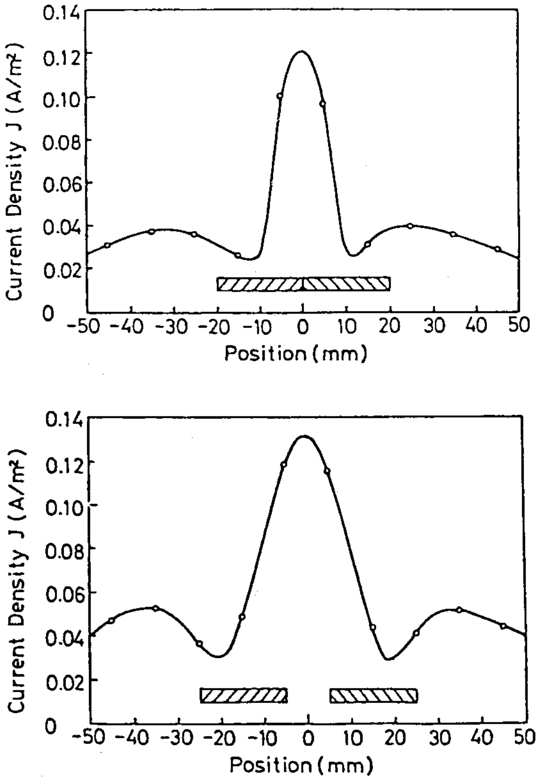

FIG. 6. Changes of current density with the distance between coils.

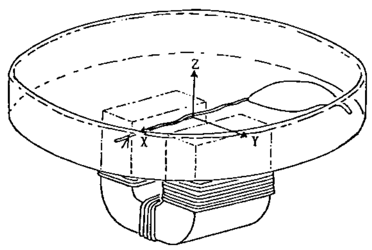

FIG. 7. Magnetic stimulation of a frog nerve-muscle preparation.

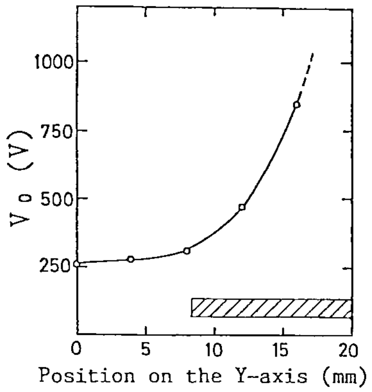

FIG. 8. Change of capacitor voltage V with the position of nerve trunk on the Y axis. The curve indicates thresholds for nerve excitation. The nerve trunk was shifted from $Y = 0$ to 15 mm in Fig. 7.

A pair of coils of a dimension 2.0 units in diameter is positioned at $X = 0.0$, $Y = \pm 2.0$, and $Z = 6.0$ units.

Let us calculate eddy current densities on the Y axis assuming that the resistivity $\rho = 1/\sigma = 3\ \Omega$ m, current in the one-turn coils $I = 1.0$ kA, frequency $f = 1.0$ kHz, and 1 unit $= 0.01$ m.

Figure 6 shows the results. The current density at the target between two coils, marked with a hatched pattern, makes a peak which is higher by 2–3 times than current densities at nontarget regions. The ratio of peak value at target to values at nontarget increases with decrease in distance between coils, and the ratio is the highest when the coil distance is zero.

EXPERIMENTAL RESULTS AND DISCUSSION

To demonstrate the validity of the proposed method, an experiment was carried out using frog nerve-muscle preparations. The nerve-muscle preparation was put in a nerve chamber filled with Ringer's solution, and the chamber was positioned over a U-shaped core, as shown in Fig. 7. The U-shaped 50% Fe-Ni magnetic core of which the sectional area 16×40 mm^2 is the distance between poles 16 mm, and a winding of 60 turns, was used. The core was driven by discharge of capacitor bank through a thyristor switch.

The circuit parameters of the capacitor 118–470 μF, inductance of the coil 566 μH, and the capacitor voltage 260–800 V gave a discharged current of a 100–500 A peak and 0.1–1.0 ms duration. This discharged current drove the magnetic core which generated time-varying magnetic fields of 0.25–1.22 T.

Figure 8 shows the change of capacitor voltage V_0 with the position of nerve trunk on the Y axis. The curve indicates thresholds for nerve excitation. The nerve trunk was positioned over the magnetic core, parallel to the X axis, and the magnetic nerve stimulation was performed. When the nerve was positioned in the area between magnetic poles, the nerve was excited by a capacitor voltage $V_0 = 260$ V, and muscle contraction was observed. In contrast, when the nerve trunk was positioned outside the magnetic poles, the nerve trunk was unable to be stimulated even by a three times of capacitor voltage $V_0 = 750$ V.

ACKNOWLEDGMENTS

The authors wish to thank Professor Y. Oomura and Professor N. Akaike for their valuable discussions, and S. Hayamizu and S. Saruwatari for their assistance.

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