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Transcranial magnetic stimulation: Improved coil design for deep brain investigation

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This paper reports on a design for a coil for transcranial magnetic stimulation. The design shows potential for improving the penetration depth of the magnetic field, allowing stimulation of subcortical structures within the brain. The magnetic and induced electric fields in the human head have been calculated with finite element electromagnetic modeling software and compared with empirical measurements. Results show that the coil design used gives improved penetration depth, but also indicates the likelihood of stimulation of additional tissue resulting from the spatial distribution of the magnetic field. © *2011 American Institute of Physics*. [doi:10.1063/1.3563076]

I. INTRODUCTION

Transcranial magnetic stimulation (TMS) is a noninvasive method for activating neurons in the brain. The technique has been used to study brain function and is utilized for a variety of diagnostic and therapeutic applications for psychiatric disorders and neurologic diseases.[1,2] Coils typically used for TMS are circular or "figure-of-eight" shaped and are presently limited to inducing stimulation in superficial cortical regions of the brain due to field intensity reducing rapidly with distance from the coil.[3,4] The ability to produce an electric field of sufficient magnitude to initiate an action potential at depth in the brain would enable further applications of the technique. Focal stimulation at depth in the brain is not possible due to physical constraints, but a reduction of the decay of the field as a function of distance from the coil offers significant opportunities for stimulation of subcortical regions, without which TMS will cause discomfort due to direct activation of muscles and nerves in the scalp.[5]

A coil design, the "Halo coil"—a large circular coil capable of being placed around the head—has been developed to increase the magnetic field at depth in the brain if used together with the existing circular and "figure-of-eight" coils typically used for TMS. The design has been optimized using finite element modeling (FEM) software incorporating both homogeneous and more realistic heterogeneous head models. The Halo coil improves the penetration depth of stimulation by allowing more energy to be deposited into regions that are deeper in the brain, thus enabling the stimulation of subcortical regions that are not reachable with available commercial coils without encountering adverse physiological effects.

Figure 1 gives an overview of the Halo coil, the circular coil, and heterogeneous MRI-derived head model of an adult male. The Halo coil has inner and outer radii of 138 and 150 mm, respectively, and for this simulation we used only five turns. In this study the Halo coil is operated simultaneously with a typical circular coil of mean diameter 90 mm and 14 turns located 100 mm above the Halo coil. A constructed Halo coil was found to have an inductance of 17.966 μH at a frequency of 10 kHz and a resistance of 0.048 Ω.

In this study, the Halo coil was used together with a circular coil, as it provides less decay of field as a function of distance than a conventional "figure-of-eight" coil.[3] A "figure-of-eight" coil can alternatively be used together with the Halo coil to increase localization of stimulation at the expense of penetration depth.

II. DETAILS OF THEORETICAL AND EXPERIMENTAL ANALYSIS

FEM calculations have been performed using SEMCAD X software,[6] as it contains a low frequency solver specified for solving biomedical problems based upon the magneto-quasi-static method for solving electric field. The 3D human head model primarily utilized in this study is the Standard Anthropomorphic Model (SAM), originally developed by the EUREKA project SARSYS, a European Collaborative Research Programme.[7] Previous studies in TMS coil design have relied on simplified spherical homogeneous volume conductors for head modeling purposes despite evidence that tissue heterogeneity and anisotropy have a significant effect on the electric field induced in the brain.[8] As such, a more realistic heterogeneous head model was also obtained from the IT'IS Foundation. This realistic model, as shown in Fig. 1, was generated from MRI data of a 34-year-old male adult, comprising 44 separated tissues, with a spatial resolution of 0.5 mm, for which electric parameters can be individually applied. This model is useful for accurately predicting the

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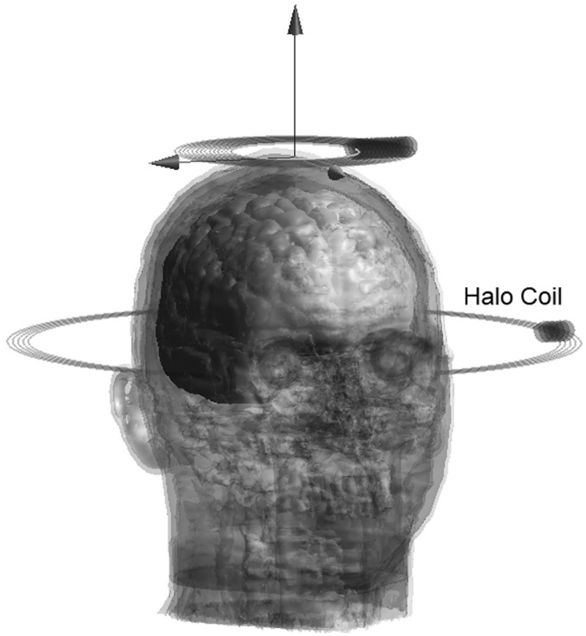

FIG. 1. Halo coil and 90 mm circular coil with heterogeneous MRI-derived head model of an adult male.

site of neuronal stimulation during TMS due to the variation in conductivities of the different brain tissues.[9]

The models incorporated a sinusoidal magnetic flux density with a frequency equal to 2381 Hz and a current of 5 kA where stimulator output was specified at 100%. SAM head model properties for conductivity, relative permittivity, and relative permeability were set to 0.33 S/m, 11 000, and 1.0, respectively. Magnetic field mapping was performed on a constructed Halo coil, using a Gaussmeter and axial probe with an active area of 0.46 mm^2 and a bandwidth equal to dc-20 kHz, supported by a multiaxis positioning scanner system with a movement precision of 0.01 mm. The coils were energized using a Magstim Rapid stimulator[10] set to 50% or 100% output. These experimental measurements were compared with FEM calculations of magnetic field in free space using the software program MAGNET.[11]

III. RESULTS AND DISCUSSION

The magnetic field generated by the circular 90 mm coil operated alone and with the Halo coil in the central coronal slice of the head model was studied for comparison, with the vertex of the head located at 0 m on the z axis, and the current loops of the circular coil being 3 mm above and the current loops of the Halo coil being 97 mm below the surface of the head. The decay rate of magnetic field along the coil axis was reduced and the spatial distribution was changed as a result of using the Halo coil.

The magnetic field strength of the Halo coil at 20 and 40 mm below the vertex of the head is shown in Fig. 2. In both instances the magnetic field was increased in deeper regions of the head compared with the magnetic field produced by the circular coil when operated alone.

The electric field induced inside the head model gives a greater indication of the site of stimulation than the magnetic field. Figure 3 shows electric field distributions for the central coronal slice of the head model. In the design with the Halo coil, it is seen that higher field intensities are present at depth in the head model, but also that high field intensities are present at the periphery of the model.

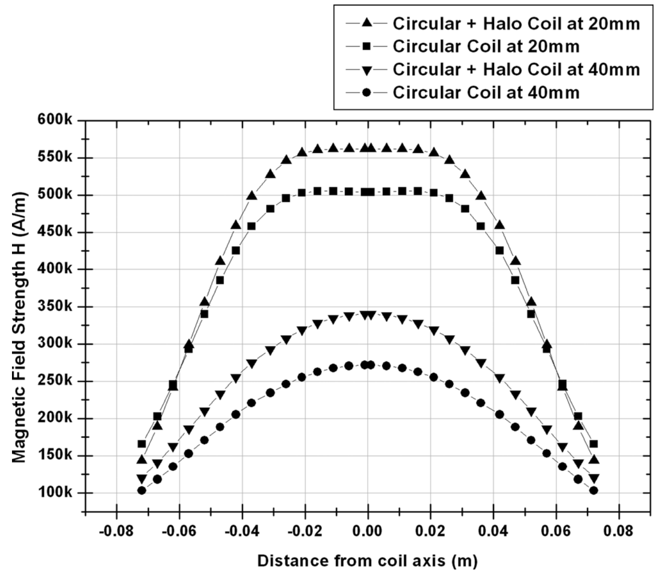

FIG. 2. Calculated magnetic field at 20 and 40 mm below the vertex of the head.

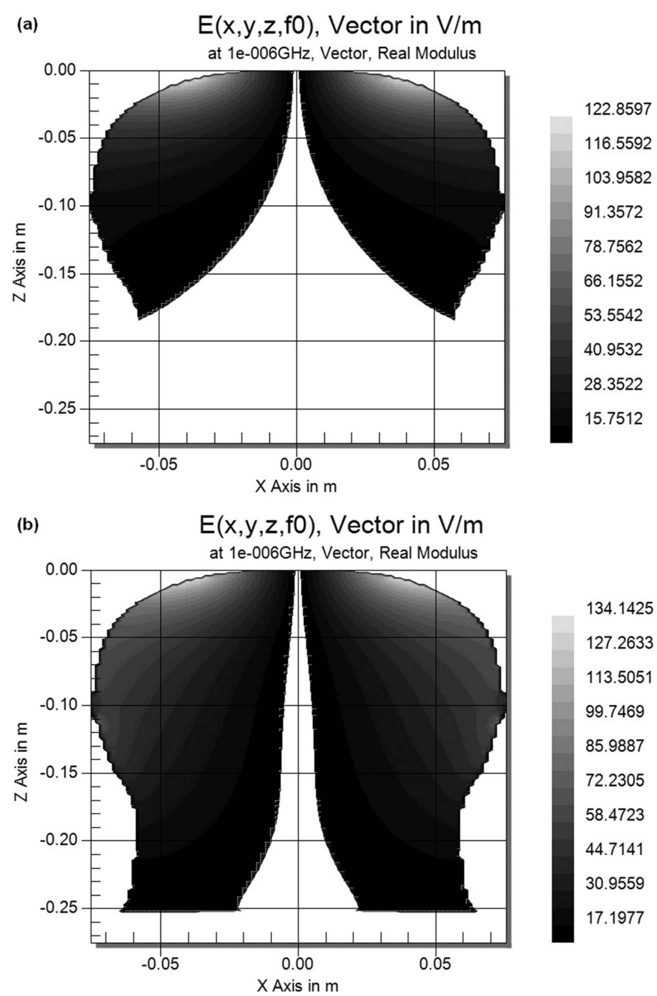

FIG. 3. Contour plots of electric field distribution in central coronal slice of (a) circular 90 mm coil alone and (b) with Halo coil.

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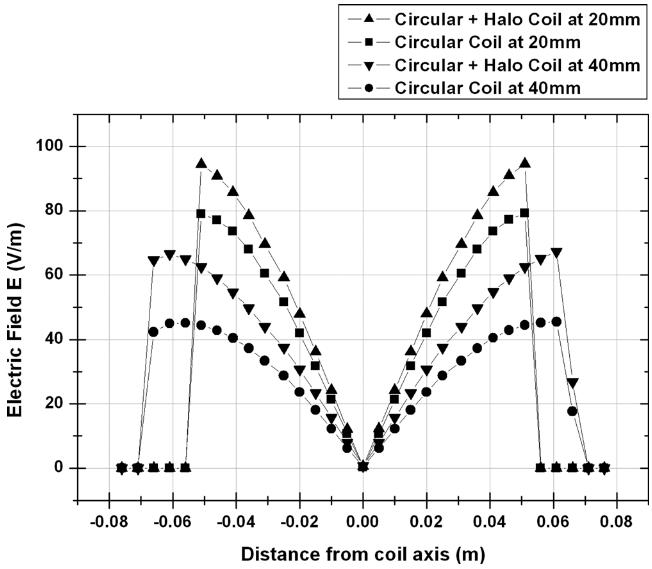

FIG. 4. Calculated electric field at 20 and 40 mm below the vertex of the head.

The electric field strength of both coils is shown in Fig. 4, at 20 and 40 mm below the vertex of the head model. At both distances the electric field is increased throughout the head. This demonstrates the ability of the Halo coil to produce an electric field of sufficient magnitude to initiate an action potential in neurons further into the brain than a flat circular coil operated alone.

Figure 5 shows a comparison of the attenuation of magnetic field along the common coil axis between the mapped data and a FEM calculation based on the coil dimensions for the circular coil when operated alone and with the Halo coil.

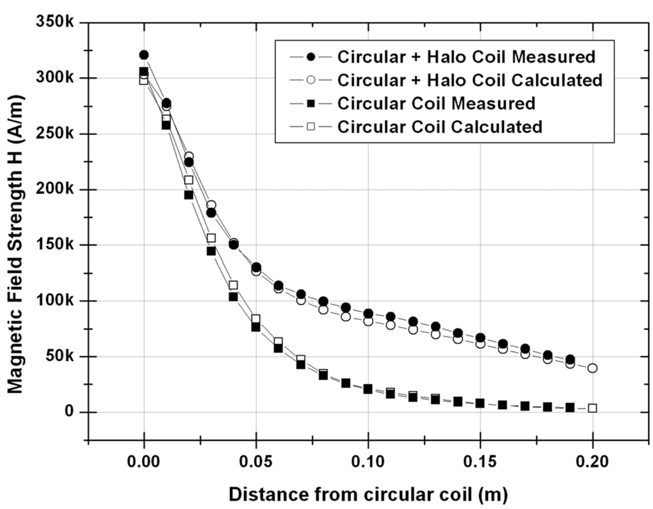

FIG. 5. Attenuation of magnetic field strength along common coil axis from surface of circular coil.

The calculations and experimental measurements show very good agreement in both amplitude and rate of decay.

Along the coil axis the design with the Halo coil increased the magnetic field strength by 10% (50%) at a distance of 20 mm (50 mm) from the circular coil compared with the circular coil design alone.

In addition to penetration depth, localization of stimulation is an important criterion in the design of TMS coils. The Halo coil does not increase the localization of electric field but existing methods to suppress the surface field could be employed together with the Halo coil in order to improve the localization of the field.

IV. CONCLUSION

Theoretical calculations and experimental measurements have been made to assess the performance of a coil design for TMS. Both methods of analysis have shown that an improved penetration depth is achieved with the presence of the Halo coil compared to a standard circular coil configuration. This enables the stimulation of the brain at greater depth than is currently achievable with existing coil designs. The results show promise for expanding the use of TMS for diagnostic and investigatory applications as it provides significant advantages over alternative invasive methods of stimulating neurons at depth in the brain.

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