Electric Field Characteristics of Low-Field Synchronized Transcranial Magnetic Stimulation (sTMS)

Zhi-De Deng, *Member, IEEE*, and Sarah H. Lisanby

***Abstract*— Low-field synchronized trancranial magnetic stimulation (sTMS) was hypothesized to have significant therapeutic effects in patients with major depressive disorder by entrainment of neural oscillations. The sTMS device is comprised of neodymium magnets mounted over multiple brain regions and set to rotate at the patients alpha frequency. We characterized the electric field strength and distribution of sTMS using the finite element method. We found that the maximum induced electric field strength on the surfaces of the head and cortex are approximately $0.06\,\mathrm{V\,m^{-1}}$ and $0.02\,\mathrm{V\,m^{-1}}$, respectively. These field strengths are an order of magnitude lower than that delivered by transcranial current stimulation.**

I. Introduction

Conventional magnetic neurostimulation systems use a current-carrying coil to generate a time-varying magnetic field pulse, which in turn produces a spatially varying electric field—via electromagnetic induction—in the central or peripheral nervous system. An alternative approach to generating the time-varying magnetic field is by means of moving permanent magnets. Several systems have been proposed [1], [2], [3], involving rotation of high-strength neodymium magnets. One of these systems, termed synchronized transcranial magnetic stimulation (sTMS), was explored as a treatment of major depressive disorder (MDD) [4].

The sTMS device is comprised of a configuration of three cylindrical neodymium magnets mounted over the midline frontal polar region, the superior frontal gyrus, and the parietal cortex. The speed of rotation for the magnets was set to the patient's individualized peak alpha frequency of neural oscillations, as obtained by pretreatment electroencephalography recorded from prefrontal and occipital regions while the patient remained in eyes-closed, resting state [5]. The hypothesized mechanism of action is that entrainment of alpha oscillations, via exogenous subthreshold sinusoidal stimulation produced by sTMS, could reset neural oscillators, enhance cortical plasticity, normalize cerebral blood flow, and altogether ameliorate depressive symptoms [6]. In a multicenter, double-blind, sham-controlled trial of sTMS treatment of MDD, there was no difference in efficacy between active and sham in the intent-to-treat sample [4]. In a subset of per-protocol patients, there was significant treatment effect at six-weeks [4].

No direct electrophysiological evidence of the hypothesized mechanism of sTMS was reported, nor was the stimulation intensity and distribution well characterized. In this work, we evaluate the electric field characteristics of sTMS using the finite element method.

Z.-D. Deng and S. H. Lisanby are with the National Institute of Mental Health, National Institutes of Health, Bethesda, MD 20892, USA. This research was supported by the Intramural Research Program of the NIMH. Correspondence: `zhi-de.deng at nih.gov`

II. Methods

The finite element model was implemented in COMSOL Multiphysics (COMSOL, Burlington, MA) using its version of the IEEE Specific Anthropomorphic Mannequin (SAM) phantom (Fig. 1). The head model (stator) has uniform, isotropic electrical conductivity of $0.33\,\mathrm{S\,m^{-1}}$ and relative permeability of 1. Three cylindrical magnets (rotators) are positioned along the midline: Magnet #1 is located over the frontal pole just above the eyebrows. Magnet #2 is $7.1\,\mathrm{cm}$ away from Magnet #1, approximately overlying the superior frontal gyrus. Magnet #3 is $9.2\,\mathrm{cm}$ away from Magnet #2, approximately overlying the parietal cortex. Each magnet is $2.54\,\mathrm{cm}$ in diameter and height, diametrically magnetized, with a residual flux density of $0.64\,\mathrm{T}$. The axes of rotations are perpendicular to the sagital plane; and the rotation velocity is set to $10\,\mathrm{Hz}$, corresponding to approximately peak alpha frequency. The resulting adaptive mesh consists of 56,825 tetrahedral elements.

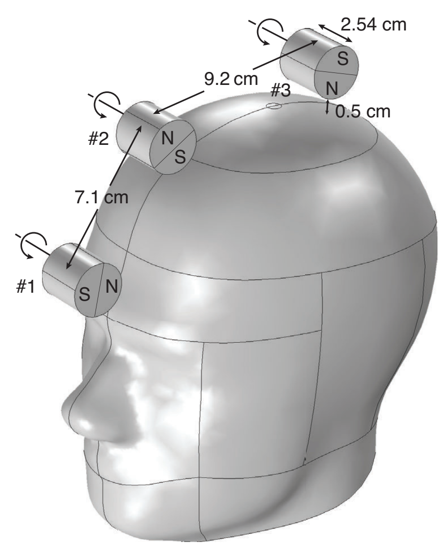

Fig. 1. Dimensions and placement of the three cylindrical magnets in the sTMS system.

Under the vector potential formulation, Ampère's law was first applied to all domains:

$$\sigma\frac{\partial \mathbf{A}}{\partial t} + \nabla\times\left(\frac{1}{\mu}\nabla\times\mathbf{A}\right) = 0, \tag{1}$$

and a magnetic flux conservation equation for the scalar magnetic potential was applied to current-free parts of both

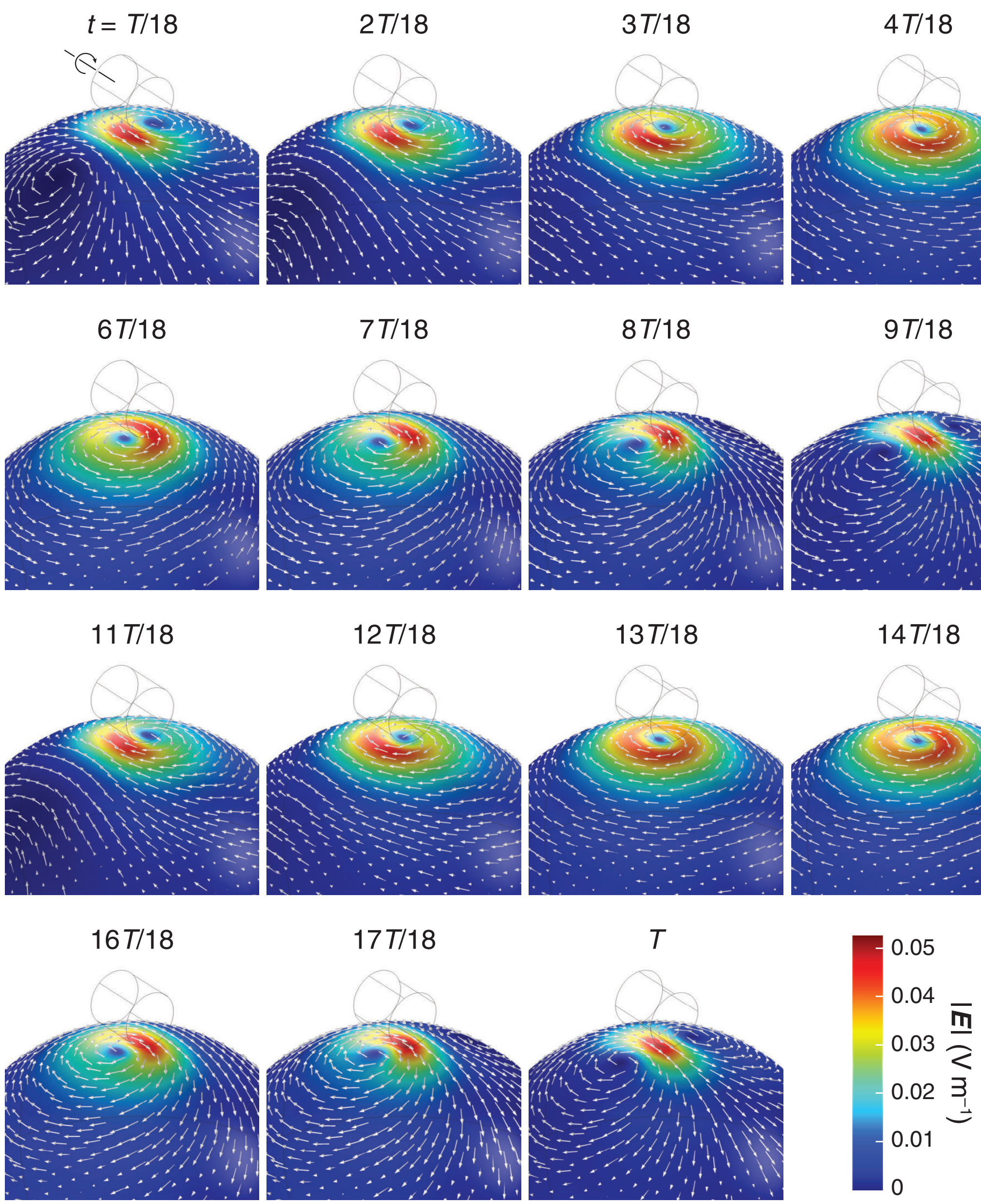

Fig. 2. One full revolution (period $= T$) of a single rotating magnet in steady-state.

the rotor and stator:

$$-\nabla \cdot (\mu \nabla V_{\mathrm{m}} - \mathbf{B}_{\mathrm{r}}) = 0. \tag{2}$$

Continuity in the scalar magnetic potential was enforced at the interface between the rotor and stator.

A stationary solution was first obtained using a direct solver (MUMPS), and then the time-dependent problem (in 10 degrees rotation steps) was solved. This assumes that the transient effects of initiating the rotating magnets have decayed, and the final solution reflects steady-state behavior.

III. Results

Fig. 2 shows the electric field distribution of a single rotating magnet in a sphere head model with radius of $8.5\,\mathrm{cm}$. As the magnet rotates, the electric field switches from a figure-8 pattern (when the magnetic dipole is perpendicular to the head sphere at multiples of $T/2$) to a circular pattern (when the magnetic dipole is parallel to the head at multiples of $T/4$). The peak induced electric field strength at the surface of the head is approximately $0.05\,\mathrm{V\,m^{-1}}$, in the direction parallel to the rotation axis of the magnet.

Fig. 3 shows the electric field distribution of the full sTMS configuration in the SAM head model. The stimulation is broadly distributed over midline frontal polar, medial frontal, and parietal regions. The peak induced electric field strength at the surface of the head is approximately $0.06\,\mathrm{V\,m^{-1}}$. At a depth of $1.5\,\mathrm{cm}$ from the head surface, corresponding to the depth of the cortex, the electric field strength attenuates to approximately $0.02\,\mathrm{V\,m^{-1}}$.

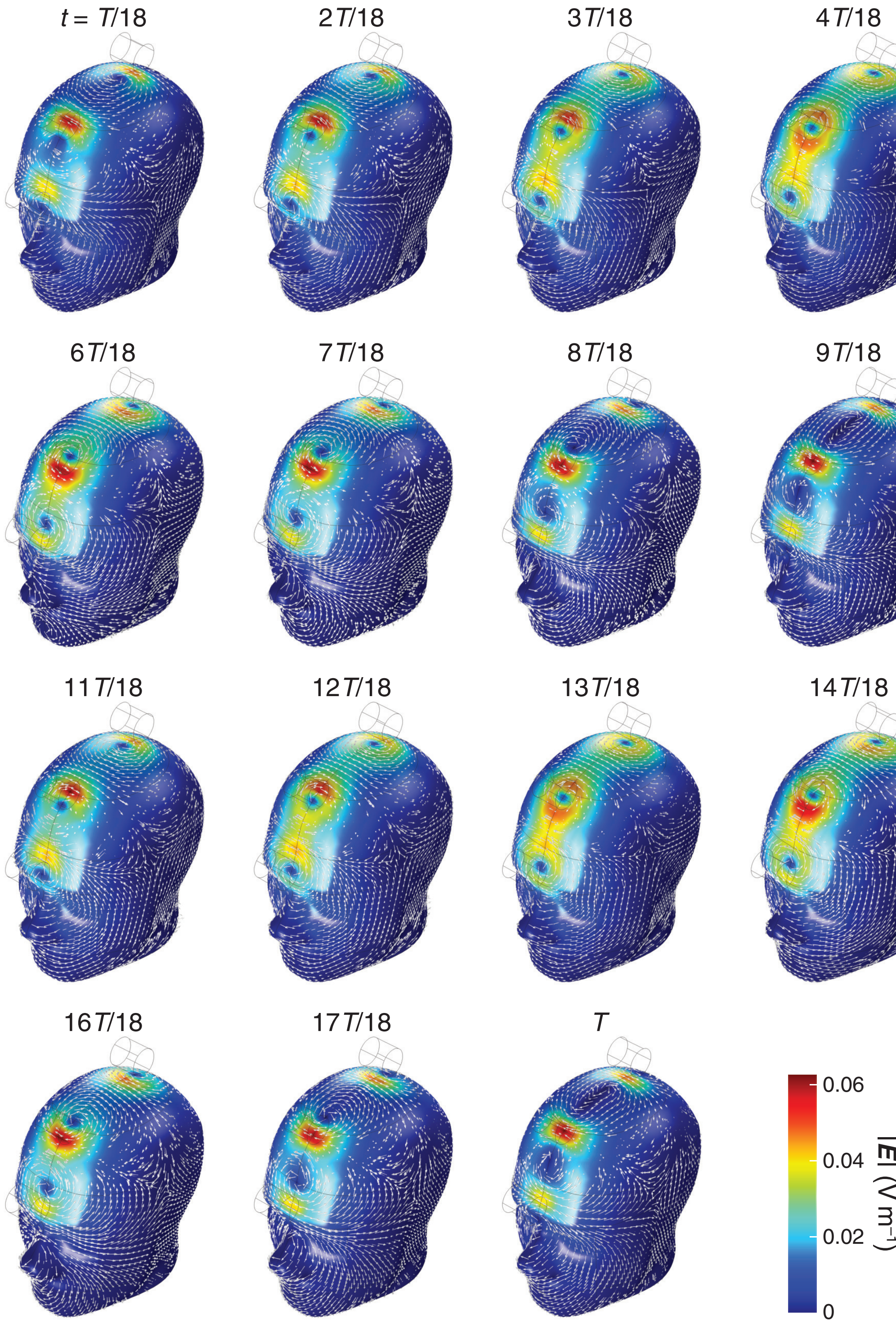

Fig. 3. One full revolution (period $= T$) of the full sTMS configuration in steady-state.

IV. Discussion

Jin and Phillips estimated the intensity of the sTMS stimulation to be approximately 0.1% that of standard TMS [5]. However, this estimate was based on comparison of maximum surface fields and does not account for boundary conditions of the head. Our simulation with a head model suggests that the peak electric field strength at the level of the cortex is approximately $0.02\,\mathrm{V\,m^{-1}}$. This field strength is an order of magnitude lower compared to those induced by transcranial current stimulation (tCS) [7] and low field magnetic stimulation (LFMS) [8]. The sTMS field strength is comparable to that of low-intensity repetitive magnetic stimulation (LI-rMS) in an *in vitro* model, which has been shown to alter cellular activation and gene expression in an organotypic hindbrain explant, and in a stimulation frequency-specific manner [9]. Thus, the low field strength of sTMS could be biologically active.

In this work, we simulated the sTMS system at a fixed rotational frequency of $10\,\mathrm{Hz}$. The frequency of peak alpha oscillation across individuals can vary between 8 and $13\,\mathrm{Hz}$. The sTMS depression study observed that in a small group of subjects who did not received stimulation at the correct individualized alpha frequency, their outcomes were inferior to those treated at the correct indvidualized alpha frequency [4]. It should be noted that since the induced electric field strength is proportional to the frequency of rotation of the magnets, individualizing the rotational frequency could introduce variability in the induced electric field strength across individuals. Higher field strength can be achieved by increasing the rotational speed. However, neuronal activation becomes inefficient at very high frequencies. Finally, the interaction between field strength and excitation frequency could be nonlinear, as demonostrated in a transcranial alternating current stimulation study[12].

Helekar and Voss proposed a device comprised of an assembly of high-speed rotating cylindrical magnets [3]. These N52 grade magnets are smaller ($3/8\,\mathrm{in}$ in height and $1/4\,\mathrm{in}$ in diameter), and have stronger surface field ($B_\mathrm{r} = 1.48\,\mathrm{T}$) compared to the sTMS magnets. The magnets are axially magnetized, but the axis of rotation is perpendicular to the axis of the cylinder. Thus, the induced electric field pattern resembles that shown in Fig. 2. The motor provides a no-load speed of $24000\,\mathrm{rpm}$ ($400\,\mathrm{Hz}$). Since the induced electric field strength is proportional to the angular frequency of rotation, higher rotational speed can increase the electric field strength. Helekar and Voss estimated the intensity of their high-speed rotating magnet device to be approximately 6% that of TMS, based on voltage measurements made with an inductor search coil [10]. However, measurements made in air and without the conductivity boundaries of the head would likely overestimate the electric field strength. Furthermore, smaller magnets have faster field attenuation with distance compared to larger magnets.

Watterson proposed and tested a similar high-speed rotating magnet device for stimulation of muscle nerves [2]. In a series of *in vitro* experiments on the cane toad sciatic nerve and attached gastrocnemius muscle, Watterson and Nicholson observed that nerve activation was achievable with a rotational frequency of $230\,\mathrm{Hz}$ [11]. The activation of peripheral nerves is thought to be more sensitive to the gradient of the electric field. To maximize the field gradient, Watterson's device employs a 'bipole' configuration, comprising two diametrically magnetized cylindrical magnets next to one another with opposite magnetization directions [11].

V. Conclusions

We evaluated the electric field characteristics of the sTMS system of rotating magnets using the finite element method. We found that the maximum induced electric field strength at the level of the cortex is approximately $0.02\,\mathrm{V\,m^{-1}}$, which is an order of magnitude lower compared to those delivered by transcranial current stimulation and low field magnetic stimulation. Future work would include simulation of sTMS in anatomically-accurate head models derived from individual brain scans and treatment parameters. Direct electrophysiological data should also be collected to validate the proposed mechanism of action.

References

[1] J. W. Phillips and Y. Jin, "Devices and methods of low frequency magnetic stimulation therapy," US patentus 20 130 137 918 A1, 2013.

[2] P. A. Watterson, "Device including moving magnet configurations," US patentus 0 163 305A1, 2014.

[3] S. A. Helekar and H. U. Voss, "Method and apparatus for providing trancranial magnetic stimulation (TMS) to a patient," US Patent 0 276 182 A1, 2014.

[4] A. F. Leuchter, I. A. Cook, D. Feifel, J. W. Goethe, M. Husain, L. L. Carpenter, M. E. Thase, A. D. Krystal, N. S. Philip, M. T. Bhati, W. J. Burke, R. H. Howland, Y. I. Sheline, S. T. Aaronson, D. V. Iosifescu, J. P. O'Reardon, W. S. Gilmer, R. Jain, K. S. Burgoyne, B. Phillips, P. J. Manberg, J. Massaro, A. M. Hunter, S. H. Lisanby, and M. S. George, "Efficacy and safety of low-field synchronized transcranial magnetic stimulation (sTMS) for treatment of major depression," *Brain Stimul*, vol. 8, no. 4, pp. 787–794, 2015.

[5] Y. Jin and B. Phillips, "A pilot study of the use of EEG-based synchronized transcranial magnetic stimulation (sTMS) for treatment of major depression," *BMC Psychiatry*, vol. 14, no. 13, 2014.

[6] A. F. Leuchter, I. A. Cook, Y. Jin, and B. Phillips, "The relationship between brain oscillatory activity and therapeutic effectiveness of transcranial magnetic stimulation in the treatment of major depressive disorder," *Front Hum Neurosci*, vol. 7, no. 37, 2013.

[7] P. C. Miranda, A. Mekonnen, R. Salvador, and G. Ruffini, "The electric field in the cortex during transcranial current stimulation," *Neuroimage*, vol. 70, pp. 48–58, 2013.

[8] M. L. Rohan, R. T. Yamamoto, C. T. Ravichandran, K. R. Cayetano, O. G. Morales, D. P. Olson, G. Vitaliano, S. M. Paul, and B. M. Cohen, "Rapid mood-elevating effects to low field magnetic stimulation in depression," *Biol Psychiatry*, vol. 76, no. 3, pp. 186–193, 2014.

[9] S. Grehl, D. Martina, C. Goyenvalle, Z.-D. Deng, J. Rodger, and R. M. Sherrard, "In vitro magnetic stimulation: a simple stimulation device to deliver defined low intensity electromagnetic fields," *Front Neural Circuits*, vol. 10, no. 85, 2016.

[10] S. A. Helekar and H. U. Voss, "Transcranial brain stimulation with rapidly spinning high-field permanent magnets," *IEEE Access*, vol. 4, pp. 2520–2528, 2016.

[11] P. A. Watterson and G. M. Nicholson, "Nerve-muscle activation by rotating permanent magnet configurations," *J Physiol*, vol. 594, no. 7, pp. 1799–1819, 2016.

[12] V. Moliadze, D. Atalay, A. Antal, and W. Paulus, "Close to threshold transcranial electrical stimulation preferentially activates inhibitory networks before switching to excitation with higher intensities," *Brain Stimul*, vol. 5, no. 4, pp. 505–511, 2012.