URSI AP-RASC, Sydney, Australia, 17-22 August 2025

Development of Optimized Coils for Deeper Transcranial Magnetic Stimulation

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Transcranial magnetic stimulation (TMS) has been widely applied to the treatment of various neurological and psychiatric disorders, demonstrating therapeutic efficacy for drug-resistant cases. Due to the attenuation of the magnetic field with distance from the coil, conventional TMS primarily affects the cerebral cortex. In recent years, the application of TMS in clinical treatments has expanded, and several studies investigated the therapeutic effects of multiple coils with different depths of electric field penetration. These studies suggest that coils capable of reaching deeper brain regions exhibit enhanced therapeutic outcomes, likely due to their ability to stimulate both deeper cortical layers and subcortical structures more uniformly.

In this study, we fabricated a novel coil designed to deliver electric fields to deeper brain regions while maintaining balance between stimulation depth and focality. The analytical description of the desired electric field provides a theoretical upper limit on penetration depth.

To facilitate a theoretical understanding of field distribution, we approximate the brain as a sphere with uniform electromagnetic properties and analyze the magnetic and induced electric fields using vector spherical harmonics. Our research focuses on the development of coil design methodologies based on inverse problem-solving. In this approach, we first define a desired electric field distribution within the brain and subsequently optimize the coil winding geometry to achieve this distribution. By decomposing the electric field into multipole expansions, we identify that the first-order term exhibits the least attenuation with depth but results in a widely dispersed field. By superimposing the second-order term, we achieve a more localized stimulation pattern. The optimization was performed by finding a set of multipole-expansion coefficients which leads to maximizing the depth index of electric field. The corresponding magnetic field can be determined, enabling the derivation of an optimized coil winding configuration via the target field method. Through this framework, our research group has developed coils capable of generating deeper electric fields with spatial targeting.

Additionally, we evaluated the electric field intensity generated in a numerical model replicating the conductivity distribution of the human head. The results showed that at a depth of 20 mm, corresponding to the anterior cingulate cortex, the electric field exceeded 130 V/m. This suggests that the electric field reaches subcortical regions, including the anterior cingulate cortex.

For therapeutic applications, it is necessary to generate pulsed magnetic fields at frequencies above 10 Hz. However, this process induces heat generation within the coil, necessitating an effective cooling mechanism. To address this challenge, we employed a hollow copper pipe as the conductor, circulating insulating oil through its internal channels for efficient cooling. To fabricate a coil with the optimized complex three-dimensional structure, we developed a novel manufacturing process utilizing numerically controlled press-forming technology. This method enables continuous deformation of the hollow pipe conductor to achieve the desired coil shape. The outer casing was fabricated using 3D printing, and silicone rubber was injected into the gap between the conductor and casing for mechanical support. Performance testing of the completed coil confirmed its ability to generate a sufficiently strong magnetic field. The inductance of the coil was measured at 18 μH, making it well-suited for integration with a driving circuit. Furthermore, under conditions simulating clinical treatment, the coil operated continuously while maintaining a surface temperature below 40°C, demonstrating effective thermal management.

Our findings contribute to the advancement of TMS technology by enabling deeper brain stimulation, thereby enhancing its therapeutic potential for neurological and psychiatric disorders.

1. A. Iino, M. Fushimi, J. Tabata, T. Kikuchi, Y. Soejima, M. Wada, S. Nakajima, Y, Noda, M. Sekino, "Development of transcranial magnetic stimulator coils that physically achieve the deepest stimulation based on the inverse problem approach," IEEE Transactions on Magnetics, vol. 60, pp. 1-5, 2024.

2. S. Ueno and M. Sekino, "Figure-eight coils for magnetic stimulation: From focal stimulation to deep stimulation," Frontiers in Human Neuroscience, vol. 15, pp. 805971, 2021.