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Anatomically accurate and individualized brain phantoms of humans and small animals for invasive and non-invasive electromagnetic neuromodulation

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Non-invasive brain stimulation techniques such as transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS) have emerged as a promising therapeutic procedures for various neurological and psychiatric disorders. To facilitate rigorous and ethical research, the development of individualized brain phantoms has become imperative. This paper presents a novel methodology for creating an individualized human and rat brain phantoms to simulate neuromodulation effects induced by TMS. The study utilizes Magnetic Resonance Imaging (MRI) and Computed Tomography (CT) images from public databases, employing statistical parametric mapping (SPM) to create anatomically accurate brain molds which are then cast with a carbon nanotube CNT, polydimethylsiloxane (PDMS) composite to mimic brain conductivity. Several phantoms are fabricated using this technique and are subjected to TMS stimulation from varrious TMS coils.

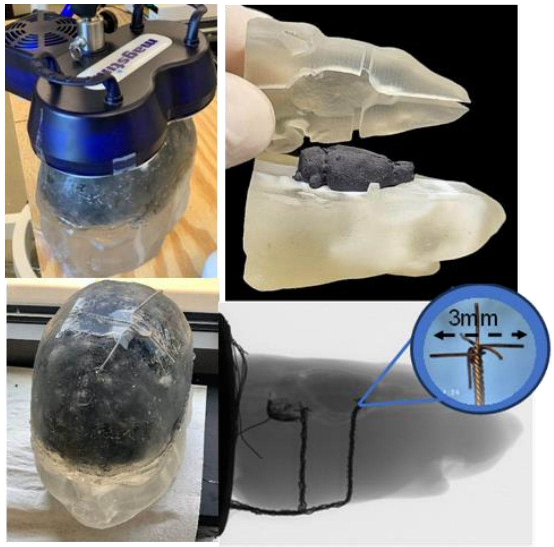

Figure 1. Human and animal brain phantoms mimicking brain structure and electrical conductivity accurately

Here, we present a physically-accurate head phantoms that allows measurement of the TMS-induced E-field strengths in-situ. The 3D printing based approach allows us to recreate complexities in anatomy. We used publicly available magnetic resonance imaging (MRI) and computed tomography (CT) images [1], along with the SIGMA rat brain atlas [2] for anatomical segmentation and reconstruction of an anatomically accurate model through the use of inkjet printing and injection molding. The development of the phantom involved integration of computational image processing of the MRI/CT data with advanced 3D printing method. We show how this approach can produce subject-specific brain phantoms. In addition to complex anatomical accuracy, our technique for creating this phantom features a material with tunable conductivity that mimics the electrical properties of the brain. Polydimethylsiloxane (PDMS) and carbon nanotubes are used to create the precise conductivity required. The carbon nanotubes form a conductive network on the nanoscale within the polymer. The connectivity of this network is directly related to the bulk conductivity of the material and is simply modified by altering the loading percent of the CNT. Induced electric fields are measured via tri-axial dipole probes (TDP). Dipole probes measure electric fields by detecting the voltage difference between two points in space, which correspond to the elctric field component along the axis of the dipoole. Each dipole consists of two conductive elements separated by a small distance, and the elctric field is calculated as the voltage difference devided by the seperation distance. To fully capture the elctric field's vector components three mutually orthogonal dipole probes are used. The simulated and mesured induced electric field were in agreement within an error of 5%. These measured results are still relavent for a quick and easy assesment of new coils and TMS protocols, especially in the cortical regions of the brain, before moving to live subjects.

[1] "NITRC: Templates for Long-Evans Rat Brain: Tool/Resource Info." Accessed: Dec. 02, 2024. [Online]. Available: https://www.nitrc.org/projects/tpm_rat/
[2] "NITRC: SIGMA Rat Brain Templates and Atlases: Tool/Resource Info." Accessed: Dec. 07, 2024. [Online]. Available: https://www.nitrc.org/projects/sigma_template