Single-Source Multi-Coil Transcranial Magnetic Stimulators for Deep and Focused Stimulation of the Human Brain

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Transcranial magnetic stimulation (TMS) is a tool for non-invasive stimulation of neuronal tissue for research in cognitive neuroscience and treating neurological disorders. In TMS, one or more coils located near the scalp produce magnetic fields that induce electric fields and eddy-currents in the conductive brain tissue. When the spatial gradient of the electric field aligns with a nerve fiber, an action potential is generated. Many TMS applications require excitation of specific target regions in the brain while minimizing stimulation elsewhere. Unfortunately, electric fields generated by present TMS coils diffuse rapidly as they penetrate into the brain and stimulate relatively large regions of tissue near the brain surface. This is especially true for the two most commonly used single-source systems, viz. the 'figure-8' and 'Hessed' coils (Cohen L. et al., *Electroencephalogr Clin Neurophysiol,* vol.7, no.75, pp.1-4, 350–7; Roth Y. et al., *J Clin Neurophysiol*, vol.19, no.4, pp. 361-370. Aug. 2002). To broaden the scope of present TMS applications, new coils that focus fields deeper into the brain while limiting the volume of excited tissue are called for.

This study concerns the design of planar or conformal, single-source (i.e. uniformly fed) coil arrays. Past efforts at using coil arrays for TMS were held back by the lack of robust design tools and the need to feed the array with multiple sources. Our contributions are two-fold.

(i) We propose a Pareto genetic algorithm (PGA) that, for a given array layout, determines array driving currents that minimize the volume of the excited head region V required to achieve a prescribed penetration depth d—both quantities are defined in terms an electric field excitation threshold (typically chosen to be 150 V/m). The PGA ensures feasibility of the design by safeguarding against electric fields that exceed a safety threshold (typically chosen to be 450V/m) and controlling the L1 norm of the vector of coil currents.

(ii) We develop a methodology for converting the multi-source arrays that results from (i) into a single-source coil without affecting its performance. First, each single-turn coil in the multi-channel array is replaced by a multi-turn coil comprising variable-radius loops that produce the same magnetic dipole moment when driven by a fixed current (that is chosen identically for all array elements). Next, these multi-turn coils are series-connected using a carefully designed, nonradiating feed network.

Preliminary results indicate that a 10 x 10 square array of multi-turn circular loops of diameter < 14mm is capable of exciting fields d = 27mm into the head—a depth often targeted when TMS is used for treating depression—while using $1/50^{th}$ the current and exciting 3 times less volume than figure-8 TMS coils.