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Motor cortex activation by H-coil and figure-8 coil at different depths. Combined motor threshold and electric field distribution study

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HIGHLIGHTS

- Efficacy of stimulation of hand and leg motor cortex is compared between an H-coil and a figure-8 coil.
- The motor thresholds were measured in healthy subjects, and electric field distribution induced by both coils was measured in a head model.
- The combination of the neurophysiological findings and the head model field measurements consistently point towards a more efficient activation of deeper cortical regions using the H-coil.

ABSTRACT

Objective: To compare the ability of an H-coil and figure-8 coil to stimulate different motor cortex regions.
Methods: The resting (rMT) and active (aMT) motor thresholds were measured for the right hand APB and leg AHB muscles in 10 subjects, using an H-coil and a figure-8 coil. The electric field distribution induced by the coils was measured in a head model. The combination of the hand and leg MTs with the field measurements was used to determine the depth of hand and leg motor areas via the intersection points.
Results: The rMT and aMT of both APB and AHB were significantly lower for the H-coil. The ratio and difference between the leg and hand rMT and aMT were significantly lower for the H-Coil. Electric field measurements revealed significantly more favorable depth profile and larger volume of stimulation for the H-coil. The averaged intersection for the APB was at a distance from coil of 1.83 ± 0.54 cm and at an intensity of 97.8 ± 21.4 V/m, while for the AHB it was at a distance of 2.73 ± 0.44 cm and at an intensity of 118.6 ± 21.3 V/m.
Conclusion: The results suggest a more efficient activation of deeper motor cortical regions using the H-coil.
Significance: The combined evaluation of MTs by H- and figure-8 coils allows measurement of the individual depth of different motor cortex regions. This could be helpful for optimizing stimulation parameters for TMS treatment.

1. Introduction

TMS is a technique for brain stimulation that is able to probe the brain circuitry and network in a non-invasive manner. A rapidly pulsed magnetic field induces an electric field within the cortex that stimulates individual neurons and associated networks. In the past two decades, there has been a dramatic increase in the usage of TMS for research, evaluation and treatment of various neuropsychiatric disorders (Wassermann and Lisanby, 2001; Terao and Ugawa, 2002; Ridding and Rothwell, 2007; Rossini and Rossi, 2007). However, in order to reach deeper cortical or subcortical structures, the stimulus amplitude for standard TMS coils needs to be increased to levels at which patient comfort becomes compromised by painful scalp stimulation. Furthermore, the risk of seizure is increased.

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Deep TMS is a technique introduced in 2002 to enable effective stimulation of deep brain structures (Roth et al., 2002, 2007b; Zangen et al., 2005). The technology is based on a family of coil designs termed H-coils. It has been demonstrated to induce a slower decay of electric field with distance in a head model when compared to standard TMS coils (Roth et al., 2002, 2007a). In addition, the rate of increase of motor activation thresholds was found to be lower for a deep TMS coil as the coil was moved further away from the scalp (Zangen et al., 2005). Deep TMS H-coils have been studied in recent years in various clinical applications (Levkovitz et al., 2009, 2011; Kranz et al., 2010; Harel et al., 2011, 2012; Isserles et al., 2011, 2013).

Recently, there has been a debate in the literature regarding the advantage of H-coils over conventional 70-mm figure-8 coils with regard to depth of stimulation (Fadini et al., 2009, 2010; Roth et al., 2010). It was agreed that the H-coil has deeper physical effects as reflected in the electric field profile. Yet it was suggested (Fadini et al., 2010) that this may not be a clear evidence for a better physiological effect in deeper neuronal structures.

A recent fMRI study supports the claim that the H1-coil induces deeper physiological effects relative to a figure-8 coil (Gruberger, Zangen et al., in preparation).

The aim of the present study was to compare the ability of the H-coil and figure-8 coil to stimulate topographically different cortical regions in the motor strip and to relate this to the coils' induced electric field profiles. In this manner, the motor thresholds (resting and active) for stimulation of the hand and leg areas were related to the electric field characteristics of the H-coil and the standard figure-8 coil. This study thus addresses the major biophysical properties of deep TMS with the H-coil. Other neurophysiological characteristics of deep TMS in the motor cortex including the motor evoked potential (MEP) size, latency, recruitment curve, cortical silent period, and intracortical measures of inhibition and facilitation, will be presented in a separate report.

2. Methods

2.1. Subjects

A total of 10 healthy volunteers (7 men, 3 women) participated in the study (age range: 23–41 years, mean age: 30.6 years, SD: 7.3 years). Participants were recruited from the local community through advertisements. Exclusion criteria were: (1) history of head injury, systemic uncontrolled disease or seizure disorder; (2) pacemaker, metallic implants, or any other contraindication to TMS as specified in the safety guidelines for that procedure (Rossi et al., 2009); (3) neurophysiological evidence of impairment of central and peripheral nerve conduction. The study protocol was approved by the local Ethical Committee. All subjects gave written informed consent.

2.2. TMS coils

Single-pulse TMS was delivered using a Magstim 200 (Magstim, UK) stimulator producing monophasic pulses with rise time of 100 μs and pulse duration of 1 ms.

The Deep TMS H-coil version used in this study, termed HMCDEEP (Brainsway, Israel), was specifically designed to stimulate deep structures in the motor cortex.

A sketch of the H-coil design over a human head is shown in Fig. 1. The H-coil is composed of two flexible limbs designed to conform to a human head. The right limb is rectangular with dimensions of approximately 20 × 5 cm. The left wing has a shape of a triangle with base of approximately 18 cm and height of approximately 5 cm. Each limb includes 13 windings.

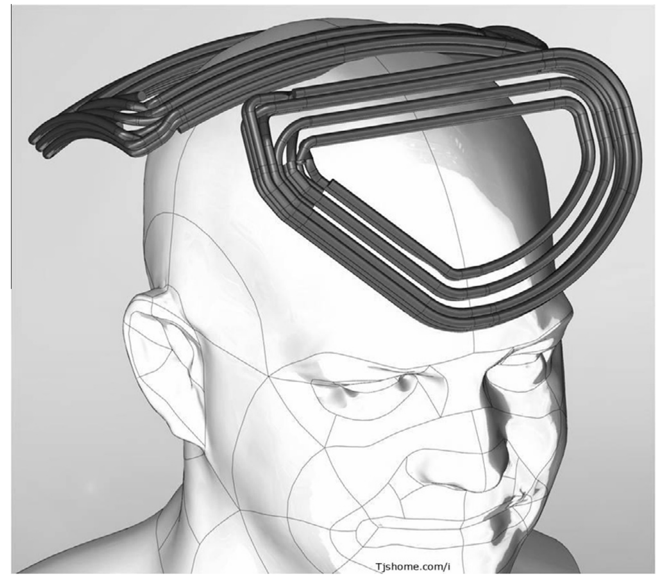

Fig. 1. A sketch of the H coil version used in this study, termed HMCDEEP, over a human head at the position for activating leg motor cortex.

The H-coils design principles essential for effective deep brain TMS have been published in several papers (Roth et al., 2002, 2007a, 2010, 2013a; Zangen et al., 2005) and book chapters (Roth et al., 2007b; Roth and Zangen, 2013b). In short, these include a flexible base complementary to the head and including coil elements tangential to the scalp, in order to minimize electrostatic charge accumulation on brain surface. Such charge accumulation has been shown (Tofts, 1990; Tofts and Branston, 1991; Eaton, 1992; Roth et al., 2002) to significantly reduce the absolute induced electric field intensity in most brain locations and especially in deeper brain regions, thus impeding the coil depth penetration. In addition, these elements must be dispersed rather than forming a dense organization. They may be organized in several groups or may be sparsely organized over the base, in order to induce from various directions a summation of the electric field in the target deep brain region that will create there a sufficiently high electric field intensity which at the same time is a high percentage of the maximal field (generally located at the brain surface). Thus, in the H-coil used in this study the main electric field is produced by the central elements of the two limbs which are separated from each other by 4 cm and have an average length of 15 cm.

The coil was designed for optimal positioning over the hand and leg motor cortex. For hand stimulation, it is placed on the left hemisphere with its central segment over the M1 region of the hand motor cortex, with an orientation of approximately 45° relative to the central sulcus. Hence the left limb is triangular so that in such position and orientation the coil's frontal edge will be above the eyebrows. For leg stimulation, the coil is positioned with its central segment over the leg motor cortex, in a lateral-medial orientation.

A standard commercial Magstim figure-8 coil (Magstim, UK) with internal loop diameters of 7 cm was used to compare to the H-coil.

The H-coil was designed to have the same inductance as the figure-8 coil (16 ± 1 μH), in order to induce the same pulse shape, simplify the comparison and prevent relative shift in motor threshold between coils (Rudiak and Marg, 1994).

2.3. Motor threshold measurements

For assessment of the resting (rMT) and active (aMT) motor thresholds, motor evoked potentials were recorded using a Nicolet