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H-coil: Induced electric field properties and input/output curves on healthy volunteers, comparison with a standard figure-of-eight coil

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ABSTRACT

Objective: To acquire information about the physical properties and physiological effects of the H-coil.

Methods: We used a robotized system to measure the electric field (E-field) generated by a H-coil prototype and compared it with a standard figure-of-eight coil. To explore the physiological properties of the coils, input/output curves were recorded for the right abductor digiti minimi muscle (ADM) as target muscle. To explore focality of stimulation, simultaneous recordings were performed for the left ADM, right abductor pollicis brevis (APB), extensor digitorum communis (EDC) and biceps brachii (BB) muscles.

Results: Physical measurements of the H-coil showed four potentially stimulating foci, generating different electric field intensities along two different spatial orientations. RMT was significantly lower for H-coil- as compared to figure-of-eight coil stimulation. When stimulation intensity for the input–output curve was determined by percent of maximum stimulator output, the H-coil produced larger MEPs in the right ADM, as compared to the figure-of-eight coil, due to the larger relative enhancement of stimulation intensity of the H-coil. When stimulation intensity was adjusted to RMT, MEPs elicited at the right ADM were larger for figure-of-eight coil than for H-coil stimulation, while this relation was reversed for distant non-target muscles, with low stimulation intensities. With high stimulation intensities, the H-coil elicited larger MEPs for all tested muscles. Onset latency of the MEPs was never shorter for H-coil than for figure-of-eight coil stimulation of the target muscles.

Conclusions: These results are in favor for a non-focal, but not deeper effect of the H-coil, as compared to a figure-of-eight coil.

Significance: This is the first neurophysiological study exploring the focality and depth of stimulation delivered by the H-coil systematically in humans. We found no advantage of this coil with regard to depth of stimulation in comparison to the figure-of-eight coil. Future studies have to show if the non-focality of this coil differs relevantly from that of other non-focal coils, e.g. the round coil.

1. Introduction

As transcranial magnetic stimulation (TMS) has become an important brain research and therapeutic tool (Terao and Ugawa, 2002), the interest in stimulating brain areas situated deeper than the superficial cortical layers affected by conventional TMS has increased. However, technical complexity and the impossibility to achieve a focal stimulation in depth – characterized by a three-dimensional local maximum of the electric field strength within the brain – (Cohen and Cuffin, 1991; Yunokuchi and Cohen, 1991; Heller and van Hulsteyn, 1992) have discouraged the pursuit of producing a coil able to stimulate non-superficial brain regions via TMS until recently.

In the last years a tentative path to a magnetic brain stimulation for targeting subcortical areas using TMS was indicated by two publications (Roth et al., 2002; Zangen et al., 2005). The means used to obtain such stimulation is a specifically designed coil: the H-coil (Zangen et al., 2005; Roth et al., 2007). Even though a "stereotactic" three-dimensional stimulation confined to deep regions without affecting more superficial ones is not obtainable with such a coil, its ability to induce a higher induced electric field (E-field) value compared to a circular coil (Roth et al., 2002) at a distant target point from the stimulating focus is remarkable.

The spatial distribution of the stimulation-induced electrical field and the orientation and direction of the current induced in the brain determines the physiological effects obtained by a magnetic coil (Brasil-Neto et al., 1992; Niehaus et al., 2000; Kammer et al., 2001; Sommer et al., 2006; Thielscher and Kammer, 2004). At present these characteristics of the electric field of the H-coil

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were defined by simulation (Roth et al., 2002), but not yet measured and quantified for a real coil with the present configuration. To obtain this information we performed physical measurements of the induced electric field of a H-coil prototype (Thielscher and Kammer, 2002) in air.

To learn more about the physiological properties of this coil, especially its efficacy and focality, we compared the focality of stimulation and input–output curves in the primary motor cortex (M1) of healthy subjects by comparing it with a figure-of-eight coil.

2. Methods

2.1. The coils

Two coils were used: the investigated H-coil prototype and a standard Magstim figure-of-eight coil with wing loop diameter of 70 mm (The Magstim Company, Whitland, Dyfed, UK).

The geometry of the prototype we tested is shown in Fig. 1. For convenience, in order to identify different areas of the coil, we divided it into parts ("Arms") according to the orientation of the current flowing in the coil itself.

2.2. Physical measurements of the coils in air medium

Both coils underwent the physical measurements in order to allow a direct comparison of the electric field (E-field) induced in a conductive means under standardized conditions (Epstein et al., 1990; Rudiak and Marg, 1994).

To perform the physical measurements the H-coil prototype and the Magstim figure-of-eight coil were connected to a Magstim Rapid stimulator (The Magstim Company, Whitland, Dyfed, UK) connected to two booster modules. An output of 70% of the maximum stimulator output (MSO) was used to perform the measurements.

The physical measurements were performed along a 3D axis system (*X*, *Y*, *Z* in Fig. 2) by use of a Kuka KR3 (Augsburg, Germany) robotized Arm (Matthäus et al., 2005). The coil was fixed on the robot by use of a custom-made aluminium flange. In order to measure the relative positions of coil, electric field sensor and robot, a Polaris infrared tracking system (NDI, Ontario, Canada) with 0.1 mm accuracy was used.

Up to 4000 points were measured underneath the surface of the coils up to 80 mm away from the surface along the *Z* axis and up to 10 mm away from the coil edge along the *X* and *Y* axis. Each point was 5 mm distant from the one aside along each one of the three axes. Hence, the robotized Arm moved 5 mm at a time along the axes drawing an ideal measurement box. For the H-coil prototype the measurement box was adapted to follow the bent shape of the coil surface.

The sensor we used was a straight piece of copper wire 10 mm long with the two extremities connected to two cables. The two cables were disposed orthogonally to the coil surface and connected to a Velleman PCS100/8031 digital oscilloscope (Velleman, Belgium) with 8 bit Voltage resolution and 8 MSamples/sec time resolution. The probing wire was oriented along the X and the *Y* axis. Thus, we measured the points box two times along two orthogonal orientations. In both cases the probing wire was held parallel to the correspondent coil bottom surface. The data acquired were than analyzed and mesh-plotted using MATLAB®.

With this setup we obtained quantitative values directly proportional to the electric field (E-field) intensity (Nayfeh and Brussel, 1985). Because the setup and the measurement protocol was the same for both coils, the induced E-field distributions were comparable.

This setup fulfilled our information needs about the coil functioning: our purpose was to compare the functioning of the two coils under the same conditions on the basis of the induced E-field characteristics, thus obtaining information about the focality of the coil and the relative strength differences for each focus.

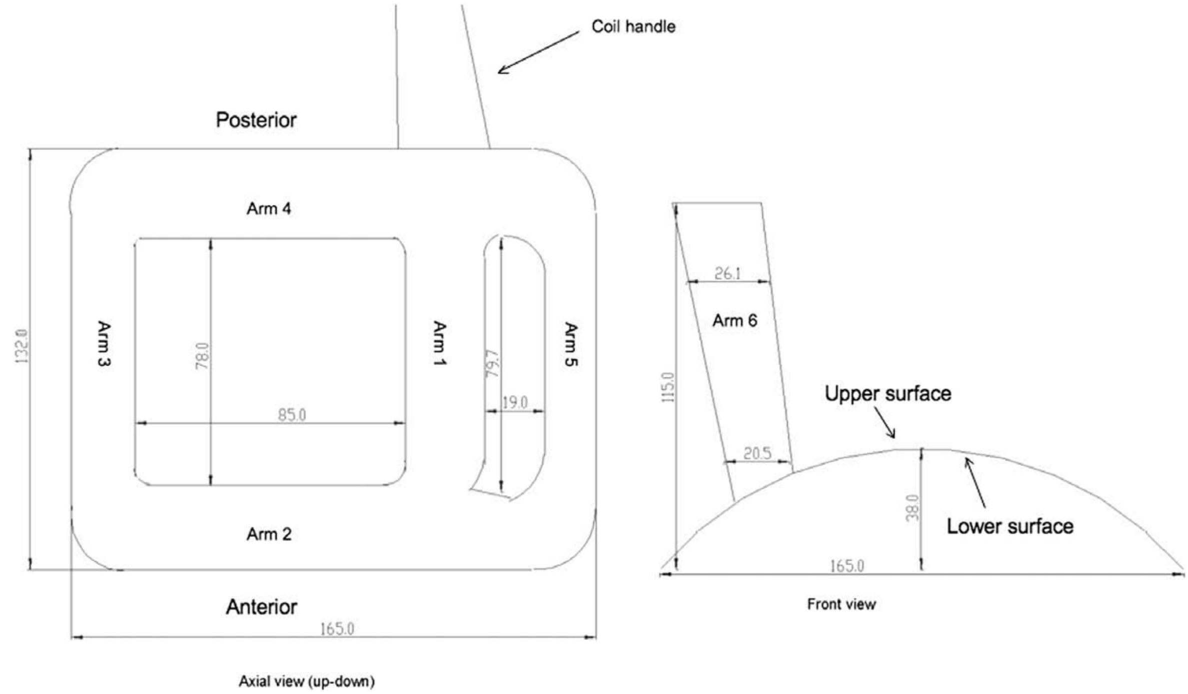

Fig. 1. A sketch of the geometry of the investigated H-coil prototype. The *axial view* shows the coil's geometric measures seen from above. The *front view* shows the geometric measures of the coil from the side opposite to the handle. The measures are expressed in millimeters (mm). The proportions of the coil are respected. For convenience, the coil has been divided in different parts indicated as "Arms". The numeration of the Arms follows the current flow into the coil. "Arm 6" was omitted in the axial view.