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Marked differences in the thermal characteristics of figure-of-eight shaped coils used for repetitive transcranial magnetic stimulation

Thomas Weyh[a], Kerstin Wendicke[a], Claudia Mentschel[b], Hannes Zantow[a], Hartwig R. Siebner[b,c,d,*]

[a]*Heinz Nixdorf-Lehrstuhl für Medizinische Elektronik, Technische Universität München, Arcisstrasse 21, 80333 Munich, Germany*
[b]*Department of Neurology, Technische Universität München, Moehlstrasse 28, 81675 Munich, Germany*
[c]*Department of Neurology, Christian-Albrechts-University, Niemannsweg 147, 24105 Kiel, Germany*
[d]*NeuroImageNord Hamburg-Kiel-Lübeck, Martinistrasse 52, 20246 Hamburg, Germany*

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Abstract

Objective: To compare the heating behaviour of three figure-of-eight shaped coils during repetitive transcranial magnetic stimulation (rTMS).

Methods: A custom-made coil (referred to as *test* coil) with a resistance-optimized conductor geometry was compared with two commercially available eight-shaped coils. Each coil was attached to the same energy source, which generated trains of 50 biphasic magnetic pulses every 20 s. Coil temperature was continuously measured during nine rTMS protocols using various combinations of stimulus frequencies (5, 10 or 20 Hz) and intensities (40, 50 or 60% of maximum stimulator output). A heating curve relating coil temperature and the number of applied stimuli was generated for each coil and rTMS condition. In eleven healthy volunteers, we evaluated the effectiveness of motor cortex stimulation. For each coil, we determined the motor threshold (MT) in the right first dorsal interosseus muscle.

Results: The slope of the heating curves of the *test* coil was markedly flattened relative to the heating curves of the two standard coils. This allowed the application of at least twice as many stimuli until the temperature of the coil reached 40 °C. Based on these data, we showed that a one-mass model could be used to accurately describe the heating behaviour of each coil. MTs determined with the *test* coil were comparable to or lower than the MTs that were determined with the standard coils.

Conclusions: The efficacy of the *test* coil to stimulate the M1 was comparable to the efficacy of the two standard coils, yet thermal characteristics were markedly improved.

Significance: Overheating of figure-of-eight shaped coils can be markedly delayed without reducing the efficacy of rTMS.

Keywords: Coil temperature; Efficacy; Figure-of-eight coil; Motor threshold; Overheating; Repetitive transcranial magnetic stimulation

1. Introduction

Since its introduction in 1985 (Barker et al., 1985), transcranial magnetic stimulation (TMS) has emerged as a safe and painless method for stimulating the human cortex through the intact scalp (Maccabee et al., 1991; Rothwell et al., 1999). A device for TMS consists of a transducing coil connected to a high-voltage, high-current discharge system which produces a strong magnetic field around the transducing coil for up to a few 100 ms (Barker, 1999). When the coil is placed on the scalp, the induced magnetic field passes without attenuation through the skull and induces an electrical current in the brain (Barker et al., 1985). The induced electrical current can excite cortical neurons depending on the intensity of stimulation.

The introduction of stimulating devices that can produce trains of magnetic stimuli at rates up to 50 Hz has considerably expanded the applications of TMS, since repetitive transcranial magnetic stimulation

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* Corresponding author. Address: Department of Neurology, Christian-Albrechts-University, Niemannsweg 147, 24105 Kiel, Germany. Tel.: +49 431 597 2703; fax: +49 431 597 2712.

E-mail address: h.siebner@neurologie.uni-kiel.de (H.R. Siebner).

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(rTMS) can induce lasting changes in cortical excitability and function (Hallett et al., 1999). This has opened up unprecedented possibilities to investigate regional cortical plasticity in health and disease (Siebner and Rothwell, 2003). Preliminary evidence also suggests that rTMS may be used to temporarily improve brain function in neuropsychiatric disorders (George et al., 1999; Siebner et al., 1999a,b; Wassermann and Lisanby, 2001).

For TMS, the stimulating coil should be highly efficient in order to produce maximal neuronal response at a given pulse energy. The stimulating coil should also be highly focal, to minimize spread of excitation to other cortical areas. Moreover, the discharge should produce minimal heat loss to avoid overheating during longer periods of TMS. So far, a figure-of-eight shaped coil design (also referred to as butterfly coil) has mainly been used for rTMS. This coil produces the largest current density in the tissue under its center with the largest component of the electric field being oriented in parallel to the wires in the center of the coil (Cohen et al., 1990; Roth et al., 1991). This coil design results in a more focal stimulation of the underlying cortex than circular coils (Cohen and Cuffin, 1991; Yunokuchi and Cohen, 1991). However, standard figure-of-eight shaped coils are far from being optimal for rTMS. In particular, the temperature rise caused by resistive heating poses a problem when longer periods of high-frequency rTMS are given. Here we compared the thermal characteristics of two standard figure-of-eight coils and a newly designed figure-of-eight coil with reduced internal resistance. Our measurements revealed that coil heating can be markedly reduced without affecting the effectiveness of stimulation.

2. Method

2.1. Technical description of the figure-of-eight shaped coils

Table 1 summarizes the technical details of the three figure-of-eight coils tested in this study. The design of the newly developed coil (referred to as '*test* coil') is illustrated in Fig. 1. The *test* coil consisted of 4 planar coils on top of each other. The coils in layers 1 and 4 had 15 turns and the coils in layer 2 and 3 had 12 turns, respectively. The mean winding diameter of each coil wing was 65 mm, ranging from 15 to 97 (layers 1 and 4) and 21 to 97 mm (layers 2 and 3). Accordingly, the dimensions of the *test* coil was 190×97 mm. The conductors were made of high-frequency Litz wire. Each filament was isolated with lacquer. The Litz wires were isolated using Capton. The 4 coil layers were connected in parallel and thus were interspersed by the same flux resulting in 4 equal inductances.

The first standard coil used for comparison was the 'Double 70 mm—Coil, Type P/N 9925' which is provided by Magstim Company (Whitland, Dyfed, UK; www.magstim.com). The surface of this figure-of-eight shaped coil (referred to as '*Magstim* coil') was flat and the two windings had a diameter of 56–91 mm (mean diameter: 74 mm). The second standard coil included in the comparison was the 'MC-B70 Butterfly Coil, Type MC-B70' provided by Medtronic-NeuroMuscular (Skovlunde, Denmark, www.medtronic.com). This figure-of-eight shaped coil (referred to as '*Medtronic* coil') had a slight bend and the turns in the centre of the coil were superimposed. The two windings had a diameter of 24–96 mm (mean diameter: 60 mm).

2.2. Experimental setup

To ensure comparability among measurements, all coils were connected to the same energy source (*MagPro* Stimulator, Medtronic-neuromuscular, Skovlunde, Denmark). This was possible because the magnetic stimulators constructed by Magstim Company and Medtronic-neuromuscular use capacitors of similar capacitances. Therefore, both coils could be operated producing the same pulse duration and configuration as designed by the manufacturer. We designed and constructed an adapter which enabled us to attach the *test* and the *Magstim* coil to the *MagPro* stimulator. This adapter also contained the electronics which evaluated the signals produced by the temperature sensors in the *test* and *Magstim* coil.

Prior to the main experiment, we discharged the capacitor of the *MagPro* stimulator through each coil. The intensity of stimulation was adjusted to 50% of maximum stimulator output. We measured the current direction and pulse duration induced in each coil with an arrangement of 3 orthogonal induction loops. The pulse durations are given in Table 1. The inductance of the *Medtronic* coil was significantly smaller (Table 1). Because the pulse length is proportional to the square root of the coil inductance, this results in a 10% decrease in pulse length relative to the other coils (Vachenauer, 1998).

In an LCR circuit the potential differences across each component are given by

$$\frac{1}{C}U_{\mathrm{C}}(t)+R_i\frac{\mathrm{d}U_{\mathrm{C}}(t)}{\mathrm{d}t}+L\frac{\mathrm{d}^2U_{\mathrm{C}}(t)}{\mathrm{d}t^2}=0 \tag{1}$$

where C is the stimulator's capacitance, U_{C} is the capacitors voltage, L is the coil's inductance and R_i is the sum of all internal resistances.

Assuming a small coil resistance R_i, the circuit is essentially an LC oscillator whose period (T) is given by:

$$T=2\pi\sqrt{L\cdot C} \tag{2}$$