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Minimal heating of titanium skull plates during 1 Hz repetitive transcranial magnetic stimulation

An important safety concern related to repetitive transcranial magnetic stimulation (rTMS), is the potential heating of metallic objects by induced eddy currents (Roth et al., 1992). For instance, conventional metallic disc EEG electrodes can heat to unsafe temperatures when exposed to rTMS, and thus can injure underlying scalp tissue (Pascual-Leone et al., 1990). A similar issue also concerns patients with implanted titanium (Ti) skull plates placed during craniotomy.

In our practice, the concern for effects of rTMS on Ti skull plates is particularly relevant for patients with epilepsy, who may benefit from a possible anticonvulsive effect of low frequency (0.3–1.0 Hz) rTMS (Theodore et al., 2002; Fregni et al., 2006). However, there is a need to establish the safety of this technique in patients who have had a craniotomy near a seizure focus (for placement of subdural EEG electrodes, for instance), and thus have Ti skull plates in the region of the stimulation site. Hence, we tested whether appreciable heating of Ti skull plates can occur with conventional low frequency rTMS treatment, and encouragingly found minimal heating of the Ti parts.

We recorded surface temperature during 30-min 1 Hz rTMS sessions from the two most common forms of Ti skull plates that are used in Children's Hospital: (1) 7 mm, 0.5 g round burrhole covers, and (2) linear 0.1 g "dogbone" plates (product No. 53-05507, and 53-05216: Stryker® Leibinger Micro Implants, Kalamazoo, MI) shown in Fig. 1a and b. These values were compared to conventional (0.7 g) gold disc electrodes (Grass Technologies Warwick, RI), that were previously shown to heat considerably during rTMS (Roth et al., 1992).

A 30-min rTMS protocol was simulated with a MindCare MagPro X100 stimulator and Figure-8 Cool-B65 Coil (Tonica, Farum, Denmark). Mock stimulation was provided for 30 min at 1 Hz (1800 pulses), at 100% machine output. The utility of using this stimulator and coil, is the liquid cooling mechanism of the Cool-B65 Coil which maintains relatively constant coil surface temperatures even with prolonged stimulation at maximal intensity. Thus, an increase in the temperature of a nearby metallic object can be attributed to the interaction of the object with induced eddy currents, rather than to conducted or radiated heat from the TMS coil.

The Ti plates were fixed in one of four positions relative to the TMS coil: (1) at the coil center, (2) at the center of one of the lobes, (3) at the coil edge, and (4) 1.0 cm past the coil edge. In positions 1–3, to avoid direct conduction of heat toward or away from skull plate, the Ti plates were separated from the coil surface by 0.5 mm. The Ti plates and EEG electrode were oriented parallel to the plane for the TMS coil surface.

Throughout the rTMS session, Ti temperature was recorded with a thermocouple (Omega Engineering, Inc., Stamford, CT) for subsequent analysis. Temperature was measured with a sampling rate equal to 0.25 Hz. Recording was done in ambient air at room temperature. TMS coil surface temperature was monitored at intervals during stimulation by an infrared thermometer (Model #22-325, Radioshack, USA), as well as the thermocouple. To simulate the environment of implanted skull plates, recordings were also made with plates attached to a water-filled thermal pad (Gaymar Industries, Inc., Orchard Park, NY) with temperature regulated to 37 °C. Temperature readings were fitted to an exponential heating curve by least-squares fit using Sigmastat 3.1 (Systat Software, Inc., San Jose, CA).

We limited testing to 1 Hz trains, the upper limit of "low frequency" stimulation with the assumption that lower frequencies would result on less heating than 1 Hz trains. Similarly, we limited testing to 100% machine output, assuming that at lower intensities would be associated with lower amplitude eddy currents and less heating. We chose to test Ti and not other metals, as this has been the most favored metal used to secure bone flaps since the gain in popularity of magnetic resonance imaging (MRI).

Simulated 1 Hz rTMS in ambient air produced minimal heating of the Ti plates, but considerable heating of gold EEG electrodes. Peak temperatures were reached within 900 s of stimulation – thereafter, temperatures reached equilibrium. Temperatures did not increase appreciably after the first 900 s of recording (Fig. 1c), likely due to cooling between pulses and heating, caused by induced eddy currents, reaching equilibrium. The peak temperatures for the Ti linear plate, burrhole cover and EEG disc electrode

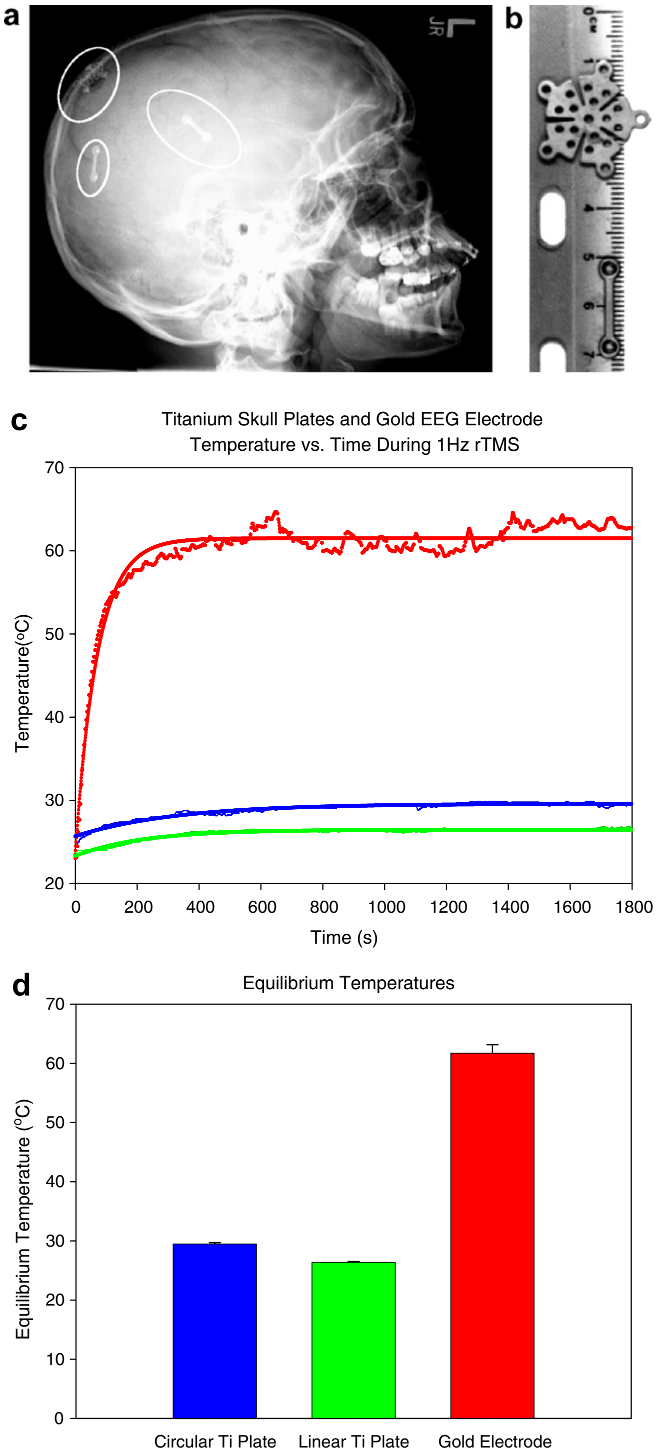

Fig. 1. Lateral skull radiograph of patient with past craniotomy and implanted circular and linear Ti skull plates (a). Identical Ti plates were used in our experiments (b). The Ti components were mounted on the TMS coil, but separated from the surface by 0.5 mm. (c) Temperatures equilibrated within 900 s of mock stimulation – red: gold EEG electrode; blue: circular Ti skull plate; green: linear Ti skull plate. (d) Average temperatures (±SD) at equilibrium for each of three metallic components (please note small error bars reflect the large sample number). *Note:* whereas the EEG disc electrode rapidly reached peak temperature >60 °C, the Ti plates increased only modestly from room temperature to ⩽30 °C. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this paper.)

were 30.2, 29.9 and 64.6 °C, respectively. At equilibrium, average temperatures for the Ti linear plate, burrhole cover and EEG disc electrode were 26.4 ± 0.2, 29.5 ± 0.2 and 61.7 ± 1.4 °C, respectively (Fig. 1d). One Way ANOVA shows these values to be significantly different ($P < 0.001$). Coil temperature ranged from 25.0 to 29.1 °C for all studies.

Of note, peak temperatures for the metallic objects were seen in the region of the center of a lobe of the figure-8, where induced currents were most likely in the same plane as the nearly-flat metallic objects (Wagner et al., 2004) We found no change in temperature of the tested components positioned 1 cm away from the coil edge.

To closer simulate a skull environment, we repeated the 1 Hz rTMS protocol with the Ti burr hole cover and the gold EEG electrode secured to a 37 °C water-filled thermal pad. There, the peak EEG electrode temperature equilibrated to 42.4 ± 0.1 °C, whereas the Ti plate temperature stabilized at 34.2 ± 0.2 °C (the lower-than-ambient temperature likely reflecting the heat-sink capacity of the TMS coil).

These data show that small Ti skull plates are not likely to heat sufficiently to injure surrounding tissue during conventional low frequency rTMS protocols, and thus low frequency (⩽1 Hz) rTMS may be safe for patients with small Ti skull plates that are in the stimulation site.

Our data also suggest that heating of gold EEG electrodes to perhaps unsafe temperatures (>60 °C) is possible during 1 Hz rTMS. Therefore, as previously suggested (Roth et al., 1992), EEG with conventional disc electrodes should be approached with caution during low frequency rTMS. However, as we found no appreciable heating of the disc electrodes positioned outside the margins of the TMS coil, injury from heat is not likely to occur in the regions of EEG electrodes anywhere but immediately beneath the TMS coil. The practical implication of this finding is that EEG with conventional disc electrodes may be performed during rTMS as long as the electrodes are sufficiently removed from the TMS coil.

Our study does not address whether heating of the Ti plates was limited by their mass, shape, or electrical properties such as resistivity. A more detailed analysis may be warranted for future studies. However, our simple methods for empiric measurement of metal component heating by simulated rTMS can be applied before most clinical protocols. We thus encourage similar quick assessment of potential heating in cases where rTMS may be applied over implanted cranial metal of different size, shape or composition than the two types of Ti skull plates tested in our study.

Last, in addition to heating of Ti skull plates and other cranial metal by eddy currents, their displacement due to Lorentz interaction of these eddy currents with the external magnetic field also warrants consideration. This concern is similar to that raised in patients with implanted nonferrous metal who undergo MRI (Sullivan et al., 1994). Encouragingly, we saw minimal displacement of loose Ti plates during simulated rTMS, not out of proportion to that attributable to vibration of the TMS coil. We also performed preliminary assessment of induced force with a table-top pendulum-bob method (data not shown) and estimate net force on the round and linear Ti components to be <0.015 N. A formal assessment of the forces exerted by rTMS on Ti skull plates may be required in the near future, but as a practical matter it seems highly unlikely that a well-seated screw into cortical bone would move with this weak force.

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