Heating of EEG electrodes during rTMS

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Abstract:
This study provides electrode heating data for modern repetitive transcranial magnetic stimulation (rTMS) paradigms for the recording of electroencephalograms (EEG) during rTMS. The concern is that during rTMS EEG electrodes can heat to an unsafe temperature. Seven electrode types were tested: silver/silver chloride, silver cup, gold cup, notched gold cup, notched silver cup, notched gold-plated silver cup, and carbon. Four of these are commercially available, including the carbon electrodes designed for MRI use. The three notched electrodes tested were standard electrodes notched using metal clippers to reduce eddy currents. The results of this study show that electrode heating is a concern when collecting EEG during rTMS. However, a number of standard electrodes or slightly modified standard electrodes are suitable for recording EEG during rTMS if certain stimulating parameters are adhered to.

Keywords:
Electrode heating
Transcranial Magnetic Stimulation
Electroencephalography
TMS-EEG combination

1. Introduction

Repetitive transcranial magnetic stimulation (rTMS) is a new technology which may be used to alleviate the symptoms of depression (Fitzgerald, 2003) and schizophrenia (Hoffman, 2005). Though it is known that brain electrical activity is altered by rTMS through Faraday induction, the sequence and regional distribution of the electro-chemical changes are not well understood. Electroencephalography (EEG) conducted during an rTMS session may help to clarify this.

The objective of this study was to determine experimentally whether modern standard or modified EEG electrodes are suitable for use in recording EEG during rTMS without the recording electrodes heating to a temperature that could cause thermal skin damage. This study builds on previous work by Pascual-Leone et al. in 1990 and Roth et al. in 1992 that helped clarify the heating of metal electrodes during rTMS. This study adds to their analysis the newly available carbon EEG electrodes available from Biopac Inc. and reanalyzes notching electrodes to reduce eddy currents (Pascual-Leone, 1990; Roth, 1992).

Many research groups currently use different electrodes to record EEG during rTMS and no standard choice has yet been determined. This study has been conducted to provide quantitative evidence for the safe use of intact or slightly modified commercially available EEG electrodes during rTMS.

2. Electrode Heating

The safe temperature an electrode can reach without causing cutaneous damage depends on the exposure time. To determine these thresholds we looked to a human study conducted in 1947 on healthy subjects that applied surface heating to the point of producing a first degree (1°) burn, i.e. a mild burn of the top layer of the skin characterized by pain and redness but without blistering. Condensing the results of this study we compiled a time-surface temperature table of thresholds for thermal injury of human skin relevant to our current experimentation. This compilation is shown in figure 1.

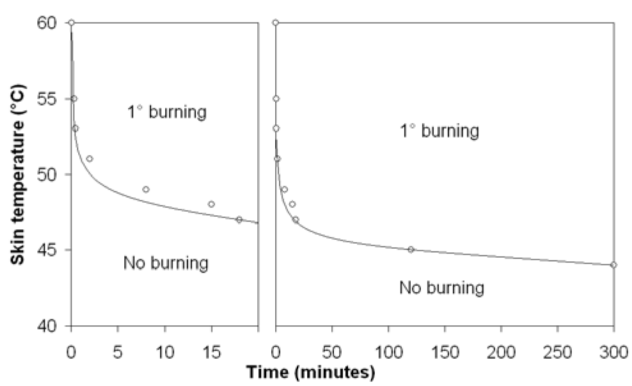

Figure 1: Time-temperature thresholds for burning of human skin. For points above the curve a first degree (1°) burn can result. For points below the curve no burning should occur. Source: Moritz et al., 1947.

Given that current rTMS treatment can include as many as 2,400 pulses at a frequency of 0.25Hz up to 20Hz, electrode heating is a concern for causing thermal skin damage. A typical rTMS treatment of 10Hz with train length of 80 pulses given once every minute would last 10 minutes for an 800 pulse treatment and 30 minutes for a 2,400 pulse treatment. From figure 1 we determine that for a 30 minute study, 46°C is the hottest temperature any scalp EEG electrode should be allowed to heat to. This is not to say that at all temperatures below 46°C no thermal damage will occur, because subjects will vary in their skins susceptibility to burning (Moritz, 1947). As well, any level of discomfort such as heat spots should be avoided. However, 46°C is a good estimate of an absolute upper limit.

The estimated range of normal body temperature in an adult is 36°C to 37.5°C (Guyton, 2000, pg. 823). If we take 37.5°C as the high-end skin temperature and use our previously determined skin temperature of 46°C as the temperature at which a 1° burn can occur during a combined TMS-EEG study, we see that the maximum temperature increase of electrodes attached to human skin allowed should be less than 8.5°C for a rTMS session lasting no more than 30 minutes. To err on the safe side and ensure no 1° burns, the temperature increase of the electrode in the worst position possible (that with the largest perpendicular magnetic field creating the most substantial planar electric field and thus the greatest heating) should be chosen such that it is less than 8.5°C.

The temperature increase of an electrode per stimulus is directly related to the electrical conductivity of the electrode, the square of the radius of the electrode and the square of the stimulus strength (Roth, 1992). Looking at conductivities of different materials (Table 1) that could be used as electrode material we can hypothesize which electrodes will be suitable for rTMS-EEG studies.

Table 1: Electrode conductivities (σ)

Material	Conductivity (x 10^6 S/m)
Silver	62.9
Gold	41.0
Carbon	0.029

Source: Serway, 2000, pg. 847

3. Materials and Equipment

Temperature measuring equipment used was a thermistor temperature probe with 0.01°C accuracy (Digi-Sense LN5775, Cole-Parmer, Illinois) calibrated to +/- 0.2°C and read to 0.1°C. The TMS machine used was a Magstim Super Rapid. The TMS coil used was a Magstim figure-of-eight air-cooled coil P/N 1640 (Inner diameter 56mm, outer diameter 87mm, 9x2 turns, 16.4μH inductance, 0.93Tesla peak magnetic field). Four commercially available EEG electrode types were tested. They were: (i) XLTEK reusable EEG/EP electrodes Part no. #101339 (silver cup, 10mm diameter, 2mm hole). (ii) Standard gold cup electrodes (10mm diameter, 2mm hole). (iii) Ag/Ag Cl surface electrodes model F-E5SCH-48 (10mm diameter, 2mm hole, Grass Technologies). (iv) EL258RT Ag-AgCl reusable, general purpose, 8mm diameter, no hole, radiotranslucent carbon electrodes with carbon leads (Biopac Systems Inc.). Additionally, the above mentioned gold cup and silver cup electrodes were pie notched to reduce eddy currents and also tested, and a gold-plated silver cup electrode (10mm diameter, 2mm hole, Nicolet) was fully notched and tested.

4. Method

All testing was done on a ¼ inch sheet of plywood that was marked with a 1cm grid pattern to help ensure accurate coil placement. Electrodes were attached using EEG paste (Ten20 conductive EEG paste). Testing parameters used in this study mirrored those used in standard rTMS treatments, which are 10Hz stimulation for up to 8s trains and 20Hz stimulation for up to 3s trains. It is known that temperature increase of electrodes varies approximately in proportion to the square of the stimulus strength (Roth, 1992), thus stimulator intensity is a very important factor in electrode heating. Stimulus intensity applied was set at 85% of our stimulating machine's maximum intensity to slightly exceed 110% of motor threshold (MT) of an average subject at our own and other rTMS laboratories (Thut, 2005).

Multiple electrode tests were conducted, plus the control case, where only the temperature probe was present with no electrodes. For coil selection we chose to use a figure-of-eight coil since it heats electrodes significantly more than a circular coil (Roth, 1992). Figure 2 shows how electrodes were positioned in relation to the stimulating coil.

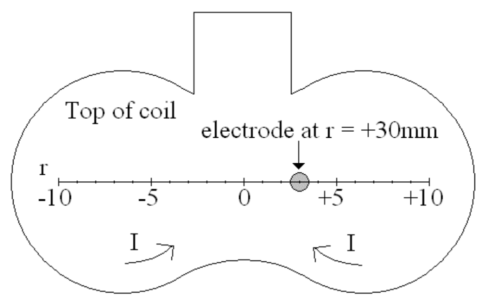

Figure 2: Stimulating coil showing how electrodes were positioned underneath with respect to the r-axis, labeled in cm.

Variable values were selected to provide the maximum heating while minimizing the number of experimental trials needed by using the work of Roth et al. (1992) to help determine optimal heating parameters. Looking at figure 2, and applying a standard x-axis and y-axis, electrode position was not varied along the y-axis because electrode heating under a symmetrical coil is largest along the x-axis at y=0 (Roth, 1992). A mechanical arm was used to position the coil and hold it in place during testing.

5. Results and Discussion

Room temperature during testing was 23°C. Coil temperature during testing was between 24°C and 26°C, held within that range by an air cooling system attached to the coil. Electrode heating was due to eddy currents created within the electrodes by the large varying magnetic field and to a lesser extent by conduction of heat from the coil itself.

Looking at the thermal conductivity differences of the human arm versus the test case of plywood, wood has a thermal conductivity of 0.08W/m·°C, while a human, composed largely of water, would have a thermal conductivity closer to that of water which is 0.6W/m·°C (Serway, 2000). In comparing the wood used to skin on the human head, heat would be better conducted away by the head, meaning that temperature results obtained on wood should be slightly higher than expected on the scalp.

All testing used the magnetic stimulator at 85% intensity, except two tests: one with no electrode present and one with the carbon electrodes. Between every test the electrodes were allowed to cool to room temperature before the next test was started. For all tests the coil was placed directly against the electrode, with an estimated distance of 10mm from the plane of the coil to the center of the electrode, accounting for the thickness of the plastic encasing the actual metal coils.

We first tested the silver electrode, varying the distance from the center of the figure-of-eight coil (r), to find the value for r where heating was a maximum. The results of this test are given in figure 3.

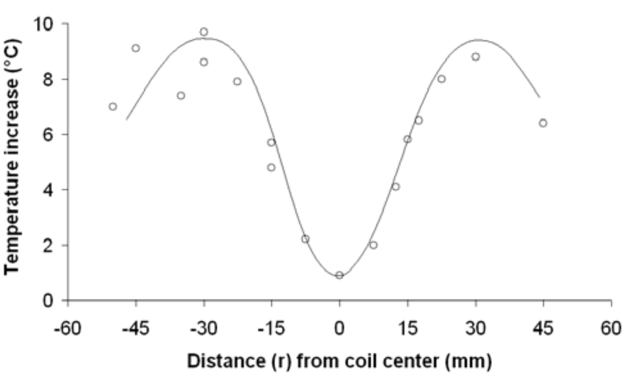

Figure 3: Temperature increase of a silver cup electrode from 3s at 20Hz at 85% intensity vs. the distance from the center of the figure-of-eight coil.

This agrees with the results presented by Roth et al. (1992) who showed that the maximum heating occurs at two locations, each half way between the center of one coil and the midpoint of a line drawn between the two centers of the two coils.

We then conducted the same 3s 20Hz test, at the maximum heating location, determined to be r = 30mm, for 6 different electrodes. Figure 4 shows the heating and cooling curves for these tests.

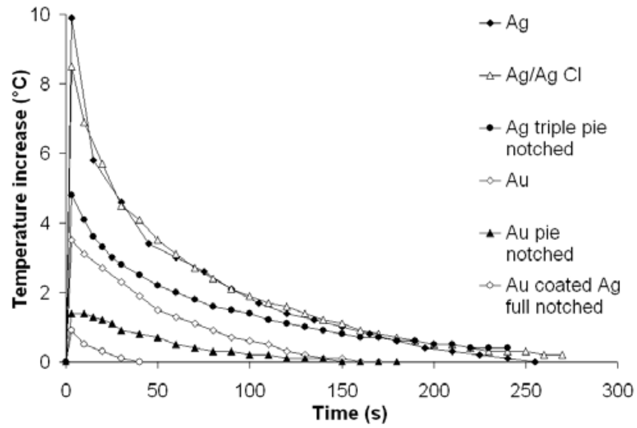

Figure 4: Temperature effects on 6 different electrodes from a single train of 3s at 20Hz at 85% intensity, r = -30mm.

Figure 5 shows three types of notching used. The pie notched electrodes did not eliminate the circular current path around the center hole and therefore did not result in as significant a heating reduction as the full notched electrode.

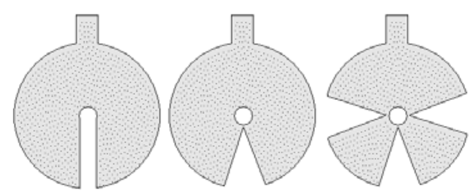

Figure 5: Differences in notching. From left to right: full notched, pie notched, triple pie notched.

The heating results of varying the distance from the center of the coil (r) for the gold-plated silver cup full notched electrode are shown in figure 6.

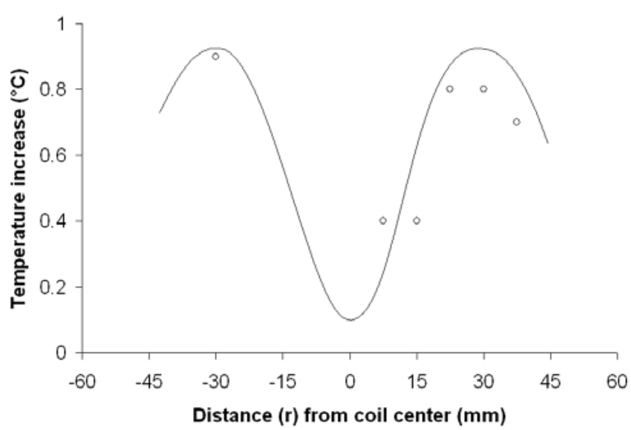

Figure 6: Temperature increase of a gold-plated silver cup electrode from 3s at 20Hz at 85% intensity vs. the distance from the center of the figure-of-eight coil.

When carbon electrodes were stimulated at 20Hz for 3s at 85% intensity, r = -30mm, the temperature rose 0.0°C. When stimulated at 20Hz for 10s, r = -30mm, at 100% intensity, the temperature rose 0.8°C. However, when the carbon electrode was removed from the stimulating environment leaving only the temperature probe and the EEG paste and we stimulated at 20Hz for 10s at 100% intensity, the temperature rose 0.3°C. This showed that the temperature probe accounted for some of the increase in temperature when 200 pulses were given. Clearly, the carbon electrodes do not pose a heating risk under normal stimulating conditions. However, they are about three times the cost of Ag/Ag Cl electrodes.

Next, we heated gold cup electrodes at 10Hz for 8s at 85% intensity to simulate a standard rTMS treatment session. The results of this test are shown in figure 7.

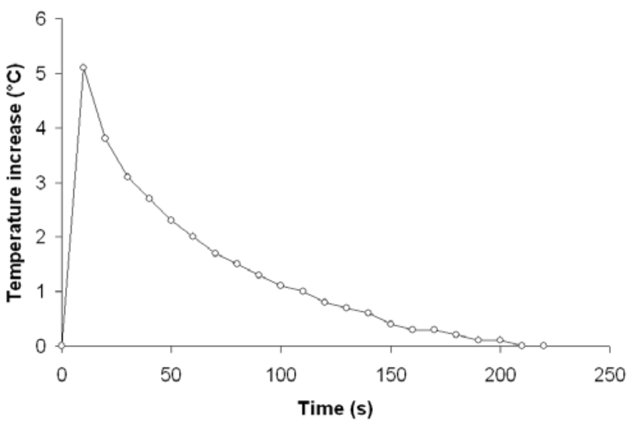

Figure 7: Temperature effects on gold cup electrodes from a single train of 8s at 10Hz at 85% intensity, r = -30mm.

Next, the same gold cup electrode was stimulated with 3 trains, starting times spaced 60s apart, of 3s at 20Hz, 85% intensity. Due to the fact that the next stimulus train started before the electrodes had a chance to completely cool, the next peak temperature reached for every pulse train after the first was significantly higher than the one before it. A plot showing the results of this test is given in figure 8.

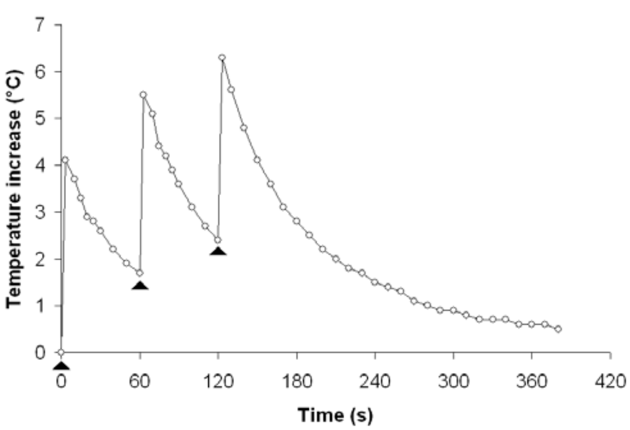

Figure 8: Temperature effects on gold cup electrodes from 3 trains of 3s at 20Hz at 85% intensity, r = -30mm. Trains were given at 0s, 60s, and 120s.

6. Conclusions

Unmodified silver and silver/silver chloride electrodes appear unsuitable for standard rTMS-EEG studies when high stimulus intensities are necessary due to the high conductivity of silver. If used at all, pulse trains should not exceed 30 pulses and electrodes should be allowed 290s to cool between trains, given the current TMS and coil parameters tested. Gold cup electrodes are suitable for rTMS-EEG studies for a Magstim cooled coil if stimulus intensity is kept below 85%, trains do not exceed 80 pulses, and electrodes are allowed to cool for 220s between stimulus trains. However, notching does work, and when notched properly (a full notch) electrode heating is reduced enough to make silver and gold-plated silver electrodes suitable for a standard rTMS-EEG study. The newly available carbon electrodes should be suitable for any rTMS-EEG patient study and their heating would not be the limiting factor in selecting stimulating parameters.

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