Abstract

Background: Transcranial magnetic stimulation (TMS) produces magnetic pulses by passing a strong electrical current through coils of wire. Repeated stimulation accumulates heat, which places practical constraints on experimental design.

New Method: We designed a condensation-free pre-chilled heat sink to extend the operational duration of transcranial magnetic stimulation coils.

Results: The application of a pre-chilled heat sink reduced the rate of heating across all tests and extended the duration of stimulation before coil overheating, particularly in conditions where heat management was problematic.

Comparison with Existing Method: Applying an external heat sink had the practical effect of extending the operational time of TMS coils by 5.8 to 19.3 minutes compared to standard operating procedures.

Conclusion: Applying an external heat sink increases the quantity of data that can be collected within a single experimental session.

Abbreviations: TMS, Transcranial Magnetic Stimulation; MSO, Maximum Stimulation Output.

Introduction

Transcranial magnetic stimulators produce magnetic pulses by passing strong electrical currents through coils of wire (Barker AT, Jalinous R, 1985). Repeated stimulations accumulate heat (Weyh, Wendicke, Mentschel, Zantow, & Siebner, 2005) and this limits the duration of experiments. Some coils have design features such as internal venting to manage heat dissipation (Rossi, Hallett, Rossini, & Pascual-Leone, 2009). However, these coils are typically designed for rTMS protocols that use rapid but low-powered pulse trains, which may not meet the needs of neurophysiological experiments requiring high stimulation magnitudes. The additional bulk of these cooling systems is also an obstacle to designs requiring the placement of multiple coils on one patient.

We designed a heat sink that can be pre-chilled and placed in contact with TMS coils while they are in use. The heat sinks were manufactured from cotton flannel, cotton broadcloth, and cotton thread and filled with Linum usitatissimum (common whole flaxseed). Breathable fabrics were chosen to allow airflow and prevent condensation. Two separate sizes were manufactured for the 40mm and 50mm alpha branding iron coils weighing 124 grams and 149 grams, respectively (see Figure 1). An elastic band sewn into the heat sink ensured close contact with the upper surface of the coils. We tested the efficacy of this accessory in managing heat dissipation in TMS experiments.

Figure 1 about here

Materials and Methods

Figure-of-eight branding iron coils were attached to two $magstim_{200}$ stimulators which were controlled by an MacMini computer (OSX v10.10.5) running Python (v2.7.1) extended with the MagPy package and connected to the stimulators by custom built Quickfire cables adapted by from McNair (2017). Stimulators were triggered remotely with an inter pulse interval of 10 seconds to simulate a common experimental parameter (Giovannelli et al., 2009; Howatson et al., 2011; Iwata, Jono, Mizusawa, Kinoshita, & Hiraoka, 2016). Stimulation continued until the internal temperature of the coils triggered automatic safety shutoff, or to a maximum of 500 trials. The internal temperature of the coil was recorded before the onset of the experiment and immediately after each stimulation using the system's internal sensors. The number of trials completed before reaching maximum temperature was taken as an index of the number of trials that would be practicable for TMS experiments.

This procedure was repeated with 40mm and 50mm alpha branding iron coils, with stimulator power set to 55, 65, and 75 percent of maximum stimulator output (%MSO), and with or without the application of an external heat sink. Heat sinks were pre-chilled to -20°C. Permutations of coil size, stimulation power, and heat sink were replicated four times each in random order. Sessions were conducted in a climate-controlled room set to 22°C. The ambient room temperature was verified by analog thermometer prior to each session. Coils were allowed to return to room temperature between sessions.

Results

We constructed linear models (Bates, Maechler, Bolker, & Walker, 2015; R Core Team, 2017) to predict the number of trials before automatic shutoff from the coil size, stimulation power, and the presence/absence of the heat sink (see Figure 2). A comparison of linear models revealed no main effect of coil size $F(1, 36) = 0.013$, $p = 0.91$, a significant main effect of stimulation power $F(2,36) = 1581.5$, $p < 0.05$, and a significant effect of the heat sink $F(1,36) = 84.8$, $p < 0.05$. However, there were also significant interactions between coil size and heat sink $F(1,36) = 8.4$, $p < 0.05$, heat sink and stimulation power $F(2,36) = 14.8$, $p < 0.05$, and a three way interaction between coil size, stimulation power, and heat sink $F(2,36) = 5.7$, $p < 0.05$.

Figure 2 about here

In light of the significant interactions we performed a battery of simple main effects within coil size and stimulation power. There was no effect of the heat sink at stimulation power of 55 %MSO for the 40mm coil [$F(1,6) = 1.2$, $p = 0.32$, CI -11.7 to 30.2 trials] or the 50mm coil [$F(1,6) = 2.0$, $p = 0.21$, CI -3.1 to 11.6 trials]. There was no effect of the heat sink at a stimulation power 65 %MSO for the 40mm coil [$F(1,6) = 1.4$, $p = 0.28$, CI -27.2 to 79.2 trials], but there was a main effect for the 50mm coil [$F(1,6) = 83.6$, $p < 0.05$, CI 67.2 to 116.3 trials]. There was a significant main effect of heat sink at stimulation power of 75 %MSO for both the 40mm coil [$F(1,6) = 79.0$, $p < 0.05$, CI 35 to 61.5 trials] and 50mm coil [$F(1,6) = 300.6$, $p < 0.05$, CI 55 to 73 trials].

Discussion

We tested a novel pre-chilled heat sink to manage overheating in TMS coils. We found that larger coils were more prone to overheating, particularly with greater stimulation power. These heat sinks are effective, inexpensive, produce no device-harming condensation, and add little bulk to the coils, which is of particular importance when conducting multi-coil experiments. The application of an external heat sink mitigated coil overheating, particularly for larger coils and with high stimulation power. At low stimulation power heat sinks may accumulate sufficient heat to act as an insulator in which condition the heat sinks may be counterproductive. Where it was effective the heat sinks prolonged the safe operation of the stimulators between 35 and 116 trials corresponding to 5.8 to 19.3 minutes of additional stimulation time. Inter-test variation in the benefit of the heat sinks may be due to differences in the time taken to move the heat sinks from the freezer to the onset of stimulation. The use of these heat sinks in neurophysiological experiments with TMS would allow for more data to be collected in a single session.

We recommend these external heat sinks for experiments that must use standard coils lacking built-in cooling hardware, at high stimulation powers as is common in neurophysiological studies. In practical application, we have found it feasible to position coils over their targets prior to applying the heat sinks. It may also be useful to design experiments with breaks in the stimulation paradigm that would allow researchers to remove or replace heat sinks that are no longer cooler than the ambient temperature of the laboratory.

The flannel outer covering also provides an opportunity to increase the aesthetic appeal of TMS coils with no detrimental heating or power effects. Coil aesthetics is of particular relevance for populations that may experience anxiety about undergoing neurostimulation, such as pediatric patients (Rajapakse & Kirton, 2013). This feature may have potential similar to the practice of training patients with pediatric-friendly mock scanners in the context of magnetic resonance imaging, which alleviates procedure related anxiety in both the patient and the family (De Bie et al., 2010).

Conflicts of Interest

We declare no conflicts of interest.

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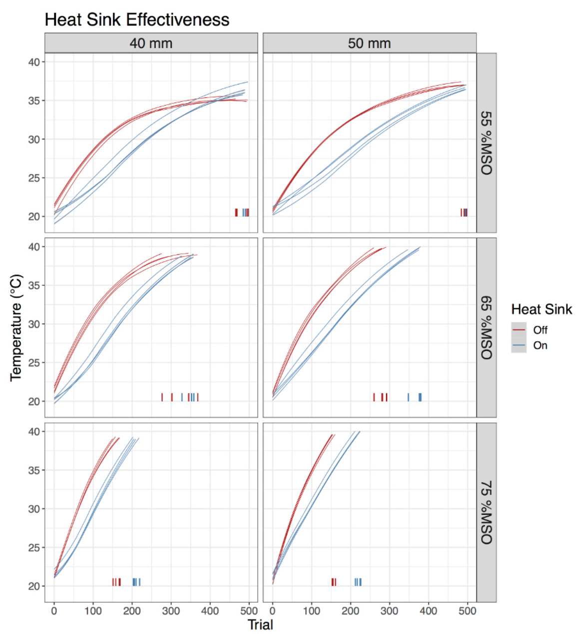
Figure Legends

Figure 1: Upper) Heat sinks installed on branding iron coils. Lower) Superior and inferior views.

Figure 2: Lines show the progressive heating of TMS coils over successive stimulations. Rug plots show the trial on which coils reached maximum temperature. These indicate the number of trials completed before triggering an automatic shutoff with the exception of the few cases in which the full complement of trials was completed.


Heat Sink Effectiveness
40 mm
50 mm
55 %MSO
65 %MSO
75 %MSO
Temperature (°C)
Trial
Heat Sink
Off
On
20
25
30
35
40
0
100
200
300
400
500