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The heating of metal electrodes during rapid-rate magnetic stimulation: a possible safety hazard

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Summary The temperature of electrodes and metal disks positioned close to a coil was measured during rapid-rate magnetic stimulation. The temperature rise ranged from a fraction of a degree to almost half a degree per stimulus pulse and increased with the electrical conductivity of the metal, the square of the electrode radius and the square of the stimulus strength, and was independent of the electrode thickness. During a brief high-frequency train, the temperature increase from each pulse added; during a long, high-frequency train the temperature increase approached a steady state. After the stimulus ended, an electrode on the arm cooled with a time constant of about 45 sec. A standard silver EEG electrode on the surface of the skin did not increase in temperature enough to induce a skin burn if the stimulating rate was below 0.4 Hz or the total number of stimuli was less than 20. Heating was reduced by cutting gaps in the electrode.

Key words: Magnetic stimulation; Safety; Burn; Electrodes

Commercially available magnetic stimulators can deliver stimuli at rates of up to 0.5 Hz (Cadwell 1989). At this low rate they seem unable to evoke the same behavioral and physiological effects that are caused by higher frequency trains of electric stimuli, thereby limiting the applicability of magnetic stimulation for the study of higher cortical functions. The recent introduction of a magnetic stimulator capable of stimulating at rates of up to 30 Hz might expand greatly the applications of magnetic stimulation. Pascual-Leone et al. (1991a) have reported the induction of speech arrest when delivering trains of up to 25 Hz over the presumed Broca's area, thereby accurately predicting hemispheric dominance for language in accordance with the results of intracarotid amytal injections. With the possibility of delivering trains of pulses at high frequencies, however, specific new safety aspects of magnetic stimulation need to be considered (Pascual-Leone et al. 1991a,b). At present, experience with rapid-rate magnetic stimulation is limited. The surface EEG, and the results of a neurological examination and the Mini-Mental Test, were unchanged in all subjects following delivery of trains of magnetic stimuli (Dhuna et al. 1991; Pascual-Leone et al. 1991a). In epileptic patients, no changes in the seizure frequency or seizure type have been found after rapid-rate magnetic stimulation (Dhuna et al. 1991). Finally, the lack of structural damage to the brain following repetitive magnetic stimulation was documented in temporal lobectomy specimens from two epileptic patients who underwent magnetic stimulation in trains and later epilepsy surgery (Gates et al. 1991).

One potential safety hazard during rapid-rate magnetic stimulation is the heating of metal objects, such as EEG electrodes, on the skin surface by the induction of eddy currents in the metal (Pascual-Leone et al. 1990). Eddy currents are defined as electrical currents induced by a changing magnetic field (Smythe 1968). The eddy currents induced in metal are much larger than those induced in the body because the electrical conductivity of most metals is more than a million times greater than the conductivity of biological tissues. These eddy currents cause Joule heating of the electrode. This heating is particularly severe if a train of stimulating pulses is delivered at a high frequency, so that the electrode does not have time to cool between pulses. In a recent report, rapid-rate magnetic stimulation over a silver/silver chloride EEG electrode caused a skin burn under the electrode (Pascual-Leone et al. 1991a). In this paper, our goal is to characterize the phenomenon of electrode heating during magnetic stimulation. We describe controlled quantitative experiments, which provide a basis for assessing the risk of

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burning, and present preliminary safety guidelines for users of rapid-rate magnetic stimulation. Strategies to reduce the risk of burns are considered.

Methods

We studied electrode heating by recording the temperature of an electrode during and after rapid-rate magnetic stimulation. Temperature was measured using a thermocouple with 0.01°C resolution (Type T thermocouple and a Model Bat-12 sensor, Sensortek, Inc., Clifton, NJ). It showed no response to magnetic stimulation if it was either in air or on the skin, unless it was near an electrode. The thermocouple was placed in a thin layer of electrode gel (Spectra 360 electrode gel, Parker Lab., Inc., Orange, NJ) in contact with the electrode and either the skin or a wooden table. Trains of magnetic stimuli were applied with either a Cadwell MES-10 magnetic stimulator (Cadwell Lab., Inc., Kennewick, WA), a Cadwell rapid-rate magnetic stimulator, or a Novametrix Magstim 200 magnetic stimulator (Novametrix Medical Systems Inc., Wallingford, CT). We studied standard silver or gold EEG electrodes [1] (Grass Instruments, Quincy, MA) and flat metal disks of different thicknesses and diameters made from aluminum, brass, and stainless steel (see Table II). The coils attached to the MES-10 and the Magstim 200 stimulators became hot after extended use. Control experiments were performed to verify that the electrode heating was not caused by the warming of the surrounding environment by the coil. The rapid-rate stimulator was water cooled, so that its coil did not get hot.

Results

The temperature increase of the electrodes and disks ranged from a small fraction of 1° to about 0.5° per stimulus pulse, depending on the position and orientation of the electrode relative to the stimulating coil, the electrode size and material, and the stimulus strength. We placed an aluminum disk (radius = 4.94 mm, thickness = 1.55 mm) at the center of a circular coil (nominally 90 mm in diameter [2]) and delivered stimuli using the Cadwell MES-10 magnetic stimulator

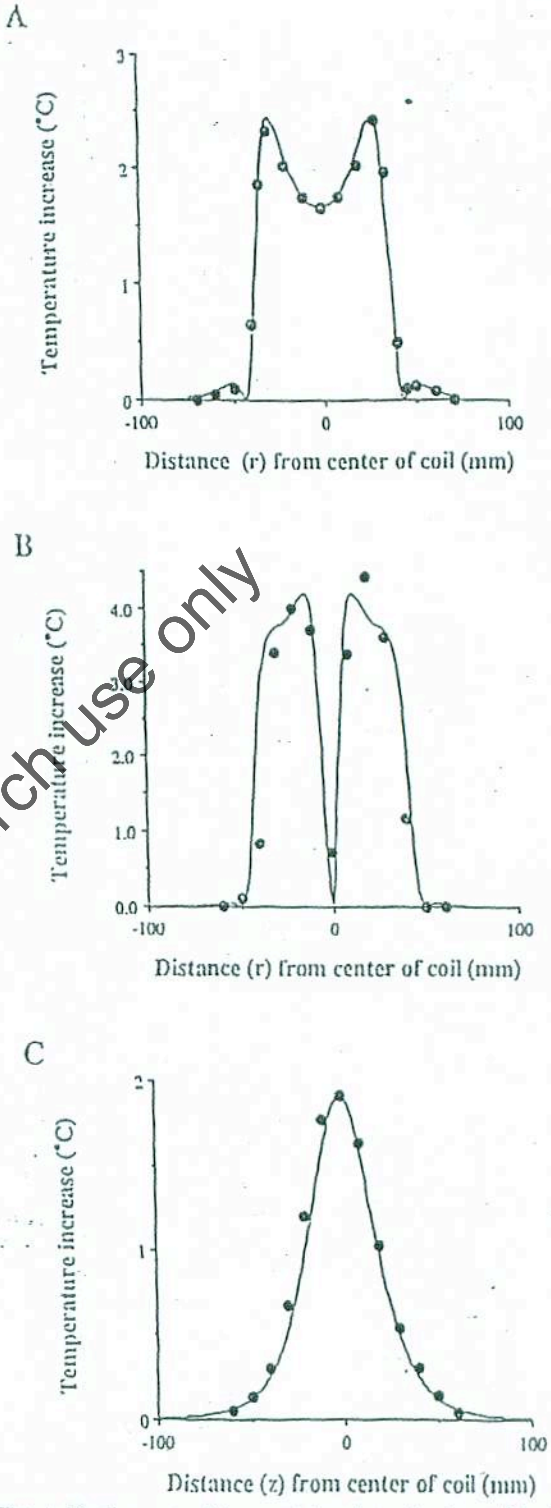

Fig. 1. The increase of temperature of an aluminum disk during magnetic stimulation with a Cadwell MES-10 stimulator, under (A) a circular coil (radius of 40 mm), and (B) a figure-8 coil (each side had a radius of 22.5 mm), at a distance r from the center of the coil. C: the temperature increase as a function of the perpendicular distance, z, from the center of the circular coil. The smooth curves in A and B are the normalized square of the magnetic field component perpendicular to the coil, calculated using the technique described by Cohen et al. (1990) and assuming that the disk lies in a plane 10 mm below the coil; the extra 5 mm account for the thickness of the plastic cover and the width of the wire. The magnetic field evaluated along the axis of a circular coil is proportional to $1/\sqrt{(z^2+b^2)^3}$, where b is the coil radius (Reitz et al. 1980). The square of this function is shown as the curve in C.

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[1] According to the manufacturer, the silver electrodes are pure, solid silver, while the gold electrodes are gold plated over a silver electrode (personal communication, Grass Instruments). The electrodes have a diameter of about 10 mm and a thickness of approximately 0.6 mm. They are not flat disks but are shaped in a cup, so that only the outer rim of the electrode is in contact with the skin. At the center of the electrode is an approximately 2 mm diameter hole.

[2] The outer plastic casing has a diameter of about 90 mm, although an X-ray of the coil shows that the wire itself lies in a loop with a diameter closer to 80 mm.

(4 pulses at 0.25 Hz, 100% of output). When the plane of the disk was oriented parallel to the plane of the coil, the temperature rise was 14 times greater than when the disk was rotated 90° so it was oriented perpendicular to the plane of the coil. The heating of this disk depended on its position relative to the coil. The disk was oriented parallel to the plane of the circular coil, and its position was varied in a plane 5 mm below the bottom of the plastic casing encapsulating the coil. Heating was greatest under the inside edge of the coil, fairly uniform below the coil center, and fell off rapidly near the periphery (Fig. 1A). For a figure-8 coil (45 mm diameter of each side; Fig. 1B), heating was greatest under each side of the coil, but was small under the coil center. We measured the heating of the disk along a line perpendicular to the circular coil and passing through its center and found that the temperature decreases monotonically with distance from the coil (Fig. 1C). We varied the output of the MES-10 stimulator between 30 and 100% and found that the temperature increase was approximately proportional to the square of the stimulus strength (Fig. 2).

We stimulated metal disks of various sizes constructed from aluminum, brass and stainless steel. The electrical and thermal properties of these metals are given in Table I. The disks were each placed at the center of the circular coil, parallel to the plane of the coil. The measured temperature increases after 4 pulses (0.25 Hz, 100%) from the MES-10 magnetic stimulator are shown in Table II. These results show how electrode heating depended on the electrode metal, radius and thickness.

TABLE I

The electrical conductivity, σ, density, ρ, and specific heat, c, of several metals.

Metal	σ ($\times 10^6$ S/m)	ρ ($\times 10^3$ kg/m^3)	c (J/kg°C)	$\sigma/(\rho c)$ (S m^2°C/J)
Silver	62.9	10.5	237	25.3
Gold	41.0	19.3	129	16.5
Aluminum	35.4	2.70	899	14.6
Brass *	16.1 [a]	8.53 [a]	376 [a]	5.02
Platinum-iridium **	4.0 [a]	21.5 [a]		
Stainless steel ***	1.36 [b]	9.93 [b]	493 [a]	0.278

All values taken from the Handbook of Chemistry and Physics (59th Ed., R.C. Weast, Ed., CRC Press, Boca Raton, FL, 1978) except as noted below:

[a] Metals Handbook, 1948 Edition, T. Lyman, Ed., The American Society for Metals, Cleveland, OH, 1948.

[b] Electrical Engineer's Handbook, Electric Communication and Electronics, 4th Ed., H. Pender and K. McIlwain, Eds., John Wiley and Sons, New York, 1950.

* Brass is an alloy of copper and zinc. Its physical properties vary with the percentage of copper in the alloy. The data given here are for 70% copper.

** The iridium content of platinum-iridium alloys vary. The data given here are for 10% iridium. We have been unable to obtain values of the specific heat of Pt-Ir alloys.

*** Stainless steel (an alloy of iron, nickel and chromium) comes in many varieties, among which the electrical conductivity varies substantially. The electrical conductivity and density given here correspond to type 304, which is the type used in our experiments. The specific heat is for type 303, which is similar in composition to type 304.

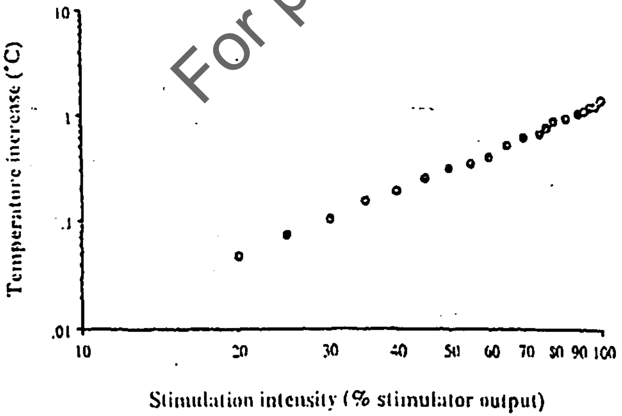

Fig. 2. The increase in temperature of an aluminum disk as a function of the percent output of the magnetic stimulator (MES-10, circular coil). In this log-log plot, the straight-line relationship indicates that the temperature increase is proportional to the square of the percent output.

We next stimulated Grass silver EEG electrodes. These electrodes were connected to their lead wires by a metal shaft which contained approximately one-third of the total electrode mass. We disconnected the lead wires from two identical silver electrodes, and then filed the metal shaft off one of them. The temperature of the electrode with the shaft removed increased by 2.63 ± 0.12°C when stimulated using the MES-10 stimulator and a circular coil (4 pulses, 0.25 Hz, 100%), while the temperature of the electrode with the shaft attached increased by 2.07 ± 0.10°C (mean and standard deviation after 3 measurements). Another silver electrode with both its shaft and lead wires intact increased in temperature by 1.94 ± 0.10°C. In a gold-plated silver Grass EEG electrode we cut a slot from the outer edge of the electrode to the inner hole. This electrode increased in temperature only about a third as much (0.85 ± 0.07°C) as an identical gold-plated silver electrode with no slot cut (2.32 ± 0.25°C) (MES-10, 100%, round coil, 4 pulses at 0.25 Hz). Finally, we placed a silver electrode approximately 10 mm below the center of one side of a figure-8 coil [3] and stimulated with the rapid-rate magnetic stimulator at 100%

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[3] A special water-cooled coil is used with the rapid-rate stimulator. It has a figure-8 shape, but unlike traditional coils the wires are curved to approximately follow the contour of the scalp.

of the output for 10 sec at 16 Hz. The temperature of the electrode rose about 76°C.

We attached a silver electrode to the surface of the skin and measured both the heating during magnetic stimulation and the subsequent cooling. Fig. 3A shows the change in temperature as a function of time for the electrode attached to the forearm during stimulation using the rapid-rate magnetic stimulator (100% output). Each train consisted of 40 stimuli delivered at frequencies ranging from 0.25 to 2 Hz. Fig. 3B shows the time course of cooling after the train was complete, on a semilogarithmic scale.

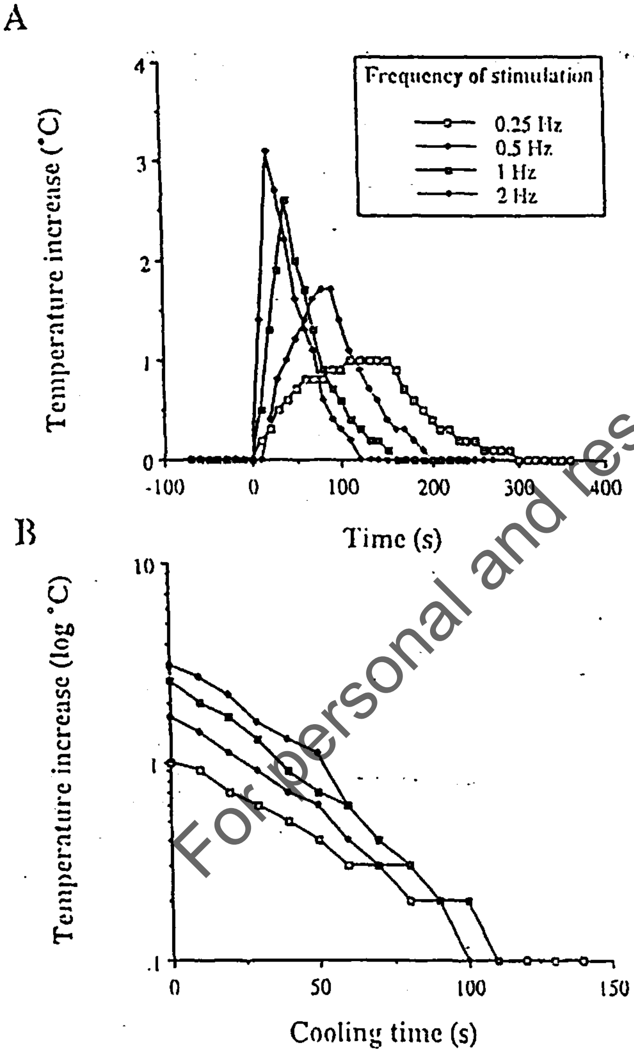

Fig. 3. A: the electrode temperature increase as a function of time for a silver electrode attached to the surface of the forearm. Stimuli were given in trains of 40 pulses, at frequencies of 0.25, 0.5, 1.0 and 2.0 Hz. B: the same data as in A, except plotted on a semilogarithmic scale and showing only the electrode cooling after completion of the train. In this particular experiment, the thermocouple was used in a mode for which it had only 0.1°C resolution. The time constant for cooling is about 45 sec. From Eq. 5, and using a ΔT of 0.1°C and a τ of 45 sec, we predict that the maximum temperature increase for each train should be 3.25, 2.68, 1.91 and 1.14°C.

TABLE II

Temperature increase of metal disks of various sizes and materials.

Metal	Radius (mm)	Thickness (mm)	ΔT (°C)
Aluminum	3.25	0.81	0.68 ± 0.08
Aluminum	3.25	1.55	0.81 ± 0.06
Aluminum	4.94	0.81	1.79 ± 0.15
Aluminum	4.94	1.55	1.71 ± 0.09
Aluminum	6.43	0.81	3.02 ± 0.21
Aluminum	6.43	1.55	2.93 ± 0.12
Brass	3.25	0.81	0.50 ± 0.18
Brass	3.25	1.55	0.51 ± 0.15
Brass	4.94	0.81	1.10 ± 0.07
Brass	4.94	1.55	1.06 ± 0.18
Brass	6.43	0.81	2.00 ± 0.13
Brass	6.43	1.55	2.00 ± 0.10
Stainless steel	3.25	0.43	0.06 ± 0.02
Stainless steel	3.25	0.66	0.06 ± 0.01
Stainless steel	3.25	0.86	0.06 ± 0.01
Stainless steel	4.94	0.43	0.11 ± 0.01
Stainless steel	4.94	0.66	0.14 ± 0.01
Stainless steel	4.94	0.86	0.13 ± 0.02
Stainless steel	6.43	0.43	0.20 ± 0.03
Stainless steel	6.43	0.66	0.21 ± 0.03
Stainless steel	6.43	0.86	0.22 ± 0.02

The disks were stimulated with a MES-10 (4 pulses @ 0.25 Hz, 100%), and the disk was placed at the center of a circular coil of radius 40 mm. All temperature increases represent the mean and standard deviation of 5 measurements.

Finally, we measured the temperature increase of a platinum-iridium electrode in a grid that could be used for subdural recording of cortical potentials. In our experiment, the grid was taped to a wooden table instead of being implanted subdurally. We used the stimulation protocol described by Hufnagel et al. (1990): the Novametrix magnetic stimulator with a round coil was centered 10 mm above the grid, and stimuli were delivered at 100% intensity every 3–4 sec for 100 pulses. We observed about a 1° increase in the electrode temperature. We repeated this experiment without the electrode grid present. Unlike in the rest of our experiments, in this case the entire temperature increase could be explained by a rise in the local air temperature due to the heating of the coil.

Discussion

Experimental results

Our results support the hypothesis that the increase in temperature of the electrode was caused by induced eddy currents and Joule heating. The rise in temperature of the electrode as a function of electrode orientation depended critically on the direction of the magnetic field. At the center of a circular coil the magnetic field is directed perpendicular to the plane of the coil. If the electrode was perpendicular to the direction of the magnetic field, the temperature rise was much greater than if the electrode was rotated by 90°. The temperature increase was largest where the square of the component of the magnetic field perpendicular to the electrode was greatest. The electrode heating followed the spatial distribution of the magnetic field, not the distribution of the electric field induced in the tissue.

The temperature rise depended on the properties of the electrode. As a general rule, the temperature increased approximately in proportion to the square of the disk radius and was nearly independent of disk thickness (Table II). The aluminum disks heated the most, followed by brass and then stainless steel. Although the geometry of the EEG electrodes was different than the metal disks, the radius and thickness of the silver Grass electrode was similar to the 4.94 mm radius, 0.81 mm thick aluminum and brass disks. Comparing the silver electrode with these disks, we see that the silver electrode increased in temperature more than any other metal tested. This sequence (stainless steel, brass, aluminum, silver) is the same as if the metals are listed in the order of increasing electrical conductivity (Table I). Thus, the greater the conductivity of the metal, the greater the temperature rise.

After the stimulus train was completed, the electrode cooled following approximately an exponential curve with a time constant of about 45 sec (Fig. 3). During long trains, the electrode temperature reached a steady-state value that depended on the stimulus frequency.

Theoretical models

Our experimental results can be explained in part using simple models that provide insight into the physical mechanisms governing the heating and cooling of electrodes. These processes are complex, and the models that we describe could be developed further. For instance, a complete study of electrode heating should take into account the effect of skin depth on the eddy current distribution in the metal (see Appendix), and a detailed analysis of burn injury in skin requires consideration of all mechanisms of heat transport through the various layers of skin (Diller 1985).

We consider a circular metal electrode of radius a, thickness h, and electrical conductivity σ in a spatially uniform magnetic field that is directed perpendicular to the plane of the electrode and has a magnitude that is changing with time [4] (Fig. 4). From Faraday's law of induction, the strength of the induced electric field, E, is

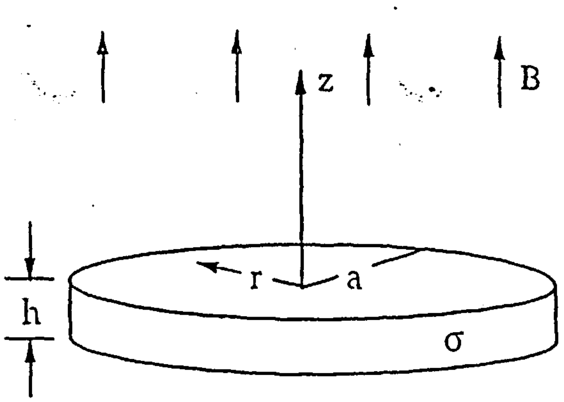

Fig. 4. A schematic diagram of the electrode, of thickness h, radius a, and electrical conductivity σ, in a magnetic field B which is uniform in space and varying with time. Cylindrical coordinates are used to specify position, with r measuring the distance radially outward from the center of the electrode, and z measuring the distance perpendicular to the plane of the electrode.

$$E = -\frac{\dot{B}}{2}r, \tag{1}$$

where r is the distance from the center of the electrode, $\dot{B}$ is the rate of change of the magnetic field with time, and the minus sign indicates that if B is pointing up in Fig. 4 and increasing with time, then E is in the clockwise direction. The current density in the electrode is σE.

The eddy currents in the electrode result in Joule heating. The rate of conversion of electrical energy into heat per unit volume is the product of the current and the electric field. If this product is integrated over the volume of the electrode, the rate of energy converted to heat, dQ/dt, is

$$\frac{dQ}{dt} = \frac{\pi\sigma h \dot{B}^2 a^4}{8}. \tag{2}$$

To determine the total energy per pulse, Q, deposited in the electrode, dQ/dt must be integrated over the pulse duration.

The resulting temperature increase of the electrode depends on its heat capacity. The specific heat, c, of a metal is usually reported as the heat per unit mass required to raise its temperature 1°. To get the heat capacity of the electrode, C, we must therefore know its mass, which in turn depends on its density, ρ, and volume

$$C = c\rho h \times \pi a^2. \tag{3}$$

The temperature increase per pulse, ΔT, is Q/C. Note that ΔT is independent of the electrode thickness and is proportional to the disk radius squared.

To determine the cumulative temperature increase of an electrode after several pulses, we must consider

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[4] The magnetic field applied during magnetic stimulation is not spatially uniform, but if the dimensions of the electrode are small compared to the dimensions of the stimulating coil, then the uniform field approximation should suffice.

how the electrode cools. Since the rate of cooling is slow compared to the pulse duration, we assume that each stimulus pulse instantaneously raises the electrode temperature by ΔT, followed by an exponential cooling with time constant τ, which may depend on the electrode thickness, blood flow, fat content of the body, use of electrode gel, etc. If N pulses are delivered starting at $t = 0$, with each pulse separated by a time Δt, then the cumulative temperature rise of the electrode at the end of the train is

$$T(N, \Delta t) = \Delta T \sum_{i=0}^{N-1} e^{-i\Delta t/\tau}. \tag{4}$$

This sum is a geometric series, which has a closed form solution; the temperature increase at the end of the pulse train is

$$T(N, \Delta t) = \Delta T \frac{1 - e^{-N\Delta t/\tau}}{1 - e^{-\Delta t/\tau}}. \tag{5}$$

If the time between pulses, Δt, is much greater than the time constant for cooling, τ, then the electrode has time to cool between stimuli and the cumulative temperature increase is just equal to the temperature increase from a single pulse, ΔT. If the time between pulses is not long compared to τ, then the electrode does not have time to cool between pulses and the temperature increases from each pulse add. For a short duration train ($N\Delta t \ll \tau$) the cumulative temperature increase is $N\Delta T$. For a long train of pulses ($N\Delta t \gg \tau$), the temperature approaches a steady-state value

$$T(\infty, \Delta t) = \Delta T \frac{1}{1 - e^{-\Delta t/\tau}}. \tag{6}$$

If, in addition, the time between pulses is small compared to the time constant for cooling ($\Delta t \ll \tau$), then the steady-state temperature increase reduces to ΔT $(\tau/\Delta t)$. Although the temperature rise per pulse, ΔT, is independent of electrode thickness, the steady-state temperature increase for a long-duration, high-frequency train could depend on the thickness through τ.

Conclusion

These simple models provide a fairly accurate prediction of how electrode heating depended on the electrode and stimulator parameters. Our experimental results verified that the increase in electrode temperature is proportional to the electrode radius squared and the magnetic field strength squared, that metals with higher electrical conductivity heat more than those with lower conductivity, and that for brief trains the temperature increase does not depend strongly on the electrode thickness.

Our results indicate that during a long train of rapid-rate magnetic stimulation the temperature of an electrode can be raised enough to burn the skin (Pascual-Leone et al. 1990, 1991a). The severity of a burn injury depends on both the peak temperature of the electrode and the time required for the electrode to cool (Diller 1985). Experimental data for skin burns indicate that a tissue temperature on the order of 50°C for 100 sec, or 55°C for 10 sec, may produce an injury (Moritz and Henriques 1947). Such electrode temperatures and durations were obtained using rapid-rate magnetic stimulation in the presence of silver electrodes.

From our data, we can formulate some preliminary safety guidelines governing rapid-rate magnetic stimulation in the presence of metal electrodes. We conservatively set an upper limit of 10°C as the maximum safe temperature rise for an electrode (Moritz and Henriques 1947). Our data suggest that the temperature of a silver EEG electrode increases by 0.5°C after one pulse of magnetic stimulation (100%, Cadwell MES-10 magnetic stimulator, electrode at the center of a 90 mm diameter coil). Using Eq. 5 and a value of 45 sec as the time constant for cooling, we can determine the maximum number of stimuli that can be delivered safely at a particular pulse frequency. The results, shown in Fig. 5, indicate that for high-frequency trains a maximum of 20 pulses can be delivered safely to a silver electrode. For rates below 0.4 Hz, an arbitrary number of stimuli can be applied and the steady-state temperature increase will be less than 10°C. If a slot is cut in the electrode, the eddy current path is disrupted so less heat is deposited in the electrode per pulse,

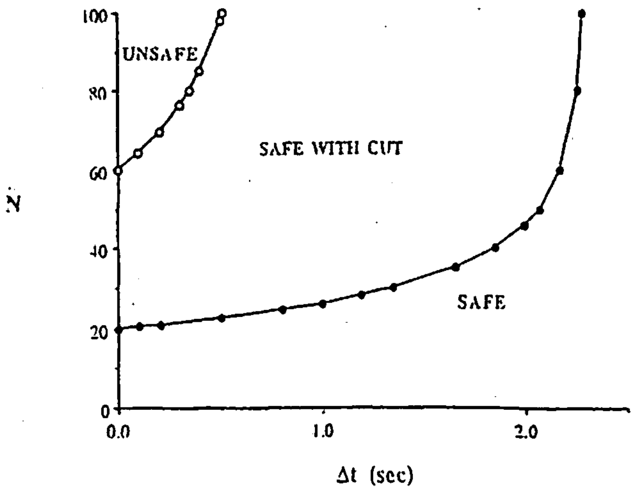

Fig. 5. The maximum number of pulses, N, that can be delivered safely, as a function of the time between pulses, for a silver EEG electrode at the center of a 80 mm diameter circular coil, stimulated by a Cadwell MES-10 stimulator at 100% output. The lower curve (filled dots) is for an uncut electrode, and the upper curve (open dots) is for a cut electrode.

allowing trains of higher frequency and duration to be delivered safely. We did not study any needle electrodes, but suspect that their long, thin shape would suppress heating in much the same way as a cut in the disk electrode did. Use of gel, tape, or collodion with the electrodes should not affect electrode heating, but may influence the rate of cooling and therefore the peak temperature rise during a long train of stimuli.

If a standard EEG electrode were to be made out of stainless steel rather than silver, about a factor of 10 less heat would be deposited in the electrode per pulse, and longer, higher-frequency trains could be applied safely. In this case, Fig. 5 can be used to determine the safety of a train if the values along the vertical axis, denoting the number of stimuli, are multiplied by 10 and the values along the horizontal axis, denoting the time between pulses, are divided by 10. For instance, it would be safe to deliver 200 stimuli at any frequency, and any number of stimuli at frequencies below 4 Hz, using an uncut stainless steel electrode. Trains of 10 sec duration at 25 Hz, which have caused burns in the presence of a silver electrode (Pascual-Leone et al. 1991a), would be safe using a stainless steel electrode with a cut. To reduce the heating even further, non-metallic electrodes can be manufactured from carbon-loaded Teflon®. Such electrodes have been shown to reduce EEG artifacts and electrode heating during exposure to electromagnetic fields (Flanigan et al. 1977).

Important limitations of these preliminary safety guidelines need to be pointed out. First, we assume a time constant of cooling of 45 sec, which may not be correct for electrodes on all parts of the body. Second, we do not know the maximum safe temperature increase for subdural electrodes placed directly on the cortical surface, so that these safety guidelines do not apply in that case. Third, despite our attempt to consider the most dangerous scenario, different magnetic stimulators, coil geometries, electrode sizes, and the exact position of the electrode in relation to the coil could all affect the safety guidelines provided.

In conclusion, 3 rules to follow during rapid-rate magnetic stimulation are:

(1) Avoid using silver or gold electrodes when applying magnetic stimulation in trains.

(2) Stainless steel electrodes on the surface of the skin are safe when stimulating at rates below 4 Hz or in trains with less than 200 stimuli.

(3) Place cuts in electrodes used during rapid-rate magnetic stimulation.

Appendix

Effect of skin depth on the electrode heating

In the mathematical model of electrode heating presented above, we assume that the electrode dimensions are much smaller than the skin depth (Smythe 1968). This approximation implies that the magnetic field produced by the eddy current induced in the electrode is small compared to the magnetic field produced by the current in the coil. This condition is not met during magnetic stimulation in the presence of high conductivity metal electrodes. The effect of skin depth tends to reduce the heat absorbed by an electrode. Therefore, electrodes do not get as hot during rapid-rate magnetic stimulation as predicted by our model. A silver electrode of radius 5 mm and thickness 0.6 mm has a heat capacity of 0.117 J/°C. The MES-10 with its nominally 90 mm diameter round coil has a magnetic field at the coil center that is a damped sine wave, which we have fit to the curve $B_0 e^{-t/\tau_1} \sin(t/\tau_2)$, with $B_0 = 1.24$ Tesla, $\tau_1 = 200$ μsec and $\tau_2 = 45$ μsec. According to our model, the resulting heat[5] deposited in a silver electrode at the coil center should be 0.351 Joule, implying a temperature rise per pulse of 3.03°C. The observed temperature increase of this silver electrode is about 0.66°C. This discrepancy is present in electrodes made from other metals, but it is greatest for those made from silver. For stainless steel electrodes, which have a relatively low electrical conductivity, the measured and calculated temperature rise agree to within the uncertainty of the experiment. The skin depth effect may explain at least part of the discrepancy for the other metals.

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[5] The total energy required by the MES-10 stimulator per pulse is 450 J (Cadwell 1989), so that less than one-tenth of 1% of the pulse energy is dissipated as heat in the electrode.