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Temperature Changes in Nickel-Chromium Intracranial Depth Electrodes during MR Scanning

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Summary: The authors sought to determine whether there are any heating effects of 1.5-T MR scanning upon nickel-chromium electrodes and to confirm the safety of scanning these electrodes after intracranial surgical implantation in epilepsy patients. Since there was no significant temperature increase of the electrodes tested in their experiments, the authors conclude that nickel-chromium electrodes implanted in the brain are thermally safe for MR scanning.

Index terms: Seizures; Magnetic resonance, ferromagnetic implants; Magnetic resonance, physics

Surgical therapy for complex partial epilepsy requires precise identification of the seizure focus. Magnetic resonance (MR) imaging-compatible depth electrodes have been implanted stereotactically in the temporal lobes for prolonged stereoelectroencephalography recording to assist in seizure focus identification. Postimplantation MR scans offer accurate localization of electrode sites; however, in a metallic electrode, eddy currents induced by the radio frequency magnetic field applied by the MR scanner may heat the electrode. Electrode heating may raise the local brain tissue temperature, possibly to a dangerous extent. We therefore examined electrode temperature changes in a 1.5-T MR scanner. The result was also compared with the theoretical temperature change calculated from a mathematical model.

Materials and Methods

The electrode consists of a nickel-chromium (NiCr) tube (80–20 Alloy, Superior Tube Company, Norristown, PA) and eight NiCr electrode contacts for deep intracerebral electroencephalogram recording. The NiCr tube contains nickel 80% and chromium 20% with relative permeability $\mu_r = 1.02$ and electrical resistivity $\rho = 107.9$ mΩ/cm (electric conductivity $\sigma = 9.3 \times 10^6$ S/m). The NiCr tube wall is 90 ± 5 μm with the outer diameter 0.84 mm and inner diameter 0.66 mm. A bundle of five NiCr electrodes were attached around a miniaturized precision thermistor (model 44003A, YSI Inc, Yellow Springs, OH) which was connected to an ohmmeter by copper wires. Thin paper tape was wrapped around the electrode bundle to prevent heat dissipation. The bundle of electrodes was then placed between two saline bags (500 mL each) in a GE Signa 1.5-T MR scanner with the electrode axes in parallel with the scanner axis to obtain maximal heating effect. A linear head coil was used to deliver the radio frequency pulse and sense the MR signal. A spin-echo scanning sequence was applied with 800/20/2 (TR/TE/excitation). The calculated specific absorption rate was obtained from the scanner console for phantom weight of 1000 g. The thermistor resistances before and immediately after scans were sampled and converted to temperature measures by using a thermistor resistance versus temperature table.

To determine the electrode resonant frequency, a network analyzer (Hewlett Packard 3577A, 5 Hz-200 MHz) was used to measure the radio frequency absorption spectrum. An intact electrode with cable (eight insulated multistrand copper conductors ribbon cable) and connector (9-pin Winchester) was wired to a parameter test set device (Hewlett Packard 35677A, 100 KHz-200 MHz) which was connected to the network analyzer. The radio frequency absorption spectra were measured and plotted both with the electrode in air or immersed in 500 mL of saline solution.

A mathematical model (1) was used to calculate the absorption of electromagnetic waves in conductors and the electrode temperature rise. Under the assumption of perfect thermal insulation against the environment, the temperature rise $\Delta T_{theo.}$ of the metallic plate is calculated to be

$$\Delta T_{theo.} = P/V(Dt_0/C)$$

with

$$P/V = (1/\sigma\delta b)(B/m)^2 f(b/\delta),$$

$$f(b/\delta) = (\sinh(b/\delta) - \sin(b/\delta))/(\cosh(b/\delta) + \cos(b/\delta)), \text{ and}$$

$$\delta = \mathrm{sqrt}(\pi f \mu \sigma).$$

where P/V = radio frequency power loss per unit volume;

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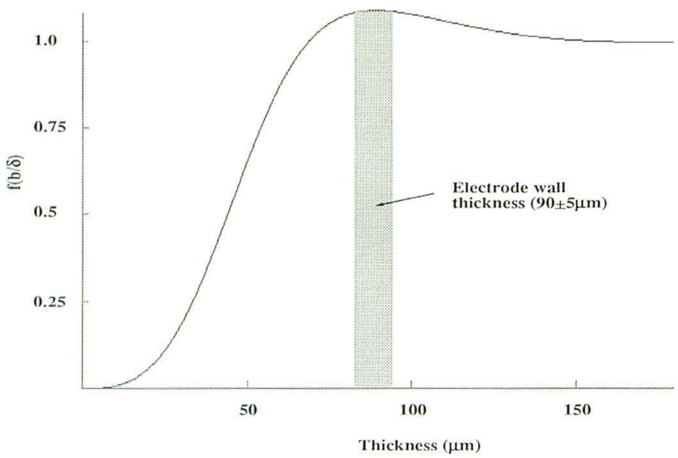

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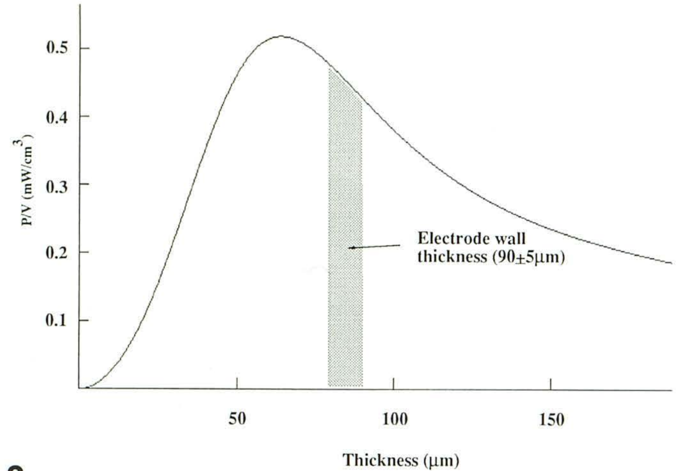

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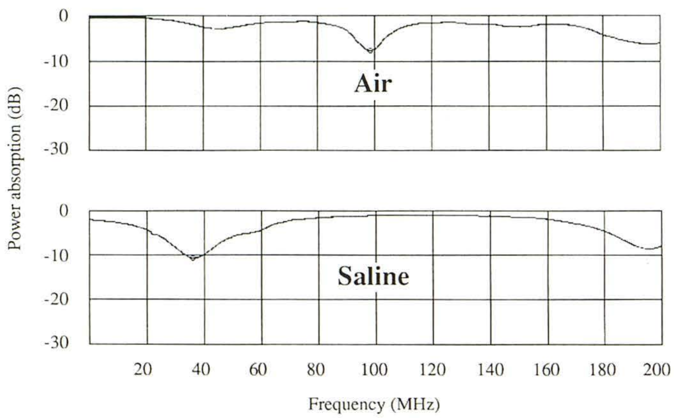
Fig. 1. Function $f(b/\delta)$ versus NiCr plate thickness. Note that, with an electrode wall thickness of 90 ± 5 mm $f(b/\delta)$ reaches the maximum value.

Fig. 2. Radio frequency power deposition per unit volume P/V vs NiCr plate thickness. With an electrode wall thickness of 90 ± 5 μm, P/V approaches the peak value. The temperature rise of the electrode, therefore, may be considered to be the upper limit of heating effects on NiCr alloy.

Fig. 3. Power absorption spectrum of an electrode assembly measured by a network analyzer. When the electrode is placed in the air, a power absorption peak (−8 dB) occurred at 99.1 MHz (*top trace*). The power absorption peak (−10 dB) is shifted to 36.6 MHz if the electrode is immersed into saline solution (*bottom trace*). Note that power absorption at 64 MHz on both traces are comparable.



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B = amplitude of radio frequency field strength at the conductor surface; δ = skin depth of the conductor; μ = permeability of the conductor; σ = electric conductivity of the conductor; b = thickness of the conductor; D = duty cycle of the MR examination; t_0 = total time of the measurement; C = heat capacity per unit volume; and f = proton resonance frequency.

The results of the theoretical calculations were compared with the experimental measurements.

Results

The electrode bundle was scanned for approximately 3 minutes. The calculated average specific absorption rate from the console was 0.734 W/kg. The electrode temperature was measured immediately after scanning. Compared to the prescan measurement, the electrode temperature increased by 0.07°C with spin-echo sequences.

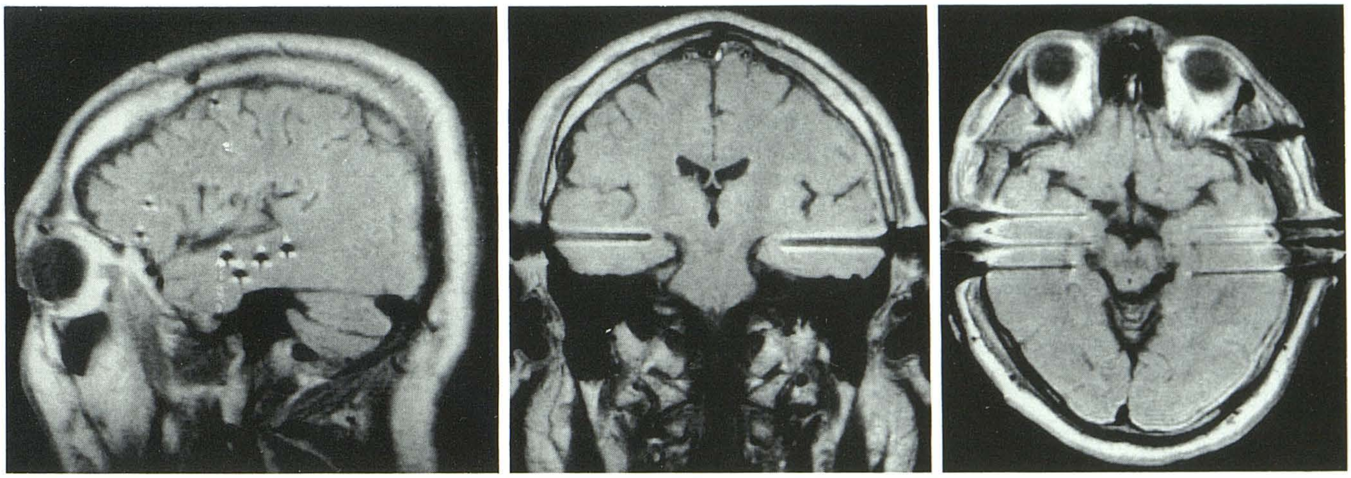
In a static magnetic field of 1.5-T, the proton resonance frequency is 64 MHz. At this frequency, the calculated skin depth (δ) of NiCr is 28.4 μm where, as stated above, $\delta = \mathrm{sqrt}(\pi f \mu \sigma)$ $= \mathrm{sqrt}(3.14 \times 64 \times 10^6 \times 1.02\mu_0 \times 9.3 \times 10^6)$.

The function $f(b/\delta)$ and calculated radio frequency power deposition per unit volume versus the NiCr plate thickness is shown in Figure 1 and Figure 2, respectively. With thermal losses neglected, the corresponding theoretical calculated temperature rise of the electrode for 3 minutes scanning is 0.107°C.

The electrode radio frequency absorption spectra are shown in Figure 3. The resonant frequency is approximately 100 MHz and the power loss at 64 MHz is about −2 dB when the electrode is in the air. When the electrode is immersed in saline, the resonant frequency drops to 37 MHz with −10 dB maximum power loss, and the power loss at 64 MHz is approximately −3 dB.

Discussion

NiCr depth electrodes are surgically implanted in epilepsy patients to aid in the anatomical localization of the seizure focus (Fig. 4). Nonferrous metallic implants present no risk to patients from magnetic field-induced torque, but there is an-



A B C

Fig. 4. Postoperative MR scan. *A*: sagittal scan; *B*: coronal scan; *C*: horizontal scan. The large distortion around the skull results from the large mass of the electrode holder, which is made from titanium. Placement of the electrode holder or NiCr electrode in the scanning field produces no movement.

other major safety concern for patients undergoing MR scanning: even with nonferrous implants, changing magnetic fields, and radio frequency fields used in MR could induce electrical currents in the metal capable of causing localized tissue heating and damage. Theoretical and experimental investigations concerning heating effects in human tissue during MR scanning have been published previously (2–5). A mathematical model has been developed and experiments have been performed to determine the heating effects of other types of metallic implants by MR examinations (1, 6). On a 1.5-T MR scanner, no significant heating effects were reported on metallic articles such as aluminum sheets, hip joint prostheses, or osteosynthetic plates. However, the NiCr electrodes implanted in our patients possess different electromagnetic properties and physical dimensions than those in previous studies. The greater electrical resistivity of the NiCr electrodes as compared with the aluminum sheets may have resulted in a much greater temperature rise during the MR scan (1), and the smaller physical volume of the electrodes as compared with hip joint prosthetics and osteosynthetic plates provides less heat capacity and may result in a faster temperature deviation. In addition, brain tissue is more sensitive to thermal change than other body tissues; therefore, the present study provided a thermal safety verification for intraoperative MR scanning of intracerebral electrodes implanted in epilepsy patients. Electrode implantation for diagnosis in epilepesy is used in over 100 surgical centers worldwide (7).

In our experiment, only a slight temperature rise (0.07°C) in the electrode bundle was observed after 3 minutes of scanning. Considering that the environmental temperature may fluctuate within this range, the measured electrode temperature difference is not significant. Our experimental results are in agreement with results calculated from a mathematical model with thermal losses neglected, since the theoretical model predicted that temperature would rise only 0.107°C over a 3-minute period.

Because the five electrodes were bundled together by thermally nonconductive paper tape and placed parallel to the scanner axis to obtain a maximal heating effect, the experimental setting represented a worst-case condition, as compared with conditions encountered during actual scanning. Because of its vascularity, brain tissue would provide a large heat sink in real conditions, and the electrodes would not be expected to raise the local temperature even during prolonged scanning. One concern about thermal safety is: if the electrode physical size and volume should change as it may in epilepsy surgery, how might the heating effect change? Buchil et al (1) described in their mathematical model that the radio frequency field induced current in a conductor is concentrated on the surface. When the metallic plate thickness to the conductor skin depth ratio (b/δ) is close to 3, maximum radio frequency power is absorbed and therefore a maximum heating effect is observed (Figs. 1 and 2). The heating effect is decreased if $b/\delta > 3$ because the radio frequency power deposition per surface area remains constant while the heat capacity increases. In a static magnetic field of 1.5 T, the proton resonance frequency is 64 MHz. At this frequency, NiCr alloy skin depth δ is 28.4 μm. Our electrode wall thickness is 90 μm so that the b/δ ratio is very close to 3. Therefore, the temperature changes measured in our experiment represent the maximum heating effect of the NiCr alloy in MR scans employing conventional parameters for brain tissue. No temperature rise would be expected to increase over this boundary following NiCr electrode physical dimension changes.

The theoretical calculated temperature rise was based on the power absorption of a nonresonant metallic plate model. Since the electrode with its cables and connector (which are open connection during the scanning) consists of components with distributed capacity and inductance, such a passive network could resonate at a certain radio frequency. More power absorption, and therefore higher temperature rises, could result if the electrode assembly resonates at the scanner radio frequency (64 MHz). Examination of the electrode resonance frequency using a network analyzer showed that, in saline, the electrode assembly resonates at 40 MHz with a −10 dB peak power absorption. At 64 MHz, the electrode power absorption is −3 dB, which is about the same level measured when the electrode is in air (−2 dB). Therefore, the temperature changes measured and calculated in our experiment are applicable to the conditions encountered in depth electrode implantation. If, however, the configuration of the electrode assembly was altered, the characteristic resonance frequency could shift closer to the scanner radio frequency. In the worst case, the maximal power absorption could be −10 dB, which is 6.3 times (8 dB difference) of the measurement in our experiment. Assuming temperature rise is proportional to the power absorption, the electrode temperature would be expected to rise only 0.4°C if the electrode resonated at 64 MHz. Considering the large heat sink volume of brain, the electrode temperature change would still be insignificant even if the electrode resonated at the exact scanner Larmor frequency.

Increasing use is being made of 3-D radio frequency spoiled T1 images for anatomical T1 relaxation information. These pulse sequences typically use gradient-echo (GRE) techniques rather than spin-echo (SE) techniques. For each duty cycle the radio frequency power deposition is typically significantly less with GRE than SE. For example, a 45° flip angle GRE sequence has 1/20th the power deposition of a standard 90°-180° SE sequence. This difference may be altered with specific variations in flip angle, number of partitions of the 3-D sequence, and technique of radio frequency spoiling. An important factor which limits the use of 3-D GRE sequences following electrode implantation is the increased T2* sensitivity of these sequences which cause susceptibility artifacts. For this reason we routinely use SE sequences, and avoid GRE sequences.

We conclude that NiCr electrodes implanted in the brain are thermally safe for MR scanning.

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Editor's Note

With this issue the AJNR begins a new feature, entitled, "Annotated Bibliography." This is **not** meant to be a section of abstracts. A number of clinically oriented, nonradiologic journals, closely allied to neuroradiology, have been selected for review by a panel of individuals. They will provide their own assessment of the value of certain articles which may be of interest to Neuroradiologists. The purpose of this section is **not** to provide a ready list of quotable sources but rather to direct readers to articles of neuroradiologic interest in clinical journals.