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Original Research

Investigation of the Factors Responsible for Burns During MRI

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Numerous reported burn injuries have been sustained during clinical MRI procedures. The aim of this study was to investigate the possible factors that may be responsible for such burns. Experiments were performed to investigate three possible mechanisms for causing heating in copper wire during MRI: direct electromagnetic induction in a conductive loop, induction in a resonant conducting loop, and electric field resonant coupling with a wire (the antenna effect). Maximum recorded temperature rises were 0.6°C for the loop, 61.1°C for the resonant loop, and 63.5°C for the resonant antenna. These experimental findings suggest that, contrary to common belief, it is unlikely that direct induction in a conductive loop will result in thermal injury. Burn incidents are more likely to occur due to the formation of resonant conducting loops and from extended wires forming resonant antenna. The characteristics of resonance should be considered when formulating safety guidelines. J. Magn. Reson. Imaging 2001;13:627–631. © 2001 Wiley-Liss, Inc.

Index terms: MR safety; burns/thermal injuries; patient monitoring; focal heating; RF energy absorption

THERE IS EVIDENCE of focal heating and patient burns sustained while undergoing clinical investigation employing MRI (1–3). The majority of these thermal injuries occurred when the patient was connected to some form of physiological monitoring device, and the burn usually occurred where the skin was in contact with the monitoring sensor or cable (4–8).

Reports filed with the FDA and those presented in the literature have described this problem, and preventative guidelines have been formulated. Despite this, heating remains a problem for clinical MRI, particularly when the patient is unable to indicate a sensation of heat (e.g. due to general anesthesia).

In earlier publications, thermal effects during MRI have been studied in a variety of metallic implants (passive and active) and devices, and often no significant temperature increases have been detected (9–15). Thus, these studies have not provided an explanation of the mechanism responsible for patient burns during MRI.

As yet, no studies exist in the literature that methodically evaluate these burns sustained during MRI. Commonly, it is believed that currents induced in conductive media by the MRI environment may cause these thermal injuries. Currents are induced by two magnetic fields: the pulsed magnetic gradient field and the pulsed radiofrequency (RF) field. These fields vary with time, and if the changing magnetic flux lines intercept an electrically conductive loop, an electromotive force (EMF) will be induced in the loop. Although direct current induction has not been experimentally demonstrated to be the source of these burn incidents, preventative recommendations (i.e., avoid loops in monitor cables) are presently based on this theory. The aim of this study is to investigate whether this single hypothesis is valid, and also to investigate other factors that may contribute to these burn incidents. The secondary aim of the study is to provide experimental data which may serve as a basis for more informed formulation of preventative guidelines.

THEORY: POSSIBLE HEATING MECHANISMS IN MRI

Electromagnetic Induction Heating

The time-varying gradient magnetic fields and the RF electromagnetic fields used in MRI can induce voltages in conductive media and cause current to flow. These circulating currents cause power loss by ohmic heating and this is known as induction heating (16).

Electromagnetic induction heating of monitoring cables has often been considered to be the primary cause of thermal injuries sustained during MRI. Formation of a loop in the monitor cable would increase the circuit's inductance, and therefore, larger currents would be induced with greater heating of the cable.

Electromagnetic Induction Heating of a Circuit in Resonance

The worst case electromagnetic induction heating (i.e., maximum current induction) will occur when a circuit is in a resonant condition (17). A conducting coil exposed to time-varying magnetic fields is equivalent to

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an electric circuit having an inductance L, a capacitance C, a resistance R, and a voltage oscillating at an angular frequency ω. The resonant condition is achieved when $\omega = 1/\sqrt{LC}$.

Thus, resonance occurs at the frequency at which the inductance and capacitive impedances are equal and opposite, so that they exactly cancel one another. Therefore, either the capacitance or the inductance may be altered to tune a circuit until resonance occurs at a specific frequency.

Heating Due to the Antenna Effect

Lengths of monitoring cable can be considered as RF wire antennae that will be sensitive to the electric component, rather than the magnetic component, of the RF radiation used in MRI.

As a receiving device, the antenna captures electromagnetic waves to extract power from them. The electromagnetic waves enter the antenna and have associated with them electric charges and corresponding currents. Resonant antennae exhibit current and voltage standing wave patterns formed by reflections from the open ends of the wire (18).

Resonance is achieved when the antenna is approximately half a wavelength long (half-wave dipole antenna). When resonance is achieved, the electrical energy remains confined to the immediate vicinity of a given antinode. Thus, the highest electric field of the antennae is at the tip.

Another important aspect of this resonance phenomenon is that the electric properties of the media surrounding the antenna and the operating frequency f determine the wavelength:

$$\lambda = \frac{c}{\sqrt{\epsilon} f} \quad (1)$$

where c is the velocity of light and ϵ is the electrical permittivity of the surrounding media.

METHODS AND MATERIALS

This study concentrates on the heating of copper wires during MRI. The experiments were performed using a standard, clinical 1.5-T Magnetom whole body unit (Siemens Medical Systems). RF pulses were generated using both a spin echo (SE) imaging sequence and a turbo spin echo (TSE) sequence (the latter to simulate worst case heating). The body coil was used for RF excitation. The whole body specific absorption rate (SAR) values were all less than 2 Wkg^{-1}.

A Nortech NoEMI-Ts fiber optic thermometry system was used to achieve real time temperature measurement of the copper wire (response time 0.5–1 s). The accuracy of the temperature measurement is greater than $\pm$ 1°C over the range of 40–250°C. The sensor was attached to the copper wire at the point of interest. However, as many of the experiments produced excessive heat, attachment of the sensor to the wire became problematic and often resulted in the sensor separating from the wire early in the pulse sequence. Thus, the results from the experiments in which excessive heating was obtained may be lower than the actual temperature rise.

Electromagnetic Induction Heating

Electromagnetic induction heating was investigated by positioning closed coils of copper wire (of varying lengths and geometries) in the MR unit and exposing them to the time-varying magnetic gradients and RF fields (the ends of the wire were soldered together to achieve a good electrical connection). The coils were positioned perpendicularly to the RF field (other orientations were also investigated) and the rate and exposure of RF radiation were gradually increased to investigate heating of the copper wire. The copper coils were placed between two polystyrene blocks for thermal insulation (to optimise the detection of any temperature change). For each wire, the initial temperature was recorded after a period of 20 minutes to allow attainment of thermal equilibrium. Using the fiber optic probe, the temperature of each coil was measured during the SE sequences. In an effort to induce temperature elevations, the acquisition parameters were set as follows: repetition time = 300 msec; echo time = 15 msec; number of slices = 10; number of phase-encoding steps = 256; number of signal averages = 10; acquisition time = 12 minutes and 56 s. This results in more 90/180-pulse combinations (51200) than in most typical SE-based imaging sequences. In addition to this, to simulate worst case heating, TSE sequences were performed with a turbo factor of 10.

Electromagnetic Induction Heating of a Circuit in Resonance

Electromagnetic induction heating of a resonant circuit was investigated by connecting the appropriate capacitance to the coils of copper wire to achieve resonance at 63.87 MHz (a Marconi Q-meter was employed to determine the required capacitance). For this series of experiments, after preliminary studies had shown significant heating, the circuits were placed on wooden slats and positioned in the MR unit (perpendicularly to the RF field). For each wire, the initial temperature was recorded after a period of 20 minutes to allow attainment of thermal equilibrium.

Heating Due to the Antenna Effect

Heating due to the antenna effect was also investigated by placing lengths of copper wire in the MR unit and exposing them to gradient and RF fields. The wire was investigated in various positions and geometrical configurations. To find resonance, 300-cm lengths of copper wire were shortened by increments of 5 and 10 cm. In case of significant heating, the wire was placed on a wooden slat. The lengths of wire were placed parallel to the static magnetic field in an off-center position within the MR unit, as this position is essential for the interaction of the RF with the antenna (the electric component of the RF is spatially inhomogeneous and low around the coil center).

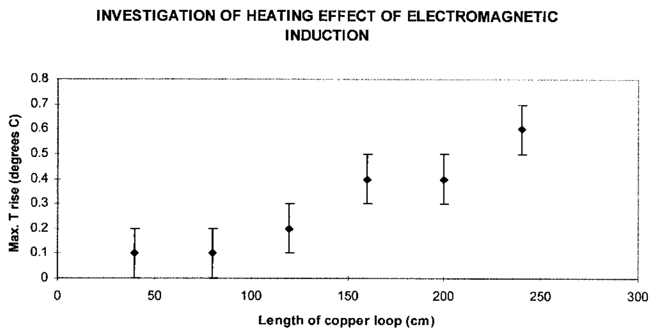

Figure 1. Plot of maximum temperature rise recorded for each length of copper wire.

Figure 3. Evidence of significant heating at the tip of the copper wire as a consequence of finding the resonant length. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

RESULTS

Electromagnetic Induction Heating

The maximum temperature rise recorded for both long duration SE and TSE sequences for each length of wire is plotted in Fig. 1. As shown, the maximum temperature rise recorded was 0.6 ± 0.1°C. Thus, although electromagnetic induction did induce heating in the copper loop, the temperature elevation would not result in thermal injury.

Electromagnetic Induction Heating of a Circuit in Resonance

The maximum temperature rise recorded for each resonant circuit is plotted in Fig. 2. As shown, significant temperature increases were recorded with the maximum being an increase of 61.1 ± 0.1°C. While performing these experiments, evidence of significant temperature increase also presented itself in the form of visible sparking of the capacitor (in some instances, the wooden slat was burned black below the capacitor). Therefore, the findings of these experiments indicate that, should a large loop be formed during MRI that may be in or near resonance, sufficient electrical energy may be induced to break down the capacitive component of the circuit and thus cause thermal injury.

On finding this significant heating effect, the gradient coils were turned off and the experiments repeated. This demonstrated no change, as the sparking and temperature rise was still apparent, and therefore, the heating was a consequence of RF-induced currents.

Heating Due to the Antenna Effect

Initially, the resonant length was found by positioning the wire completely in the RF transmit volume to maximize RF exposure. On finding resonance, there was sufficient heating at the tip of the wire to burn the wooden slat as shown in Fig. 3. In agreement with theory, the resonant length ($\lambda/2$) was just short of 235 cm (using Eq. 1: $c = 3 \times 10^8 \mathrm{msec}^{-1}$, $\epsilon = 1$, and $f = 63.87$ MHz).

In order to mimic the clinical situation, the wire was extended out of the MR unit (as would monitor cables) and the temperature at the tip of the wire was monitored. The maximum temperature rises are as shown in Fig. 4. The largest temperature rise recorded was 63.5 ± 0.1°C at a length of 220 cm of copper wire.

As before, the gradient coils were turned off and the experiment repeated to confirm that this heating was a result of the RF radiation. Sparking and temperature

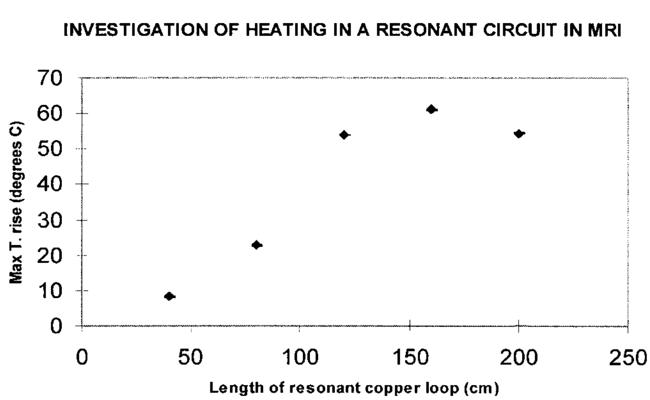

Figure 2. Plot of maximum temperature rise recorded for each resonant circuit.

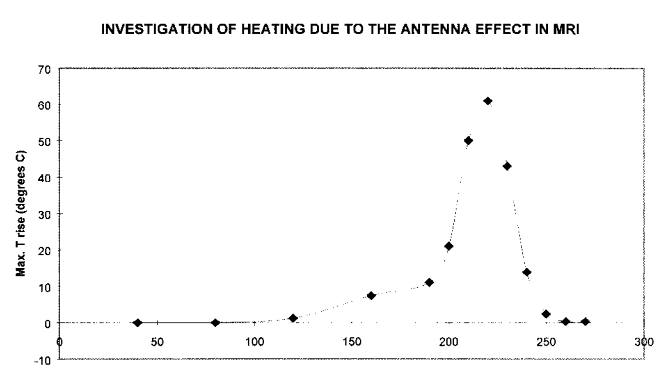

Figure 4. Temperature at tip of wire vs. length of copper wire.

increase were still apparent, indicating that the heating is indeed a result of the RF.

DISCUSSION

When investigating heating due to direct electromagnetic induction, insufficient heat was produced to induce thermal injury using long SE sequences and TSE sequences. This suggests that, contrary to common belief, thermal injuries are not likely a result of direct current induction in electrically conductive loops during MRI. This finding is in agreement with various reports in the literature investigating heating of conductive implants and devices in which heating due to electromagnetic induction has not been found to cause significant temperature increases (9–15,19). Therefore, another mechanism may be responsible for these burns.

Significant temperature rises were recorded when investigating resonant circuits. Temperature changes of greater than 60°C resulted in circuit temperature exceeding 80°C (initial circuit temperature approximately 20°C), which would be sufficient to cause thermal injury. The visible sparking of the capacitor and consequent burning of wood provided unquestionable evidence that this mechanism provides enough heat to induce thermal injury. Therefore, should a conducting loop be formed during MRI that may be in or near resonance, sufficient electrical energy may be induced to break down the capacitive component of the circuit and cause thermal injury.

Significant temperature increases were also recorded when studying heating due to the antenna effect. Again, strong evidence of significant heating was provided in the form of visible sparking at the tip of the wire when resonance had been achieved. Therefore, it is possible that extended monitoring cables may cause thermal injury as a result of this antenna effect. In the burn incidents previously referred to (4,6), it was specified that cable loops had been avoided. Therefore, resonating waves along a straight length of cable wire would appear to be the only mechanism by which this excessive heating could be explained. As demonstrated, the highest electric field of this dipole antenna occurred at the tip of the wire, which explains the localized heating. However, this heating is a function of many variables, including static magnetic field strength, coil geometry, wire length, placement of wire in the MR unit, and the electrical characteristics of the media surrounding the wire. Again, this finding agrees with various reports in the literature investigating heating of pacing and guide wires, in which significant heating has been recorded at certain lengths of wire, in agreement with the antenna theory (13,20–24).

This finding has several implications when considering patient monitoring during MRI. First, as heating due to the antenna effect depends on the sensitivity to the electric component of the RF field, positioning cables in close proximity to the inside wall of the MR bore will increase the possibility of thermal injury (a consequence of the inhomogeneity of the electric field component). Also, any factor that increases the RF amplitude will increase the likelihood of burns. Therefore, as the power and frequency of the pulsed RF field increases with the field strength of the magnet, thermal injuries may be more likely with high-field RF systems. The antenna length is a critical factor of this heating effect, but the issue is complicated by monitoring cables being partially exposed in air and partially in contact with the patient, with the consequence of inherent difficulties in determining the resonant length. Table 1 shows the resonant antenna length in air at common field strengths. However, as discussed previously, the quantity of energy absorbed by a body in an RF field is also affected by environmental factors, i.e., absorbed energy depends on the electrical properties of the material(s) surrounding the body, and therefore the figures in Table 1 should only be used as a broad guideline.

Table 1
Resonant Antenna Lengths in Air at Common Field Strengths

Field strength (T)	Resonant antenna length in air (m)
0.5	7.04
1.0	3.52
1.5	2.35
2.0	1.76
2.5	1.41
3.0	1.17

The experience gained through these experiments can be applied to metallic cables and monitoring leads. This study shows that existing safety guidelines may not be adequate to prevent burns from occurring, as they do not take into account heating due to resonance. The complex nature of this resonance phenomenon does pose specific problems for the formulation of safety guidelines. However, characteristic features of resonance, such as avoiding resonant length of cables, should be taken into consideration. It should be noted that there is no clear maximum value to the amount of heat that can be produced if a specific situation gives rise to resonance, since the amount of electrical energy is determined by dielectric losses in the environment and the reflective properties at the tip.

Although our experiments showed that direct current induction produced only a mild heating effect, we cannot rule it out as a possible mechanism for burn incidents in practical MRI. The results of this study, however, indicate that resonant circuit and antenna phenomena can provide dramatic heating effect, and they are most likely to be the major factors causing burn incidents in MRI.

CONCLUSION

The hypothesis of direct current induction in a conductive loop created by monitoring cables and the patient's skin was experimentally investigated, with the results indicating that any temperature rise due to this mechanism would most probably be insufficient to cause thermal injury.

Following this, resonant circuits were studied, as the maximum current would be induced in this situation, to examine the worst case electromagnetic induction heating. Significant temperature increases were recorded with additional evidence of significant heating presented in the form of visible sparking of the capacitive component and burn marks on the wooden slat.

Therefore, experimental findings indicate that avoiding loop formation in monitoring cables remains an important factor in preventing thermal injury, as this will minimize the inductance of the circuit and therefore reduce the possibility of forming a resonant circuit.

Monitoring cables behaving as antennae were also investigated. At the resonant length, evidence of significant temperature increase was presented in the form of visible sparking at the wire tip and burning of the wooden slat. It is therefore possible that extended wires may cause thermal injury as a result of this antenna effect. The highest electric field of this dipole antenna occurs at the tip of the wire, which would explain the localized heating reported in the majority of burn incidents.

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