RF Heating Due to Conductive Wires During MRI Depends on the Phase Distribution of the Transmit Field

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In many studies concerning wire heating during MR imaging, a “resonant wire length” that maximizes RF heating is determined. This may lead to the nonintuitive conclusion that adding more wire, so as to avoid this resonant length, will actually improve heating safety. Through a theoretical analysis using the method of moments, we show that this behavior depends on the phase distribution of the RF transmit field. If the RF transmit field has linear phase, with slope equal to the real part of the wavenumber in the tissue, long wires always heat more than short wires. In order to characterize the intrinsic safety of a device without reference to a specific body coil design, this maximum-tip heating phase distribution must be considered. Finally, adjusting the phase distribution of the electric field generated by an RF transmit coil may lead to an “implant-friendly” coil design. Magn Reson Med 48:1096–1098, 2002. © 2002 Wiley-Liss, Inc.

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In the rapidly developing field of interventional MRI, localized RF heating near the tips of long metal devices used during MR scanning has become a major safety concern (1–3). Common to all studies of RF heating of wire-shaped devices is the presence of resonant device lengths at which RF heating is the most intense. This resonance had been empirically observed but not quantitatively modeled nor accurately predicted until our recent study of RF heating at the tips of totally inserted wires (4). The effects of varying wire properties (diameter, insulation thickness) and the properties of the tissue it was placed in (electrical conductivity, thermal conductivity, perfusion) were explored. This theoretical understanding and experimental validation established safety thresholds on the SAR (specific absorption rate) of pulse sequences used with totally inserted wires.

The existence of a resonant length, at which a wire has the greatest heating potential, suggests that to improve safety wire lengths should be either longer or shorter than this resonant length. This leads to the nonintuitive notion that putting more metal in the body may actually be safer, in some cases, to avoid this resonance.

We will show that the resonance phenomenon depends on the characteristics of the RF transmitter, particularly the phase distribution of the incident electric field. There exists an electric field distribution in which a wire will show no resonant length but will cause more and more heating as the wire gets longer. Present designs for volume transmit coils will likely have near uniform phase distributions since this maximizes the coil’s quality factor. However, older designs may have nonuniform phase distributions. Therefore, the RF heating characteristics of a conductive wire cannot be stated without reference to a specific transmit coil design. However, it is possible to formulate the transmit phase distribution that will generate the maximum tip-heating for a given wire so that its safety characteristics can be stated independently of the specific MR transmit coil used. In addition, the results of this study suggest a design criterion for “implant-friendly” RF transmit coils.

MATERIALS AND METHODS

The RF pulses of an MRI scan induce currents on conductive objects in the sample, causing localized amplification of the surrounding electric field and consequent SAR distribution. Calculating the electric field distribution surrounding a good conductor in a known incident electric field requires solving the Helmholtz equation, subject to the boundary condition that the total tangential electric field on the surface of the conductor is zero (5). We have previously shown that the method of moments can be used to solve this problem numerically (4).

Here, we applied the Galerkin method of moments, described in detail elsewhere (6), with a modified driving function. The method of moments formulation leads to the following matrix equation:

$$Z I = V \quad [1]$$

where $I$ the unknown current distribution discretized into $N$ elements ($N \times 1$ vector), $V$ is the discretized driving function due to the incident electric field ($N \times 1$ vector), and $Z$ is a discretized impedance matrix that is calculated for the specific geometry of the problem ($N \times N$ matrix). This is a matrix representation of Ohm’s law. The unknown current distribution is found by inverting the impedance matrix:

$$I = Z^{-1} V = Y V. \quad [2]$$

where $Y$ is the admittance matrix.

Once the discretized current distribution is known, the total electric field in the whole space can be calculated by superposition. A detailed description of the method of moments can be found in Ref. 7.
Rather than the center-driven dipole antenna examined in Ref. 6, the wires examined here have a driving function that exists along the entire wire. Two driving functions were examined. The first was the case of a uniform (in magnitude and phase) electric field oriented parallel to the straight wire, the same driving function described in Ref. 4. Parallel orientation of the electric field maximizes coupling of the wire to the field.

The second driving function was designed to maximize the RF heating at the wire tip. It was a uniform (in magnitude only) electric field, again oriented parallel to the straight wire, whose phase at each location along the wire was such that the phase-shifted current that each element induced at the wire tip had identical phase. With identical phase, contributions from each location would add constructively, thereby maximizing the tip charge.

Mathematically, this was accomplished by choosing the phase of the incident electric field at each point, $i$, to be the negative of its complex admittance with the tip element ($m = 1$):

$$\angle v_i = -\angle y_{ti}$$  \hspace{1cm} (3)

where $V = [v_m]$, $Y = [y_{mn}]$.

Once the induced currents were determined, the total electric field was calculated and converted to SAR. This resultant SAR distribution was normalized by the uniform SAR distribution from the incident electric field to generate an SAR gain distribution.

To report meaningful numbers, the SAR gain distribution was combined with a semianalytic solution (8) of the bioheat transfer equation to generate a safety index (4), the maximum steady-state temperature that can be expected in vivo, normalized to the input power of the MRI pulse sequence used. The safety index incorporates the SAR amplification due to the device and physiological heat transfer characteristics. The safety index was calculated using thermal properties of resting muscle (thermal conductivity $\lambda = 0.4$ W/m°C, perfusion $P = 2.7$ ml/100g/min) (9).

Calculations were performed at 64 MHz, the Larmor frequency for 1.5 T. In all calculations, the bare wires were assumed to be totally immersed in an infinite homogeneous medium (electrical conductivity $\sigma = 0.5$ S/m, permittivity $\varepsilon_r = 77$ are representative values for human tissue at 64 MHz (10)).

RESULTS

Figure 1 shows the RF heating characteristics of the two examined situations. For each wire length, the maximum tip-heating case always has equal or greater heating potential than the uniform phase case. Significant divergence begins to occur for wire lengths approaching and beyond a half wavelength. In addition, the maximum tip-heating case shows no resonance, but rather, increases monotonically.

Figure 2 shows the actual phase distribution that created the maximum wire tip heating for a 30 cm wire. The linear portion of the phase distribution has a slope (14.6 rad/m) that is equal to the real part of the wavenumber in the medium. This completely linear phase is plotted on the same axes for comparison. The maximum tip-heating phase distribution is asymmetric, indicating that heating is optimized on only one of the tips. In this case, it is the tip at location 0 cm.

Since the maximum tip-heating phase distribution of Fig. 2 is mostly linear, the effect of a truly linear excitation phase distribution was also examined and the results are shown in Fig. 3. The dotted line represents the result of applying an incident electric field with a linear phase ramp of 14.6 rad/m. It is virtually indistinguishable from the maximum tip-heating case.

DISCUSSION

Are Wires Longer Than a Half Wavelength Inherently Safer?

This study demonstrates that the phase distribution of the RF transmitter affects the resonance characteristics of con-
ductive wires in MRI. For wire lengths longer than a half wave, linear phase distributions of the transmit EM field could cause increased RF heating at the wire tips. It is also very conceivable that MRI situations could arise where the phase of the incident electric field was indeed linear, with its slope equal to the real part of the wavenumber—plane wave excitation, for example. As a rule of thumb, therefore, shorter wires are intrinsically safer than longer ones. Attempting to avoid resonance by lengthening a wire beyond a half wave is not recommended.

**Is Safety Index Independent of the MRI System?**

The electric field phase distribution that body coils generate is presently not reported because it does not affect imaging performance. However, since the results of a previous study (4) matched the theoretical prediction using a uniform phase transmit field, it is likely that the phase is close to uniform for the body coil of the specific scanner used in that study. However, other coil designs, particularly older ones, may not necessarily have a similar phase distribution.

The results of this study indicate that for the safety index to truly be independent of the scanner used, the maximum tip-heating transmit phase distribution (or its linear approximation) must be used to generate the safety index.

**Is an “Implant-Friendly” Body Coil Design Possible?**

It has been possible to formulate the conditions of maximum tip-heating transmit phase distributions that eliminate any possibility of destructive wire-tip field interference between current elements. It should also be possible to formulate a condition whereby severe phase cancella-

![Graph showing wave length and safety index](image)

**FIG. 3.** Comparison of maximum tip-heating phase (solid line) and 14.6 rad/m linear phase (dashed line). The linear phase is always less than the maximum tip-heating case but is virtually indistinguishable from it.

**REFERENCES**


**CONCLUSIONS**

The phase distribution of the electric fields generated by the RF transmitter affects the RF heating properties of a conductive wire during MRI. Shorter wires are intrinsically safer than longer ones. The safety index, in order to be a truly scanner-independent measure of a device’s safety, must be calculated with the maximum tip-heating transmit phase distribution. Finally, the results of this work suggest a criterion for designing “implant-friendly” transmit coils.

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