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Original Research

Heating Around Intravascular Guidewires by Resonating RF Waves

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We examined the unwanted radiofrequency (RF) heating of an endovascular guidewire frequently used in interventional magnetic resonance imaging (MRI). A Terumo guidewire was partly immersed in an oblong saline bath to simulate an endovascular intervention. The temperature rise of the guidewire tip during an FFE sequence [average specific absorption rate (SAR) = 3.9 W/kg] was measured with a Luxtron fluoroscopic fiber. Starting from 26°C, the guidewire tip reached temperatures up to 74°C after 30 seconds of scanning. Touching the guidewire may cause sudden heating at the point of contact, which in one instance caused a skin burn. The excessive heating of a linear conductor like the guidewire can only be explained by resonating RF waves. The capricious dependencies of this resonance phenomenon on environmental factors have severe consequences for predictability and safety guidelines. J. Magn. Reson. Imaging 2000;12:79–85. © 2000 Wiley-Liss, Inc.

Index terms: interventional MRI; safety; RF heating; endovascular; guidewire; nitinol

IN THE RAPIDLY DEVELOPING field of interventional MR, concern has been growing about radiofrequency (RF)-induced heating in metallic devices (1,2). The standard guidewires used in percutaneous endovascular radiological procedures have a stainless steel core and therefore are unsafe in the MR environment. Another frequently used guidewire is the nitinol-core Terumo (Tokyo, Japan) device. Although it has no ferromagnetic components, nitinol is an electrically conductive material, and the RF pulses in the MR scanner produce electrical currents in and around conductors, resulting in heat production (RF heating). In this paper, we concentrate on the RF heating of this nitinol-containing guidewire.

According to Maxwell's theory of electromagnetism, one may discriminate between three mechanisms by which heating can be evoked by RF radiation: 1. Heating from eddy currents. These eddy currents are produced by RF radiation in each volume of conducting material, even small volumes. 2. Heating from induction loops. These situations may occur when using electrocardiographic/electroencephalographic leads, for example (3,4). The induced potentials can be calculated from the dimensions of the loop in combination with the intensity and direction of the incident RF field.

The two effects mentioned above have been studied for many devices (5,6) and have in common that no storage of electrical energy within the device takes place. The thermal energy is produced directly and instantaneously by the incident RF radiation. Various devices (needles, implants) have been tested for heating by eddy currents (2,5); the heating rarely exceeds a few degrees Celsius.

In this paper, however, we concentrate on a third effect that may emerge if conductors of sufficient length are present in the RF field: 3. Heating by resonating RF waves along conductors. If such a resonance occurs, the incident RF wave is bounced back at the end-points of the wire-like structure, causing the reflected RF waves to travel back and forth along the longitudinal axis of this structure, in such a way that standing RF waves are formed. Therefore, in contrast to mechanisms 1 and 2, storage of electrical energy along the wire takes place.

Other groups have already indicated the occurrence of resonating RF waves along catheters, for example, for active tracking (7–9). Within these catheters, long coaxial cables are incorporated over the full length of the catheter, in order to transport electrical signals from the distal tip to the proximal end. It should be emphasized, however, that the structure of a nitinol core guidewire is not equivalent to that of a coaxial cable: the guidewire consists of a single conducting core, with a thin isolating layer. Therefore, the results of the RF heating experiments on tracking catheters cannot simply be considered valid for guidewires without experimental verification.

In this paper, we specifically investigate the RF heating properties of intravascular guidewires with a metal core. Preliminary studies from our group (10,11) indicate that it is possible to create experimental conditions in which significant RF heating is produced at a nitinol guidewire tip. Ladd and Quick (12), as well as Atalar (13), have tested a method to eliminate the resonant RF heating in tracking catheters. Ladd and Quick reported

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satisfactory results using a triaxial cable, in which quarter-wavelength coaxial chokes were realized by soldering the primary and secondary shields together and removing the secondary shield a quarter wavelength from the solder point. If such a method were to be applied to guidewires, this would entail the application of two extra conducting coaxial layers, which would significantly alter the mechanical properties (flexibility) of the guidewire.

It is in the very nature of resonance phenomena that the intensity of the resonance is hard to predict because it depends heavily on the environment of the resonating device. In fact, it is the combination of the device together with its environment that constitutes the resonating system. This will be discussed in more detail in the theory section. In short, the amount of heating that may be produced around a resonating guidewire, given an RF field of a certain intensity, is not an intrinsic feature of the guidewire, but depends on a large and rather poorly defined set of environmental factors. This inherent complexity, and hence unpredictability, has severe consequences for safety. In this paper however, we do not consider the formulation of safety margins for the use of nitinol-containing guidewires.

Instead, the aim of this study is to answer two questions: 1. Can resonance be evoked experimentally in a set-up resembling an MR-guided vascular intervention using a nitinol guidewire? 2. What temperature rise may this resonance produce, and what are its dependencies?

Once excessive RF heating of a guidewire is measured in our set-up, we conclude that resonating RF waves play a role in that particular situation, since eddy currents are not capable of producing such excessive heating within an RF field produced by an MR scanner.

THEORY: RESONATING RF WAVES

The conducting core of the guidewire acts like a linear dipole antenna and the core of a transverse electromagnetic (TEM) waveguide at the same time, as will be explained below. The direction of the E-field of the RF wave alternates with the frequency f of the RF field. The guidewire is excited as a dipole antenna. The excitation of a dipole antenna in a conductive medium (like blood and tissue)evokes a relaxation phenomenon: a TEM wave (14). These TEM waves travel along the guidewire, since the combination of the guidewire and its environment serves as a electromagnetic waveguide. The TEM waves are partially reflected at points where there is a sudden change in the waveguide impedance Z, such as the distal tip and the entry point of the guidewire. At a reflection point, the fraction of the wave that is reflected equals $\beta = (Z_2 - Z_1)/(Z_1 + Z_2)$, in which Z_1 and Z_2 are the waveguide impedance before and beyond the reflection point, respectively.

As a result of multiple reflections, a number of TEM waves are superimposed along the guidewire. Generally, these superimposed TEM waves will largely annihilate each other. In some specific situations, however, the superimposed TEM waves form standing waves (resonance), creating a strong build-up of electrical energy along the wire. In such cases, the strong local electrical field near the guidewire causes displacement currents in the layer directly surrounding the wire, producing heat within this layer. This layer may consist of blood, but may also include part of the vessel wall, because guidewires tend to lie against the vessel wall. In the latter case, part of the heat production takes place directly within the vessel wall, which aggravates the risk of tissue damage. In such a case the cooling by the blood flow is less effective.

To specify the conditions for resonance more quantitatively, we give a brief description of a mathematical model from which these conditions are derived.

Let the length of the part of the guidewire that is within the body be denoted by L. Since the principal reflection points are at the guidewire tip and at the point of entry of the wire into the body, the length between the reflection points is also L. Let the total electrical field at position x along the wire at time t be denoted as $\mathbf{E}_{\mathrm{TEM}}(x,t)$. The amount of energy, averaged over an interval Δt, of the local electrical field accumulated along the wire (diameter $2r_o$) as a whole, within a thin layer of thickness δr surrounding the wire, equals $2\pi r_0 \delta r/\Delta t \int_0^{\Delta t} dt \int_0^L dx\, \epsilon(x)\, |\mathbf{E}_{\mathrm{TEM}}(x, t)|^2$ in which $\epsilon(x)$ is the dielectric constant of the tissue at position x.

Since $|\mathbf{E}_{\mathrm{TEM}}(x,t)|^2$ is of the form $|\mathbf{E}_{\mathrm{TEM}}(x,t)|^2 = [Re(E_{\mathrm{TEM}}(x)\mathbf{e}^{-i\omega t})]^2$,in which $\omega = 2\pi f$ and $E_{\mathrm{TEM}}(x)$ is a time-independent complex scalar, the time-oscillating factor reduces to a factor $\frac{1}{2}\Delta t$ in the time integral (provided that $\Delta t \gg 1/f$). The energy integral now yields:

$$\pi r_0 \delta r \int dx\, \epsilon(x)\, |E_{\mathrm{TEM}}(x)|^2 \tag{1}$$

in which $|E_{\mathrm{TEM}}(x)|$ is the absolute value of the complex scalar $E_{\mathrm{TEM}}(x)$. Let the guidewire be in a stretched position in a direction indicated by the unitvector $\hat{\mathbf{u}}_{\mathbf{x}}$. The TEM waves have a wavevector $k\hat{\mathbf{u}}_{\mathbf{x}}$, parallel to the wire. Along the full length of the wire, excitation takes place by the RF from the scanner, resulting in a superposition of reflected TEM waves described by the complex scalar $E_{\mathrm{TEM}}(x)$. To start with, we consider the complex scalar $E_{\mathrm{TEM},\,0}(x)$ describing the superposition of reflected TEM waves that would result if an RF excitation, of unit strength and frequency f, would take place at the proximal tip only. The $E_{\mathrm{TEM},\,0}$ has the form of a series expansion, in which the exponent of the reflected fraction β indicates the number of times that the wave component corresponding with that term has been reflected, α represents the continuous attenuation of the TEM wave due to dissipation, and C is a real scalar coupling constant:

$$\begin{aligned} E_{\mathrm{TEM},0}(x) &= C(e^{(ik-\alpha)x}) + \beta e^{(ik-\alpha)(2L-x)} \\ &+ \beta^2 e^{(ik-\alpha)(2L+x)} + \beta^3 e^{(ik-\alpha)(4L-x)} + \beta^4 e^{(ik-\alpha)(4L+x)} \\ &+ \beta^5 e^{(ik-\alpha)(6L-x)} + \beta^6 e^{(ik-\alpha)(6L+x)} + \cdots \end{aligned} \tag{2}$$

Rearranging factors in Eq. [2] using a geometrical power series of $\beta^2 e^{(ik-\alpha)2L}$ and evaluating this series using $\sum_{n=0}^{\infty} (\beta^2 e^{(ik-\alpha)2L})^n = 1/(1 - \beta^2 e^{(ik-\alpha)2L})$, yields:

$$E_{\mathrm{TEM},0}(x) = Ce^{(ik-\alpha)x} + C(\beta e^{(ik-\alpha)(2L-x)} + \beta^2 e^{(ik-\alpha)(2L+x)})/(1 - \beta^2 e^{(ik-\alpha)(2L)}) \quad (3)$$

In case of the E_{TEM} in Eq. [1], however, the complete guidewire is excited by the RF, instead of just the proximal tip. The strength of the excitation RF field along the wire is given by:

$$E_{\mathrm{RF}}(x) = Ae^{i(\mathbf{k}_{\mathrm{RF}} \cdot \hat{\mathbf{u}}_x)x} \quad (4)$$

in which the constant A is the excitation amplitude, and $\mathbf{k}_{\mathrm{RF}}$ is the wavevector of the RF wave, being parallel to the $\mathbf{B}_0$ of the scanner, and having a length k_{RF} that is approximately $k_{\mathrm{RF}} = 2\pi(f\sqrt{\epsilon_{\mathrm{body}}})/(c\sqrt{\epsilon_0})$.
For $f = 64$ MHz and $\epsilon_{\mathrm{body}} \approx 80\ \epsilon_0$, (15), we have $k_{\mathrm{RF}} = 11.9\ \mathrm{m}^{-1}$, corresponding to a wavelength of $\lambda_{\mathrm{RF}} = 52$ cm, since $\lambda_{\mathrm{RF}} = 2\pi/k_{\mathrm{RF}}$. The E_{TEM} is calculated by a convolution-like operation involving E_{TEM} and E_{RF}:

$$E_{\mathrm{TEM}}(x) = \int_0^L E_{\mathrm{RF}}(\xi)\ E_{\mathrm{TEM},0}(x - \xi)\ d\xi \quad (5)$$

To find conditions for resonance, we now list some of the mathematical conditions under which the expression for stored electrical energy (Eq. [1]) is maximized, bearing in mind Eqs. [3], [4], and [5]: 1) Excitation wavevector match: $k \approx \mathbf{k}_{\mathbf{RF}} \cdot \hat{\mathbf{u}}_{\mathbf{x}}$. If L and α would approach infinity and zero respectively, k should be exactly equal to $\mathbf{k}_{\mathbf{RF}} \cdot \hat{\mathbf{u}}_{\mathbf{x}}$, as is easily verified using the Parseval and convolution theorems. The intensity of the resonance therefore depends on the direction $\hat{\mathbf{u}}_{\mathbf{x}}$ of the guidewire. In a first approximation, considering the wire as the core of a wavepipe of infinite width, the wavelength of the TEM waves $\lambda_{\mathrm{TEM}} = 2\pi/k$ is equal to λ_{RF}. The exact value of λ_{TEM}, however, depends on the guidewire construction as well as the dielectric constants ϵ of the tissues that make contact with the guidewire. 2) Optimal reflections: $\beta \approx 1$. The value of Z_2, and hence the value of β is influenced by vascular geometry near the tip, and by the presence of stenoses. 3) Resonating length match: This is achieved if the denominator in Eq. [3] approaches zero, which implies that $e^{(ik-\alpha)2L} \approx 1$. As a result, resonating length match for L is achieved if $2kL \approx 2\pi, 4\pi, 6\pi, \ldots.$ or, equivalently, since by the wavelength of the TEM wave equals $\lambda_{\mathrm{TEM}} = 2\pi/k$:

$$L \approx \tfrac{1}{2}\lambda_{\mathrm{TEM}},\ \lambda_{\mathrm{TEM}},\ \tfrac{3}{2}\lambda_{\mathrm{TEM}},\ \cdots \quad (6)$$

As was mentioned above, the value of λ_{TEM} depends on many factors. Therefore it can not be simply stated that resonance will occur if L is a multiple of 26 cm.

In summary, the better the conditions for resonance are met, the more sensitive the intensity of the resonance becomes to the many factors that cause small deviations from ideal reflection and phase coherence. This causes capricious dependencies on various factors in the environment of the guidewire and prohibits the indication of a clear ceiling value for the intensity of the resonance. On basis of the theory above, we formulate the following key features of resonant RF heating along guidewires: 1) The occurrence of resonant RF heating depends on a large set of factors in the environment of the wire and is hard to predict. 2) There is no clear ceiling to the amount of heat that can be produced if a specific situation gives rise to resonance.

MATERIALS AND METHODS

We performed our experiments with a Terumo standard angiography guidewire, consisting of a nitinol (nickel-titanium) tapered core, surrounded by polyurethane. The surface of this guidewire is coated with a thin layer of hydrophilic polymer, and its maximum outer diameter is 0.035 inches. The length of the guidewire is 150 cm.

All experiments were performed on a Philips 1.5.T Gyroscan NT scanner (Philips Medical Systems, Best, The Netherlands), using a gradient echo sequence with specific absorption rate (SAR) = 3.9 W/kg, which is the maximum SAR allowed by the scanner within its standard safety limits. This SAR value is a spatially averaged value, which is assessed automatically by the scanner and displayed on screen. In all experiments we used the body coil. Furthermore, we placed a closed plastic bottle filled with 10 liters of $CuSO_4$ solution (770 mg/l) in the center of the bore, as a standard procedure for a proper response during the preparation phase of a scan. This bottle stayed in this position during all experiments but made no contact with the guidewire and is not part of the model under investigation.

We used two methods to measure the temperature of the guidewire: liquid crystal paint (Edmund Scientific, Barrington NJ) and a Luxtron 790 (Luxtron, Santa Clara, CA) fluoroscopic fiberoptic temperature sensor (16). The liquid crystal paint changes color from reddish brown to blue over the temperature range 25–30°C. We used this paint to monitor the temperature of the part of the guidewire that was not immersed in saline. The black color of the Terumo meets the demand that the paint should be applied onto a black background in order to let the color changes within the paint be visible. The temperature of the immersed tip of the guidewire was measured by the Luxtron fibertip that was attached to the guidewire tip with a thin thread. After each measurement, the guidewire was cooled to room temperature.

We performed two types of experiments: 1. Qualitative experiments, to explore the heating behavior of the guidewire in a number of typical situations, and 2. Quantitative experiments, to measure the temperature rise in a set-up simulating an endovascular intervention.

Qualitative Experiments

To gain insight into the types of situations that give rise to excessive heating, we positioned the guidewire in various positions and bends within the bore. Furthermore, in some situations, we immersed the guidewire in saline (9g NaCl per liter H_2O), in order to simulate the presence of biological tissue surrounding the guidewire. To this end, an oblong bath, consisting of one-half

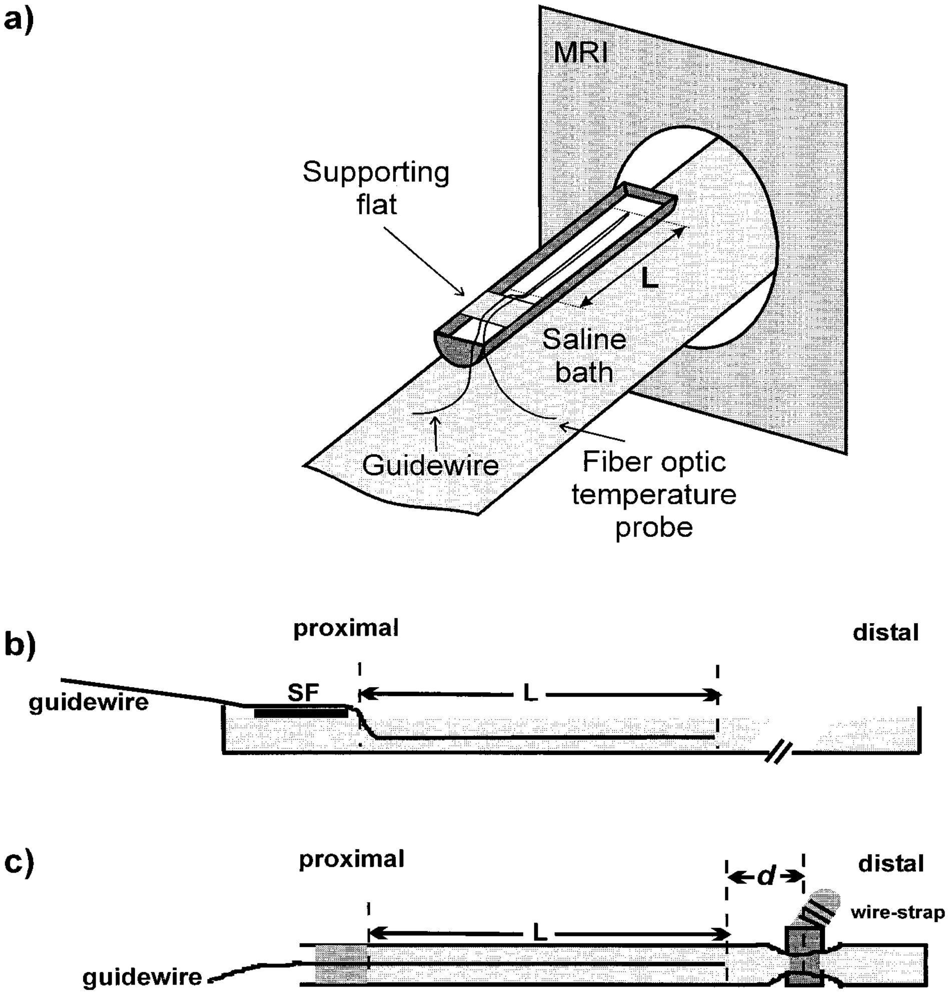

Figure 1. a: Experimental set-up showing an oblong bath filled with saline, resting on the table and lying parallel to the B_0 field in an extremely off-center position within the bore of the MR scanner. The distal part of the guidewire is immersed in the saline bath. The supporting flat surface (SF) can be moved in order to change the immersed length L of the guidewire. b: Sagittal view of the same set-up, showing the immersed length L. c: Sagittal view showing the guidewire partly inserted into a straight rubber tube filled with saline. An artificial stenosis was created using wire straps. Again, L is the immersed length of the guidewire, and d is the distance between the center of the stenosis and the distal guidewire tip.

of a plastic pipe of 7 cm internal diameter that was cut in two along its long axis, was filled with saline and equipped with a movable supporting flat surface (SF) in order to control the length of the immersed portion of the guidewire (Fig. 1a,b). In the following, the tip of the guidewire that is located closest to the center of the bore is referred to as the distal tip. The guidewire was suspended in the bath using thin thread in order to avoid contact with the bottom of the bath.

We also examined the influence of touching the proximal part of the guidewire by the gloved fingers of the interventional radiologist. In one instance, in order to avoid the distortion of the temperature measurement that would result from the direct transfer of body warmth from the fingers to the wire in case of direct contact, we applied a 4 cm long balloon, fabricated from a latex glove, and filled with Elmed contact gel, to one of the radiologist's fingers. The contents of the balloon were cooled to 20°C and constituted an electrical capacitative coupling between the radiologist and the guidewire, thus being a model for direct touch. After each measurement, the guidewire was allowed to cool down to 20°C.

Quantitative Experiments

We inserted the guidewire into a straight rubber tube (length: 90 cm) of 5 mm internal diameter and 2 mm wall thickness, of which the distal end was closed, and the proximal side was left open. The tube was filled with saline, positioned at an extremely off-center position parallel to the B_0 field, and the distal part of the guidewire lay within this tube in a stretched position (Fig. 1c). By pulling the guidewire out of the tube, the length of the immersed distal part of the wire could be controlled. We now used the Luxtron fluoroscopic fiber to measure the temperature of the distal tip of the fiber. We performed two experiments

Experiment 1

We measured the temperature of the tip after 30 seconds of scanning. This measurement was performed for

Table 1
Heating of the Proximal Guidewire Tip for Various Situations

Situation	Temperature of proximal guidewire tip after 30 sec of scanning
Guidewire along straight line, parallel to B_0, no saline	Below 25°C
Guidewire in various bends, no saline	Below 25°C
Distal part (10 cm) of guidewire in saline bath	Between 25 and 30°C
Distal part (30 cm) of guidewire in saline bath	Exceeds 30°C within 5 sec
Distal part (50 cm) of guidewire in saline bath	About 30°C
Distal part (80 cm) of guidewire in saline bath	About 30°C
Touching proximal tip of guidewire with gloved fingertip; guidewire is lying straight in an extremely off-center position; no saline bath	Very hot within 5 sec
Touching proximal tip of guidewire with “extended finger”; guidewire is laying straight in an extremely off-center position; no saline bath	Exceeds 30°C within 5 sec

various lengths of the immersed part of the guidewire, by pulling the guidewire out of the tube for a few centimeters between measurements. Before each measurement, we waited until the tip was cooled down again to 26°C.

Experiment 2

An artificial 70% stenosis was formed in the tube by squeezing the tube with wire straps. This stenosis was located beyond (ie, distal with respect to) the guidewire tip (Fig. 1c). We measured the temperature after 30 seconds both without and with stenosis for various immersed lengths and distances between the distal guidewire tip and the stenosis.

RESULTS

Qualitative Experiments

The temperature of the dry proximal tip of the guidewire was monitored using the liquid crystal paint. Starting from 20°C, the temperature of the proximal tip was estimated after 30 seconds of scanning. The results are shown in Table 1.

These experiments show that excessive heating (exceeding 30°C within 5 seconds) was produced only if the guidewire was partly immersed in the saline, or if the guidewire was not immersed at all, but touched by the finger of the radiologist (with and without “extended finger”). On one occasion the experimenter got a visible burn on the skin of his fingertip when touching the proximal guidewire tip.

Quantitative Experiments

Experiment 1

The measured temperature of the distal guidewire tip after 30 seconds of scanning is shown as a function of the immersed length in Fig. 2. The experiment was performed three times, resulting in an average standard deviation of 4°C. Maximum heating (74°C) was found at about 83 cm immersed length.

Experiment 2 (Stenosis)

The results are shown in Table 2.For immersed lengths of both 55 and 65 cm, maximum heating was found if a

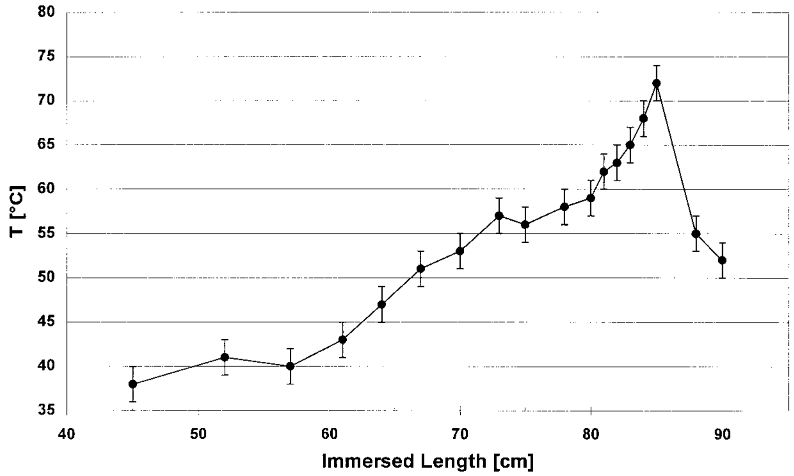

Figure 2. Graph showing the temperature of the distal guidewire tip after 30 seconds of scanning. The temperature was measured for various immersed lengths of the guidewire. Before each measurement, the guidewire tip was allowed to cool down to 26°C. Each measurement was performed three times.

Table 2
Influence of Immersed Length and Presence of a Stenosis on the Heating of the Distal Guidewire Tip

Immersed length (cm)	Heating without stenosis	Heating with stenosis	
	(Temperature (°C) of distal guidewire tip after 30 sec of scanning)	(Distance between distal guidewire tip and stenosis (cm))	(Temperature (°C) of distal guidewire tip after 30 sec of scanning)
65	48	0	42
		2	51
		5	62
		7	68
		15	49
55	42	0	46
		2	59
		5	64
		7	80
		15	52

stenosis was present near the tip (d = 7 cm; Fg. 1c). Therefore, the presence of a stenosis alters the intensity of the RF heating significantly.

DISCUSSION

We performed experiments to examine the RF heating of a nitinol-containing intravascular guidewire during MRI, and we tested for resonance on basis of two key features that we formulated in the theory section.

The experiments show that: 1. The Terumo guidewire may reach a temperature of up to 74°C in a set-up resembling a MR-guided endovascular intervention. 2. Large variations in heat production occur when repeating experiment 1. 3. There is a strong, nonlinear dependency on the position of the guidewire with respect to neighboring objects, even if the shape of the guidewire and its position and orientation with respect to the RF field remain unchanged. 4. The presence of a stenosis modifies the intensity of the RF heating significantly. 5. Significant heating was found only if the guidewire made contact with saline or other aqueous objects containing ionized salt, like body tissue and the Elmed-containing extended finger. This contact is not hampered by the thin isolating layer of the latex glove.

Since excessive heating can only be explained by the occurrence of resonance, we infer that resonating RF waves play a role in our experiments. The heating phenomenon that we found resembles the resonating RF waves found by other groups using catheters and guidewires for active tracking (7,8). Our results are applicable to all guidewires having an electrically conducting core. The conductivity differences between nitinol and other metallic materials that may constitute the core of a guidewire are irrelevant since all metals have a very high conductivity with respect to saline: the conductivity of saline is the limiting factor for the propagation of the TEM waves.

In our experiments, we did not flush the saline along the wire in order to simulate blood flow. Our experiments therefore represent the worst case scenario in which there is a poor flow in the artery that is being catheterized, while the tip is touching the intima, so that heat is produced directly within the tissues that constitute the vascular wall, as explained in the theory section.

Special prudence and reserve should be exercised when interpreting and generalizing the results of our experiments. Firs, there is no clear ceiling to the amount of heat that can be produced if a specific situation gives rise to resonance (as was explained in the theory section). Therefore, there is no unambiguous relation between each specific situation and the temperature rise that results from it. We only indicate that certain specific situations have proved to be risky. For the intensity of the excitation RF field we chose an average of SAR = 3.9 as a worst case scenario. Evidently, the produced heat, given a certain resonance situation, would be lowered if the intensity of the RF from the scanner were to be lowered during this resonance process. However, this cannot be seen as a general remedy against excessive heating, since a lowering of the average SAR produced by the scanner would result only in a linear attenuation of the produced heat with a certain factor, whereas for every new resonance situation, the amount of electrical energy that is converted to heat is unknown in the first place and has no clear ceiling value.

Practical Implications

Regarding the fact that the Terumo guidewire has excellent steerability and torque control, the heating problems connected with its use in MR may represent a somewhat unwelcome complication. Furthermore, no simple solutions seem available to avoid resonance without affecting the structure and mechanical properties of the Terumo.

A possible solution is the application of quarter-wavelength chokes (12,13). This, however, would involve application of two extra coaxial layers, which may have unfavorable consequences for the flexibility of the guidewire. Yet another possibility is to manufacture guidewires using nonmetallic materials only, like glass fiber (17), in order to make the guidewire intrinsically safe with respect to RF heating. In a more general context, the results of our experiments raise the question of whether similar resonating RF waves may occur when using, eg, catheters having a metal braiding. This is the subject of a future study.

As a general conclusion, the capricious dependencies of the intensity of resonance phenomena on environmental factors make it questionable whether it will be possible to formulate effective MR safety guidelines for guidewires with a conducting core without altering the materials or structure of the guidewire.

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