Intolerable Heating by Resonating RF Waves around Guidewires

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Introduction
In the rapidly developing field of interventional MR, there has been growing concern about RF-induced heating in metallic devices[3]. In the work reported here, we concentrate on the RF heating of a widely used intravascular guidewire, the Terumo guidewire (Tokyo, Japan), having a nitinol (Nickel-Titanium) core. Since nitinol is not ferromagnetic, the Terumo meets an important condition for MR safety. Nevertheless, nitinol is a good electrical conductor. According to Maxwell’s theory, one may discriminate between three mechanisms by which heating can be evoked in conductors by RF radiation:
1) eddy currents,
2) induction loops, e.g. when using ECG leads [2,3], and
3) resonating RF waves along conducting wires.
The first two effects have been studied for many devices [1], 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.
In this work however, we concentrate on the third effect. Resonating waves around the wire is the only mechanism by which excessive heating of a straight guidewire can be explained. The purpose of our study is to show that excessive RF heating can be evoked near the guidewire tip in an experimental set-up that resembles a MR guided endovascular intervention.
The capricious nature of resonance phenomena (as explained in the theory section below) pose specific problems to the formulation of safety guidelines. At the end, the experimental results are discussed in the light of MR safety.

Theory
In an RF field, the guidewire is excited as a dipole antenna. As the orientation of the electrical component of the exciting RF field alternates with the frequency of this field, Transverse ElectroMagnetic (TEM) relaxation waves are travelling along the guidewire with the same frequency. These TEM waves are partially reflected at the tip of the guidewire, as well as at the entry point of the wire in the artery. In some specific situations, the immersed length of the guidewire is such that the travel time of the TEM wave between the reflection points matches the frequency of the RF field of the scanner. In these cases, resonance may occur, leading to a strong build-up of electrical energy stored within the TEM waves. At the tip of the guidewire, these TEM waves produce strong displacement currents within the tissues surrounding the tip, producing heat directly within these tissues. In contrast to the eddy currents mentioned in the introduction, the heat produced by resonating TEM waves may be significant. Furthermore, there is no clear cooling to the amount of heat that can be produced if a specific situation gives rise to resonance, since the amount of TEM energy during resonance is determined by dielectric losses in the environment and the reflective properties at the tip. There are numerous factors in the environment of the guidewire that contribute to these losses and to the imperfection of the reflections. This inherent complexity and unpredictability has severe consequences to the formulation of safety guidelines.

Method
The experiments were performed using a Terumo standard angiography guidewire (diameter: 0.035 inch, length 150 cm), consisting of a Nitinol (Nickel-Titanium) tapered core, surrounded with polyurethane. We immersed part of the guidewire in saline (9g NaCl per liter H2O), in order to simulate the presence of biological tissue surrounding the guidewire. To this end, an oblong bath, consisting of one half of a plastic pipe of 7cm internal diameter that was cut in two along its long axis, was filled with saline. This oblong bath was placed parallel to the B0 field in an extremely off-center position within the bore of a 1.5 Tesla whole body MR scanner (Gyroscan ACS-NT, Philips, Best, the Netherlands). This off-center position close to the wall of the bore is essential for the interaction of the RF with the antenna. In all experiments we used the body coil, and a FastFieldEcho sequence with average SAR = 3.9 W/kg, which is the maximum SAR allowed by this scanner within its standard safety limits. Furthermore, a closed plastic bottle filled with 10 liters of fluid doped with CuSO4 was placed in the center of the bore as a standard procedure for a proper preparation scan. We inserted the distal part of the guidewire into a straight rubber tube (length: 90cm) of 5mm internal diameter and 2mm wall thickness, of which the distal end was closed, and the proximal side was left open. The tube wall was perforated with holes of 2mm diameter, with an average distance of 5mm between the holes. This was done to simulate the specific conductivity of a vessel wall. This perforated tube with the distal part of the guidewire inside it was laying in the saline bath in stretched position so that both guidewire and tube were immersed in saline. By pulling the guidewire out of the tube, the length of the immersed distal part of the wire could be controlled. For various immersed lengths, we measured the temperature of the tip after 30 sec. of scanning, using a Luxtron fluoroscopic temperature sensor. Before each measurement, we allowed the tip to cool down to 26 degr.C.

Results
The results are plotted in the figure. For an immersed length of 85 cm, a temperature of 77 degr. was reached within 30 seconds, despite of the cooling effect of the saline. We repeated these measurements for other tube lengths, and consistently found a maximum heating when the guidewire tip was at about 5 cm distance from the closed distal tube ending. This was also the case if the tube ending was replaced by a 70% stenosis. Therefore this distance seems to be more important than the immersed length as such.

Discussion
- The Terumo guidewire may give rise to heating up to 72 degr. Celsius, in a set-up resembling a MR-guided intervention.
- There is a strong dependency on the position of the guidewire tip with respect to tube endings and stenoses.

These results indicate that the heating shown in the figure was produced by resonating electromagnetic waves around the wire. This implies that the characteristic features of resonance will have to be taken in consideration (such as the lack of a clear ceiling value to the amount of produced heat, and the possible production of heat directly within the vascular wall, making the cooling by blood flow less effective, see theory section). We conclude that a mere reduction of the average SAR produced by the scanner may not be enough to guarantee the absence of injurious heating, and that modification of the guidewire is needed.

References
2 L. Lemieux et al, MRM 38, 943-952 (1997)