Heating of metallic implants and instruments induced by gradient switching

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Introduction

Up to now, heating of metallic parts (e.g., implants or instruments) due to gradient switching has been assumed irrelevant concerning MR safety. The present paper shows that for sufficiently large metallic parts located off-center significant heating can occur. Temperatures comparable to those obtain from RF-induced heating can be reached, especially if the electric resistance for the eddy currents results in power matching and if a sequence is applied exploiting the gradient capabilities of a modern MR scanner.

Methods

Theory: To investigate eddy-current induced heating, the devices were modeled as quadratic frames made of conducting material with l :side length of the frame, A: area of the frame, and q: cross-section of the conductor. Materials with different specific resistance ρ were taken into account (Cu: 0.017 Ωmm2/m, Ti: 0.554 Ωmm2/m). The energy deposed during ramp-up (or ramp-down) in dependence on the DC resistance R at given inductance L and ramp time τ and so at fixed $U_{ind} = A\ \Delta B/\tau$ can be calculated from:

$$E(R) = \int_0^{\tau} P(dt)dt = \frac{U_{ind}^2}{R}\int_0^{\tau}(1-e^{-\frac{R}{L}\cdot t})^2 dt = \frac{U_{ind}^2}{R}\left(\tau + \frac{2L}{R}e^{-\frac{R}{L}\tau} - \frac{L}{2R}e^{-\frac{2R}{L}\tau} - \frac{3L}{2R}\right)$$

with:

$$L \approx \mu_0 \cdot 2l \qquad R = \rho \cdot \frac{4l}{q} \qquad \Delta B = G \cdot d$$

(G: gradient strength, d: distance from the isocenter). $E(R)$ has a maximum at $R = R_{match}$ (Fig. 1).

Experiments: Induced heating by gradient switching was examined for quadratic wire frames as well as for sheets of copper and titanium respectively. An infrared camera with a sensitivity of 0.1 K was used for temperature monitoring.

The frames had an effective edge length of 47 mm and a conducting cross-section of 1.5 x 3 mm^2 (R_{Cu} = 0.71 mΩ, R_{Ti} = 23.1 mΩ), the metal sheets had an edge length of 50 mm and a thickness of 1.5 mm. Additionally, a copper frame with 4 mm frame width and a narrowing to 1 mm over 20 mm at one side was examined. The electric resistances of this frame and of the copper frame with 3 mm frame width were in good approximation the same. The specimens were mounted on blocks of styrofoam for thermal isolation and were examined inside the scanner in air at approximately 20 cm off-center in horizontal (x-) direction and perpendicular to the static field. A two liter bottle of water placed at isocenter was used as load for the 1.5 T MR scanner.

Heat-up of each specimen was monitored with the infrared camera for 2:10 min during the execution of a 3D true-fisp sequence, which exploited the gradient capabilities of the scanner (maximum gradient: 40 mT/m, ramp time: 250 µs, dB/dt = 32 T/s at x = 0.2 m) and which had a high gradient duty cycle (TR = 6.4 ms). RF amplitude was set to zero volts. Transverse slices with frequency encoding in x-direction were recorded, causing the read-out gradient to be mainly responsible for heating in the geometry described above.

Results

For the copper specimens, a significant warm-up could be measured (> 10 °C) whereas for the titanium specimens the temperature rise was markedly less (maximally 1 °C). Figure 2 shows the infrared images obtained from the Cu sheet and the Cu frames with the true-fisp sequence after a scan time of 2:10 min (maximum temperature almost reached). For the sheet, a nearly homogenous warm-up of the complete area was detected (Fig. 2a). The frame with the continuous thickness showed heating at the middle of the bars and still more pronounced at the corners (Fig. 2b). For the frame with 4 mm frame width and a bar narrowing to 1 mm over 20 mm at one side, the narrowed zone was responsible for enlarged voltage drop and clear heat-up (> 10 °C) could be observed for the regions adjacent to the narrowing (Fig. 2c).

Discussion

RF field induced heating of tissue near metals is well understood. The presented paper shows that for sequences with high gradient duty cycle significant heating of metallic objects can also be generated by gradient-switching. The metal object has to allow for eddy currents and must be located at sufficiently large distance from the isocenter. The electric power from the gradient fields can be converted best to thermal power in the object itself, if power matching occurs, i.e. if the electric resistance R possesses the correct value R_{match} with respect to the inductance L of the object and with respect to the ramp time τ of the gradient field.

For inductances corresponding to typical sizes of metallic implants, R_{match} has to be rather low in the region of several mΩ, either due to good conductivity of the material or due to sufficiently large cross-section. For example, frame-like metallic vertebral column stabilization (comparable in size to the examined titanium frame) could offer sufficient cross section (≈ 1 cm^2). From E(R) it follows that for larger implants power matching results at enlarged R. The deposed energy also enlarges. E.g., doubling, in comparison to Fig. 1, L and U_{ind} for constant τ results in R_{match}= 1.6 mΩ and $E(R_{match})$= 1.2 mJ (Fig. 1: R_{match}= 0,75 mΩ and $E(R_{match})$= 0,58 mJ). Given an inhomogeneous conductive cross section, a similar effect as demonstrated with the Cu frame with one narrowed bar can occur. Enlarged localized voltage drop causes an intense local heating. Since not only the z-component but all components of the magnetic field from the gradient coils are responsible for the induction of heating, the localization and the orientation of an implant with respect to this three dimensional field has to be considered.

A first examination of an artificial hip replica made of aluminum revealed heating of this massive implant (Fig. 3).The original made of titanium showed no significant warm up. Not only the heating itself, but undesired implant expansion as well could cause problematic biological effects due to pressure to the surrounding bony tissue.

Consideration should be made to extend safety testing of extended implants or instruments with respect to the described mechanisms, especially if they are made of well conducting materials. For building-up MR safe medical implants or instruments, beyond low susceptibility of an applied material low conductivity has to be claimed. Special geometrical constructions of the devices to prevent from strong eddy currents could also contribute to solve related problems.

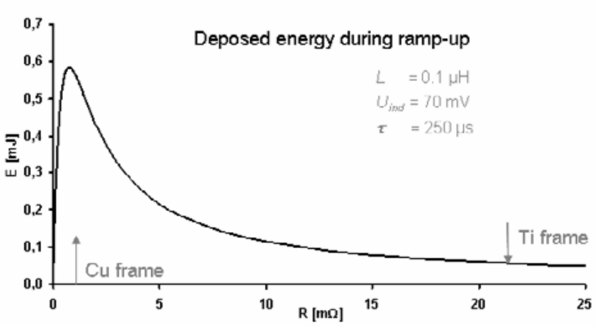

Figure 1: Deposed energy E during gradient ramp-up as a function of the electric resistance R at fixed parameters L = $0.1\ \mu H$, $\tau = 250\ \mu s$, $U_{ind} = 70\ mV$, corresponding to the metal frames. Power matching occurs for the copper frame (R ≈ 0.7 mΩ). The titanium frame shows 32-times higher resistance.

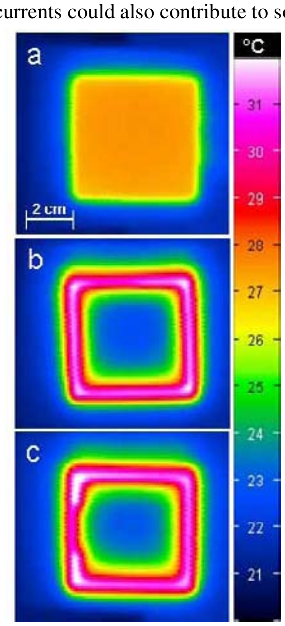

Figure 2: Color-coded infrared images of the Cu specimens obtained after 2:10 min scanning with the true-fisp sequence with high gradient duty cycle (RF pulses switched-off). Copper sheet (**a**), copper frame with constant bar thickness (**b**) and copper frame with bar narrowing at one vertical side (**c**).

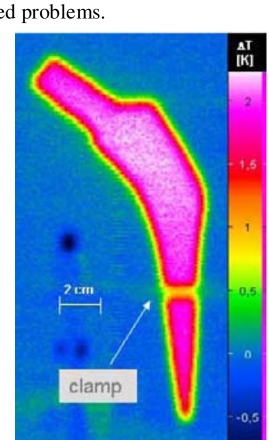

Figure 3: Color-coded ΔT image of the artificial hip replica made of aluminum obtained after 3:30 min scanning with the true-fisp sequence with high gradient duty cycle. The entire part warmed up by approximately 2.2 K. An original prosthesis made of titanium showed no warm up.