Resonant Traps as a Safety Measure: Influence of Inaccurate Tuning

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Objective

Several studies have shown that elongated conductive structures such as guidewires or cables inside catheters can cause severe heating during MRI [1,2], which poses a major safety concern for interventional MRI applications. Resonant traps are commonly used to suppress cable shield currents in RF field environments [3]. Consequently, resonant traps have also been proposed for interventional devices [4, 5]. It is an already known problem that traps may heat up and cause a temperature increase in their surrounding [4]. The purpose of this study is to investigate, if an additional issue can arise from inaccurately tuned traps. This topic is of considerable relevance, since tuning is difficult in interventional devices due to the small size, and detuning can easily occur by movement or by the influence of the surrounding tissue.

Materials and Methods

Tip heating of wires is analyzed depending on their length and trap tuning. RF cables (Huber+Suhner SM 250, length: 0.8m/1.5m equivalent to 0.17λ/0.32λ) and tunable floating shield current suppression traps [3] were used. Adjustment of the trap resonance was done on a transmission line terminated with its characteristic impedance employing a network analyzer (Agilent E5070B) and current probes.

For tip heating measurements, the cables were placed ~20cm off-axis along the patient table (1.5T Achieva MR system, Philips Healthcare) and extended with a 5cm long, 0.5mm diameter isolated Cu wire, which was placed in a block of conducting agar gel. Field concentration makes this tip the most critical point for interventional devices [2]. The tip temperature was monitored using a Luxtron 790 fluoroptic thermometer. Gradient echo MR scans with a resulting SAR of 2W/kg were applied for 7s. Frequency dependent temperature plots were derived by changing the transmit frequency of the scanner. Measurements were performed without and with a tuned (f_0=63.71 MHz) and slightly de-tuned (64.2 MHz) trap being placed at the cable center. The 1.5m cable was additionally measured with 2 traps (placed one third of the cable length from ends respectively, detuning of -0.6/+0.4 MHz relative to f_0).

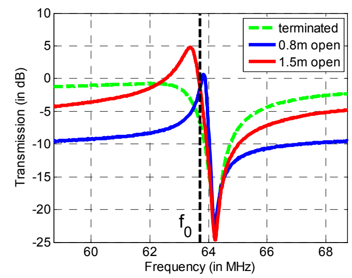

Figure 1. Transmission of de-tuned trap, measured outside MR.

Results

The transmission measurements show maximum transmission slightly below the adjusted trap resonance for the cables having open ends. For tuned traps, the transmission stays minimal at f_0, but detuning can lead to an increased transmission at or near f_0 due to said maximum, see Fig 1. The transmission corresponds to tip heating inside the MR field. The maximum tip heating employing the detuned trap is closer to f_0 for the shorter wire (0.8 m, see Fig. 2 left) with less heat being generated (ΔT=2.3 K at f_0) than for longer wires (1.5 m, see Fig. 2 middle), where the maximum is further away from f_0, but significantly stronger (ΔT=19.7 K at f_0). For the correctly tuned traps, no relevant heating can be observed in the measured frequency range. When two detuned traps are used, a maximum heating of ΔT=5.4 K is generated at f_0-100kHz (see Fig 2 right), which turns out to be more than without traps (ΔT=4.2 K).

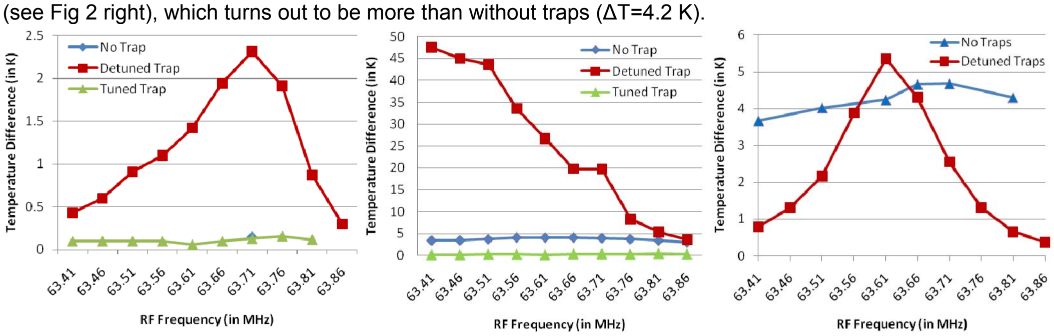

Figure 2. Tip-heating in MR (left: trap on 0.8m; middle: trap on 1.5m; right: 2 traps on 1.5m cable)

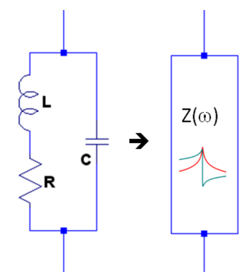

Figure 3. Simple trap Model

Discussion

The observed behavior can be understood employing a simple model (see Fig.3): The inductively coupled trap can be transformed and represented as a resistive inductance (R and L) parallel to a capacity (C). It behaves like a complex impedance, with both the reactance and the resistance being frequency dependent. The resistance reaches a maximum at a frequency ω=sqrt(1-1/(2Q^2)), $Q=\omega_0 L/R=1/(\omega_0 CR)$,$\omega_0=2\pi f_0$ and drops on both sides of this frequency. A correctly tuned trap acts as a high-impedance resistance at the operating frequency and prevents undesired cable currents. In contrast to the resistance, the reactance is negative above a specific frequency ω (ω=$\omega_0$sqrt(1-1/Q^2), ω_0=sqrt(1/(LC))) and positive below, which can be construed as an inductance. This lumped inductance can virtually extend the wire, so that it becomes resonant at f_0. For longer wires, this critical inductance occurs further away from f_0, where the resistance of the trap is also significantly reduced, i.e. a good resonator is formed. For shorter wires, the inductance for resonance is found closer to f_0, but with a higher corresponding resistance, i.e. this resonance is more attenuated.

Conclusion

Despite the known heating issues near the trap itself [4], correctly tuned traps can significantly reduce tip heating of interventional devices. Incorrectly tuned traps can result in currents and heating, which is worse than without a trap. Short wires are more sensitive to detuning, but heating is less excessive than for longer cables (>λ/4), where higher detuning can lead to a drastic increase of tip heating.

Thus, the effect of inaccurate trap tuning or inadvertent detuning has to be considered, e.g. by investigating the possible detuning. Especially trap detuning of more than 0.3% for cable segments >λ/8 should be avoided. In very bad cases (e.g. as shown above), it might be even advantageous to not use a trap.

References

[1] Konings MK et al., JMRI 12:79–85 (2000), [2] Nitz WR et al., JMRI 13:105–114 (2001), [3] Seeber DA et al., CoMR 21B(1):26-31(2004), [4] Ladd ME and Quick HH, MRM 43:615–619 (2000), [5] Patent US 2004/0263174 A1