Comparison of RF Heating in Cables equipped with different Types of Current Limitations

S. Weiss[1], B. David[1], O. Lips[1], J. H. Wuelbern[1], and S. Krueger[1]
[1]Philips Research Laboratories, Hamburg, Germany

Objective: Active interventional MR devices usually require conductors for the transmission of various types of signals, e.g. MR signal for active tracking or intravascular imaging, electrophysiological signals, ablation currents, or signals from sensors for temperature or other physiological parameters. MR-induced common mode currents in such conductors can lead to RF heating especially at the tip, but also along the conductors. Various methods have been proposed to limit such MR-induced RF currents and associated RF heating, including use of resistors [1-2], various implementations of resonant RF chokes [3-4], transformers [5], and mechanical switches [6] as current-limiting elements. Each of these approaches is applicable to a specific subset of signal types. However, the approaches have in common that they limit MR-induced RF-currents [1-6] and segment long conductive structures into short parts [3-6], effectively increasing the common mode resonance frequency of the structure. It is the objective of this work to compare transmission lines with different types of current-limiting elements with respect to RF heating at the conductor tip and at the current-limiting element.

Materials and Methods: Six different types of transmission lines were implemented, and RF heating measurements in the MR system (Achieva 1.5T, Philips Healthcare, Best, Netherlands) were performed at these transmission lines using two different methods simultaneously. Firstly, dielectric tip heating was assessed with a small block of saline-based agar containing a fiber-optic temperature probe positioned at the tip (Luxtron 790, LumaSense, CA). Secondly, an infra-red (IR) camera (VarioCam, Infratec, Dresden, Germany) was used to assess RF heating along the full length of the conductors. The following transmission lines were evaluated:
(a) thin-insulated copper wire (diameter D=150 µm, length L=235 cm, tuning the resonance of the wire to Larmor frequency),
(b) pair of highly resistive (HR) wires (L=133 cm, D≈140 µm, resistance 2 x 5.1 kΩ), e.g. for electrophysiological signals,
(c) coaxial RF cable (L=137 cm, D≈550 µm) with four miniature elongated single loop transformers for MR signals,
(d) unipolar cable including four mechanical micro switches (L= 121 cm, D≈500 µm), e.g. for RF ablation current,
(e) coaxial RF cable (L=100 cm, D≈500 µm) equipped with three resonant RF chokes inductively coupled to the coaxial shield,
(f) unipolar cable (L=87 cm) equipped with 8 miniature resonant RF chokes (micro coil, D≈1200 µm, tuned by SMD capacitor).
The cables were consecutively positioned parallel to B_0 (8.5 cm off-center, tip at z=34 cm), and evolution of RF heating over time was measured with the fiber probe and the IR camera during application of a sequence with a whole body SAR of 2 W/kg for 10 s.

Results: The maximum temperatures measured by the IR camera and fiber-probe are summarized in Tab.1. All current-limiting elements suppressed tip heating very effectively, whereas strong RF heating was found for the unprotected Cu wire. The IR movies clearly depicted RF heating occurring along the different wires, which was strongest for the two wires with micro chokes (f) and with large chokes (e) (Fig.1 & Tab.1). Temperature profiles with maxima at the wire center and minima at wire ends were found for the HR wires and the Cu wire. Lowest heating at tip and along the wire were found for the transformer cable (c) and the switch wire (d).

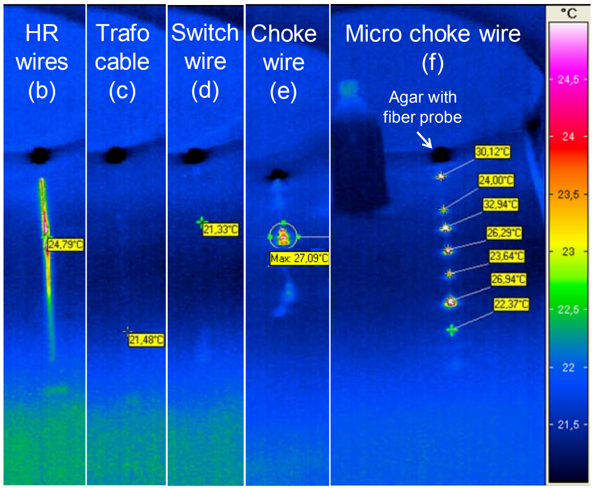

Figure 1: IR pictures of heating along various wires during a 10 s scan with SAR=2 W/kg.

Table 1: Maximum RF heating measured by fiber probe at tip and by IR camera along wire.

Wire Type	ΔT_{max} @tip	ΔT_{max} @IR
Cu wire	23K	1.9K
HR wire pair	0.1K	3.2K
Transformer	0.1K	0.1K
Switch wire	0.0K	0.0K
Chokes wire	0.2K	10.6K
Micro chokes	0.2K	11.5K

Discussion: While all methods effectively suppressed tip heating, heating at the current-limiting elements was largest for the resonant chokes due to high internal RF currents. Even for a large number of chokes applied along the wire (f), each of these chokes showed considerable heating. Transformers and open switches are capacitive and therefore non-resonant elements that avoid the risk of local heating.
The IR imaging method is suitable to quickly and globally identify sources of ohmic heating and here served well to demonstrate the difference in local heating at resonant and non-resonant elements for current limitation. However, the temperature increase depends on the heat capacity of the sample, so that fiber-optic measurements in water are mandatory for safety assessment of full devices. Still, the IR method is helpful to guide the application of fiber probes to include sources of heating along the device.

Conclusion: Resonant circuits used to limit MR-induced currents can heat up considerably, which suggests that their use should be avoided in devices that enter the patient if alternatives are available. Non-resonant elements for current limitation show less RF heating. IR imaging can be used to quickly identify hot spots caused by ohmic heating.

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