A Novel Broad-band, High Power and RF-safe Cable for MR-guided Catheter Ablation

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Objective: MR-guided electrophysiology (MR-EP) ablation procedures for treatment of arrhythmias have the potential benefit of visualizing the tissue response and improving catheter guidance. Effective measures to ensure RF safety of diagnostic MR-EP catheters have been proposed, including the use of active tracking via transformer-based cables and recording of intra-cardiac ECG via highly resistive (HR) wires [1]. However, providing trans-catheter ablation functionality remains a major challenge, mainly due to the required RF-safety to avoid tip heating [2]. To address this, we developed a broad-band, high-power PCB-based cable with integrated resonant trap circuits designed to float in the irrigation tube of state-of-the-art tip-irrigated EP ablation catheters for cooling of the traps.

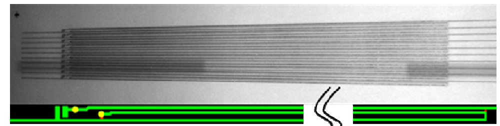

Fig. 1: Photo (top) and corresponding layout sketch (bottom) of the PCB with two inductor windings per side, via and solder pads for 01005 tuning capacitors.

Materials and Methods: A PCB layout for sub-miniature RF traps was designed to realize an array of such resonant trap circuits to form a catheter ablation cable inside an irrigation tube for RF-safe use in 1.5T MR scanners. For maximization of the trap surface exposed to the irrigation liquid, a thin PCB design was used. This allows for effective cooling of the typical local heating of traps resulting in a comparably low temperature increase of the cooling liquid.

The individual traps serve as a common mode block for currents induced by the RF of the MR system to eliminate tip heating, while the lower frequency therapeutic ablation current can still be transmitted. At the same time, spurious noise at the MR frequency is suppressed to improve MR image quality. The trap circuits have a double-sided layout based on a 25µm thin polyimide substrate. The width of a single trap is 600µm, and the length is 80mm. The copper lines are 100µm wide and 17µm thick. To realize high inductances, 60mm long and 600µm wide two-turn spirals are formed on each side and connected with same sense of winding through vias. Each of the 12 individual traps was tuned to resonance at 63.87 MHz using 01005 capacitors with 28pF total capacitance. Proper tuning was verified, and the resonance quality factor was determined by S11 measurements using weak coupling through a miniature pick-up coil of length 60mm and width 600µm. All traps were directly solder-connected using the outer connection lines of the layout (Fig.1) to form a ~1m long trap array. The trap array was then coated with varnish to reduce losses in the irrigation liquid.

The DC resistance of the ablation cable and the common mode attenuation at 63.87 MHz of a single trap of the cable was determined.

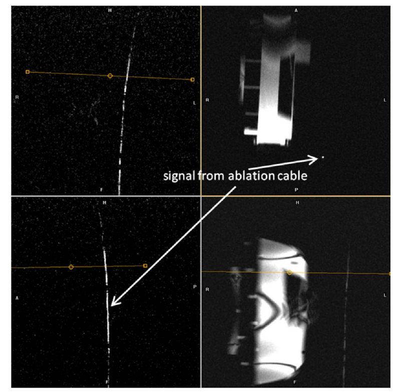

Fig. 2: MR images acquired with RF generator switched on, the ablation cable connected and the cable tip positioned in the iso-center.

First RF heating measurements were performed with the un-cooled, bare trap array positioned inside a 1.5T scanner running an imaging sequence with SAR 2W/kg (dynamic 2D b-SSFP) for 1 min. Temperature recordings were acquired in real-time with high temporal, thermal and spatial resolution using simultaneously an infrared video camera (VarioCam, Infratec, Dresden, Germany) and a fiber optic thermometer (Luxtron 790, LumaSense, CA) with a probe attached to the tip of the cable inside an agar gel block.

The trap array was then integrated into an irrigation tube for connection to an infusion, and RF heating measurements were performed as follows: Fiber-optic probes were used to measure the temperature of in-flow and out-flow of the cooling liquid (water), near the cable tip inside an agar gel block and of the irrigation tube at the trap in the middle. The complete setup was monitored with the IR camera. Temperatures were measured during 1 min of application of the same 2W/kg global SAR imaging sequence without and with infusion at various flow rates.

Finally, RF ablation tests were performed using a standard RF generator operating at ~485kHz (SJM 1500T11, St. Jude Medical, St. Paul, MN, USA) using RF ablation powers up to 30W. MRI was performed to assess the intrinsic spurious noise suppression by the ablation cable.

Results: The overall DC resistance of the cable was measured as 63.5 Ohms. The DC resistance of a single trap was 5.2Ohm. The quality factor of a single isolated trap was determined as Q = 11.38, and the common mode attenuation of one trap in the middle of the ablation cable was measured as (-14.3 ± 0.5)dB.

For the un-cooled measurements, RF heating of the traps during MR scanning up to 3.8K after 10 sec was found (scan stopped before thermal equilibrium), while no tip heating was observed due to the effective common mode blocking by the traps.

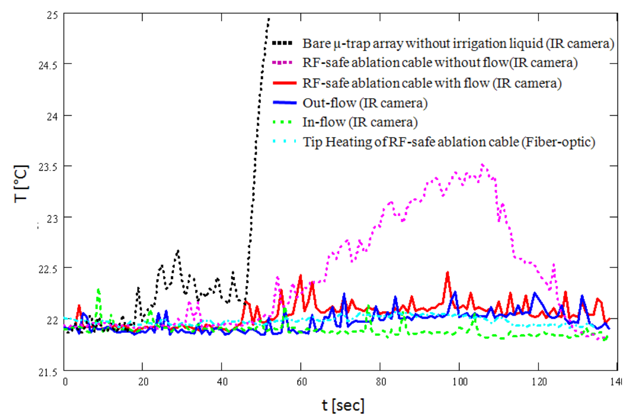

Fig. 3: RF-safety demonstration of the ablation cable during 1min of MRI with global SAR of 2W/kg. The irrigation liquid temperature rise is only 0.1K. For all experiments, no significant temperature increase was found at the tip proving the effectiveness of the traps.

With permanent irrigation no significant temperature changes are present anymore. Instead, the irrigation liquid shows a constant temperature increase by (0.1±0.1)K from in-flow to out-flow during 2W/kg SAR imaging using a very slow 3.5ml/min infusion. The maximum temperature increase in thermal equilibrium anywhere on the cable was (0.15±0.1)K, while tip heating was additionally measured fiber-optically to be less than 0.1K after 1min of MRI with a global SAR of 2W/kg. The infra-red camera measurements for all experiments confirmed that, besides the traps, no other parts of the cable showed RF heating caused by MRI.

Ablation was performed successfully in a phantom proving the therapeutic functionality of the ablation cable using ablation powers of 5W, 10W, 20W and 30W for durations of 1min. Continuous impedance recordings were successfully acquired during all ablations. The temperature of the irrigation liquid during the application of an RF ablation power of 30W rose from 10°C to 20°C in the steady state using a flow rate of 20ml/min, which is typical for this ablation protocol.

Fig.2 shows MR images acquired with an RF ablation setup at the bore with the generator in monitoring mode. In contrast to a regular ablation cable, the image quality is significantly improved and allows MRI even without additional filters demonstrating the intrinsic spurious noise suppression by the cable. The signal amplification by the resonant traps is visible.

Discussion & Conclusion: A novel RF-safe cable technology for performing catheter ablation procedures under MRI guidance has been proposed. The technology can be implemented for arbitrary MR field-strengths and can be integrated with current state-of-the-art tip-irrigated ablation catheters. It is shown that tip heating is eliminated and that the capacitors and inductors of the trap circuits are being effectively cooled by the irrigation liquid even at very slow flow rates, so that MRI-induced temperature elevations can be avoided over the entire length of the catheter. The ablation cable intrinsically blocks spurious noise at the MR frequency from entering into the bore, which may be especially helpful for capacitive or inductive noise coupling issues related to electrical equipment near the scanner during a procedure. The proposed concept provides a safe solution for catheter-based RF ablation, which allows high SAR MRI at any time during the procedure.

[1] Weiss S., et al., DOI: 10.1002/mrm.22669, MRM 2010 **[2]** Weiss, 8th Int. MRI Symposium (V48) 2010