Evaluation of a Transformer based Transmission Line for improved RF Safety of devices at 3T

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Objective: The clinical usefulness and the technical robustness of active catheter tracking during MR-guided intravascular interventions has been proven before. However, RF resonances on the cables required for active techniques may lead to excessive heating during RF transmission, which prohibits their clinical use [1,2]. Recently, it was shown that a transmission line comprising miniature transformers reduces RF heating of an active catheter very effectively at 1.5T [3,4]. It is the objective of this work to evaluate whether this concept can be applied for 3T and to optimise the transformer hardware for this purpose.

Theory: Transformers effectively divide a long cable into short sections, which improves the RF safety of the cable by strongly attenuating any common mode currents, that are responsible for RF heating. For a high common mode attenuation, the stray capacitance between the primary and the secondary loop should be as small as possible. Transformers transmit the MR signal in the differential mode, where they cause a minor signal attenuation in the order of 1.8dB per transformer. In theory, at 3T twice as many transformers per unit length of cable are required than at 1.5T, because the length of a cable that has its lowest common mode resonance at 128MHz is only half as long as a cable resonant at 64MHz. Additionally, a transformer with a given stray capacitance C_S between the transformer loops has only half the common mode impedance $X_S=1/\omega C_S$ at 128MHz, which again requires twice as many transformers per unit length of cable.

Materials and Methods: In order to limit the signal loss caused by the increased number of transformers required at 3T, new transformers were designed with a reduced loop length of 3cm instead of 5cm used at 64MHz previously. The stray capacitance C_S of these transformers was measured at 128MHz. The transformers were tuned and matched to 50Ω and their scatter parameters S_{11} and S_{21} were measured at 128MHz. To demonstrate the effect of the stray capacity on common mode resonances, the lowest common mode resonance frequency of an active tracking catheter (6F=2mm diameter, dual lumen tube, 1m insertable length) equipped with a 500µm wide transmission line in one lumen was simulated. Simulations were performed based on the measured stray capacitances of the long and the short transformer, and the number of transformers was varied. To demonstrate the reduction of RF heating by the transformers in a direct comparison, two active tracking catheters were built, one with and one without transformers. Both catheters were equipped with solenoidal tip coils that were tuned and matched to 50Ω using miniature capacitors (SMD, 0.3x0.3x0.6mm^3, Murata, Japan). In the standard catheter, a plain micro coaxial cable (0.53mm ∅, 1dB/m loss, MMK5001, Elspec, Germany) was used to connect the tip coil, and in the transformer catheter six 3cm long transformers were distributed along the cable. The scatter parameters S_{11} and S_{21} of the transformer cable were measured prior to installation. Additionally, the common mode resonance frequencies of both catheters immersed in phantom liquid were measured to validate the respective simulations. Temperature measurements were performed with each catheter immersed in phantom liquid and located 18cm off-center in RL-direction parallel to B_0 in the MR scanner (ACHIEVA 3T, Philips Medical Systems). The immersed length of the standard catheter was adjusted such that it became resonant at 128MHz with one of its higher order resonances. The transformer catheter was fully immersed, because its lowest resonance frequency was far beyond 128MHz. After the application of a balanced FFE sequence for 1min (TR=3.1ms, various α), the temperature was measured with a fiberoptic probe (Luxtron790, Santa Clara, CA) at and in the tip coil and at the distal end the distal transformer. Active tip tracking experiments were performed with the transformer catheter using the catheter tracking option of the clinical MR scanner. For these experiments, the catheter was located on the z-axis of the scanner with the tip section of the device in the isocenter. Slice tracking projection data were recorded, and the SNR of the projections was evaluated.

Results and Discussion: The stray capacitance was C_S=4.0pF for the 5cm long transformer and 2.1pF for the 3cm long transformer. Hence, the shortening of the transformer nearly balances the loss in common mode impedance that occurs at 128MHz in comparison to 64MHz. The effect of the reduced stray capacity on the simulated common mode resonance frequency is visualized in Fig.1. Six three 3cm long transformers shift the lowest resonance frequency of a 1m long active catheter model to 232MHz, whereas the 5cm long transformers achieve only a shift to 183MHz. A value of 231MHz was measured experimentally for the fully immersed transformer catheter. The transmission loss of the 5cm long and the 3cm long transformer was measured as -1.98dB and -1.75dB, respectively. The improved transmission of the short transformer can be explained with the reduced losses in the shorter leads. The overall transmission loss of the micro coaxial cable including the six transformers was -11.5dB. The results of the temperature measurements in the MR are summarized in Fig.3. For the standard catheter, the temperature increased by maximally 13.6°C inside the tip coil and by 11.1°C out side the coil for a flip angle of 22°, which corresponds to a global SAR of 4W/kg. For the transformer catheter, the temperature increased by maximally 0.4°C inside the tip coil and 0.3°C out side the coil. All temperatures reached a steady state within one minute. Active tip tracking in the phantom performed absolutely robustly, and the SNR of the magnitude projections acquired for tip tracking was 101±33.

Conclusion: A transformer based transmission line vastly improves the RF safety of an active tracking catheter at 3T. In the transformer catheter, RF heating was limited to a physiologically non-relevant level of 0.4°C whereas dangerous heating by 13.6°C occurred for a standard catheter under identical conditions. Despite the increased number of transformers required at 3T, projections for active tracking can be acquired with very high SNR, and active tracking performs robustly in the phantom. From these results it can be expected, that clinically applicable active tracking catheters can be designed for use in 3T systems.

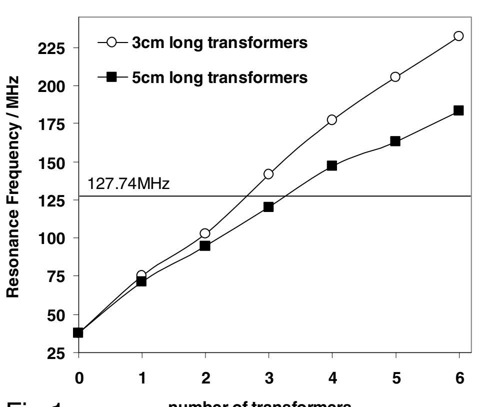

Fig.1

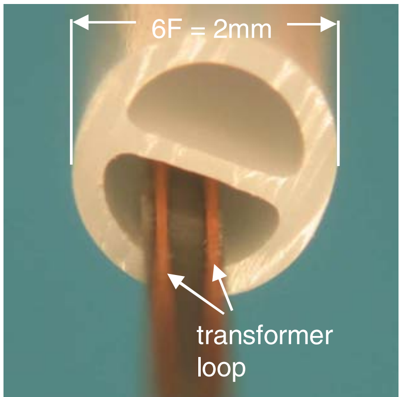

Fig.2

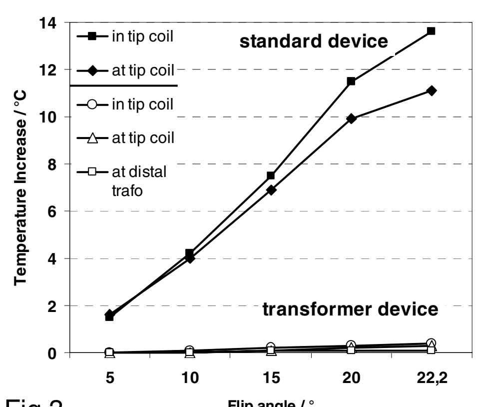

Fig.3

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