MR-visible and RF-safe low profile transmission line for active devices

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Objective: A promising method for making active devices RF-safe relies on the principle of electrical segmentation of transmission lines, thus eliminating the common mode resonance that leads to heating at the device tip [1,2]. The previously proposed transformer-based transmission line [1] uses capacitors to provide a matching between 50Ω cable segments and the inductive impedance of the transformers or the tip coil yielding a visualization of the catheter at the tip and at the transformers. In this work, we propose a transmission line based power matching technique without lumped capacitors introducing the possibility of very small diameter transmission lines and MR-visibility over the entire length.

Material and Methods: A transmission line consisting of a triaxial cable segmented by miniature transformers was designed. The two shields of the custom-made triaxial cable (Tyco Electronics, diameter 390µm) with an impedance of 8.8Ω were used for both signal transmission and distributed matching of the transformers. Transmission lines are known to transform impedances according to:

$$Z(l) = Z_0 \frac{Z_L + iZ_0 \cdot \tan(\beta l)}{Z_0 + iZ_L \cdot \tan(\beta l)}$$

, with Z_0 being the cable impedance, Z_L the load impedance, l the cable length and β the wave number. Plotting Z(l) for the given transformer design yields a power matching condition (Z → Z*) for a cable length of 31cm (Fig.1), which was therefore chosen as the length of the cable segments between the transformers. The proximal section of the transmission line was matched to 50Ω using a short triaxial cable and a series capacitor inside the hand-piece.

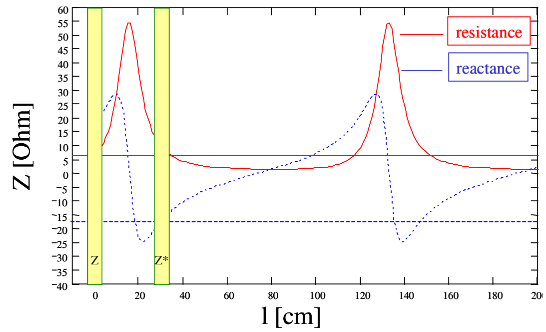

Fig.1: Load impedance transformation by a transmission line as a function of the length l.

The signal transmission properties of the line were measured and an active catheter was built. The RF safety of the catheter was compared with a catheter equipped with a standard coaxial line by performing temperature measurements for respective catheters. For each catheter, the tip was embedded into an Agar gel phantom to eliminate convective heat transfer, and a fiber optic probe measured the local heating during MR scans. The standard catheter was positioned in the MR scanner parallel to the z-axis and close to the bore such that a high temperature increase could be observed. Subsequently, the proposed catheter was brought to exactly the same location, and the temperature measurements were repeated. The catheter was then tested in an animal experiment to verify the in-vivo performance in a pig (48kg).

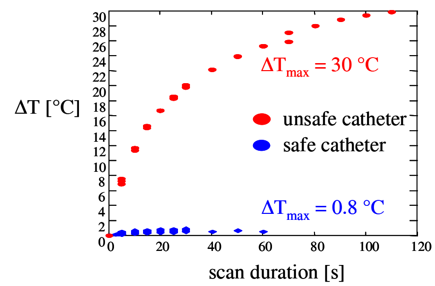

Fig.3: Temperature measurements comparing an unsafe to a safe transmission line at the tip of a catheter.

Results and Discussion:

The overall signal loss of the full transmission line was measured as –7.5dB, which is comparable with the version with discrete capacitors.

Fig.2 shows an exemplary multi-station image of the full catheter in a long water basin acquired via the catheter channel. As a result of the specific implementation, the entire line becomes resonant for differential mode currents, which, in combination with small shield imperfections, renders the entire transmission line receptive for spin signals resulting in high signal visualization along the entire length. This effect was shown to be independent from the position of the catheter with respect to the z-axis.The temperature measurements demonstrate that the proposed transmission line is RF-safe. A maximum temperature increase of 0.8°C was found for 9 different positions of the temperature probe with respect to the catheter tip. After 30s, no further temperature increase could be observed. In contrast, three of the 9 selected temperature probe positions led to a reproducible increase of more than 20°C within 30s and 30°C after 120s for the unsafe catheter, still not being in thermal equilibrium (Fig.3). The common mode resonance of the safe transmission line was measured in phantom liquid to be 133MHz.

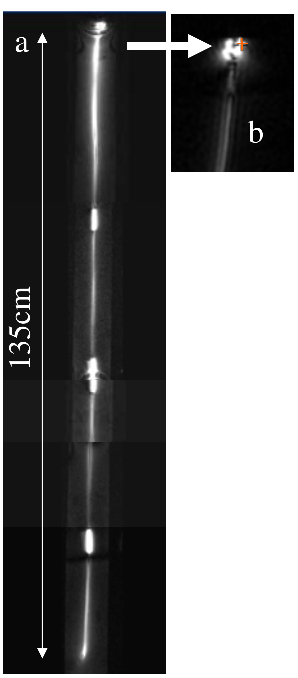

Fig.2: Phantom images: a.) RF-safe visualization of the entire catheter. b.) Active Tracking

Fig.4 shows the distal section of the catheter including the tip coil during catheterization of the left ventricle, the aorta and the left renal artery using (a) sum of squares reconstruction for catheter and imaging channel and (b) separate reconstruction of the catheter channel and overlay over the anatomical image (SSFP, TR = 3.4ms, TE =1.7ms, slice thickness = 5mm, matrix = 224, flip angle = 35°). Note, that, in principle, a very low local SNR received via the catheter channel is sufficient for device tracking, as long as the device can still be detected. Using the same catheter, active tip and scan plane tracking could be done with high accuracy and reliability (Fig. 2b).

Conclusion and Outlook:

A new RF-safe transmission line was tested for safety and performance in phantom and animal studies. The proposed concept for matching of the transformers avoids lumped capacitors and uses a low impedance cable to perform the matching in a distributed manner. This results in an active visualization of the full length of the catheter while keeping cable losses comparable to the previous version of the transformer line. An important advantage of this concept is the lower profile of 500µm with a large potential for further miniaturization.

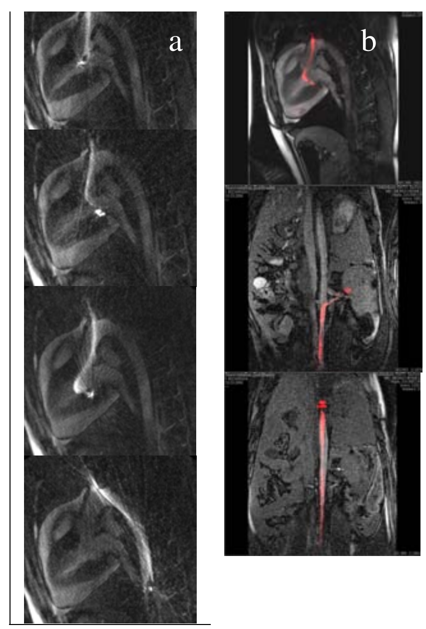

Fig. 4: a.) Image using sum of squares reconstruction of all receive channels. b.) The signal of the receive channel of the RF safe active catheter overlaid over the image.

[1] Weiss S et al., MRM 54:182–189 (2005)
[2] Umathum, R. et al, Proc. ISMRM, p1396, 2006