B_1-Insensitive Transmission Lines for RF-Safe Active Tracking of a Robotic Assistance System

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Introduction

Recently, a commercial available robotic assistance system was introduced to facilitate needle-guided interventions inside closed-bore MR systems. The robotic assistance system uses passive markers for localization, however, the use of active markers would be desirable as they allow for automatic scan plane positioning. So far, active tracking techniques are not established in clinical practice, since the conducting structures in the cables can lead to significant device heating [1]. Lately, a method for the reduction of device heating was proposed which uses transformers to segment the cables into shorter sections [2]. These transformers have been successfully integrated in intravascular catheters. Unfortunately, the transformer coils also act as small receiver coils, so that under worst case conditions tracking of a distal marker coil [3] could be compromised.

In this work, we present a modified transformer coil design which reduces the inductive coupling of the coils with a homogeneous transmit RF field. Additionally, the design significantly reduces artifacts of the transformer coils, so that structures close to the transformers are less obscured.

Materials and Methods

A transformer structure in a transmission line to suppress unwanted RF-induced common mode signals on cables can be realized with two inductively coupled loops. The loops are arranged in parallel to maximize the mutual B-field coupling and thus, the receiver signal (differential mode currents). During RF excitation with a transmit coil that is large compared to the transformer coils (e.g. the body coil) significant resonant coupling can occur if the transformer loops are oriented perpendicular to the main magnetic field. To suppress this unwanted RF coupling a new transformer coil was designed. Therefore, the loop coils were replaced by figure-of-8-shaped transformer coils where the effect of a homogeneous external magnetic coupling field cancels due to the sign reversal in the two parts of the figure-of-8-shaped pattern. A prototype figure-of-8-shaped coil system with 2 windings for each transformer side was built on a standard circuit board with the following dimensions (Fig. 1): coil length: 12.0 mm, coil width: 6.0 mm. The copper leads of the coils had a rectangular cross section of 0.4 mm × 35 µm (width ×height). The distance between primary and secondary coil was adjusted by spacers to 1.6 mm.

To demonstrate that both loop and figure-of-8-shaped transformer types have similar signal transmission properties, the scattering parameters for each transformer type were measured with a network analyzer (Advantest R3765CG, Tokyo, Japan). The coupling between the transformer coils and a homogeneous external RF field was assessed using a 14.5cm-diameter Helmholtz coil for transmission with both transformer types placed at its center. B_1-decoupling was also assessed in a commercial whole body 1.5 T MR scanner (Siemens Magnetom Symphony, Erlangen, Germany). Here, the transformer devices were terminated with 50 Ω and immersed in a water bath (500 ml H_2O with 1.0% Gd-DTPA) that was placed on the system's spine array coil. MR images of the vicinity of the transformer coils were acquired using a FLASH sequence (TR = 27 ms, TE = 6.4 ms, $\alpha = 50°$, matrix: 256×256, FOV = 150×150 mm²) to visualize the signal changes arising from inductive B_1-coupling.

Temperature measurements were performed with an unsegmented and a segmented 1.6 m-long coaxial cable (Suhner, Switzterland, G 02232, 50 Ω). Three figure-of-8-shaped transformers were used for segmenting the cable into 40 cm-long sections. At the tip of both cables small tracking coils (Ø: 6.5 mm, length: 5.5 mm, 5 windings) were mounted. To maximize possible RF heating all cables were aligned parallel and close to the magnet bore (distance: 5 cm) and were embedded in a phantom liquid (5 l H_2O, 0.9 % NaCl, 1.0% Gd-DTPA, 2% Polyacrylic Acid). The temperature increase at the tracking coils was measured with a fiber optic thermometer (LUXTRON 3100, Santa Clara, CA, USA) using a trueFISP sequence for MR imaging (TR = 3.1 ms, TE = 1.6 ms, $\alpha = 75°$, SAR = 3.6 W/kg).

Finally, three segmented cables (length: 2.0 m) with four integrated figure-of-8-shaped transformers were constructed and terminated with an active marker coil each. The coils were mounted to the instrument holder (Fig. 3(a)) of the robotic assistance system (INNOMOTION™, Innomedic, Herxheim, Germany). The marker coils were localized with a double projection technique ($\alpha = 10°$, FOV = 500 mm, 256 data points, total acquisition time 27 ms [4]) and their positions were used to define the actual scan plane during a puncture experiment (Invivo PunctureNeedle™ 150/18, Schwerin, Germany) in a grapefruit.

Results and Discussion

For the two transformer types comparable transmission coefficients were found: differential mode: -0.5 dB / -0.6 dB (loop / figure-of-8-shaped), common mode: -18.4 dB/-17.3 dB. Measurements with the Helmholtz coil showed that an additional attenuation of B_1-induced currents of -18 dB is present in the figure-of-8-shaped coils. The loop transformer coils showed significant resonant coupling with the B_1-Field of the MR system (Fig. 2(a)) leading to a bright local artifact with dark stripes, whereas nearly no artifact was visible with the figure-of-8-shaped coils (Fig. 2(b)). In the heating experiment a maximal temperature increase of 30 K/ 3.5 K was seen in the unsegmented / segmented cable (Fig. 4). In the puncture experiment the needle trajectory was clearly visible (Fig. 3(b)) indicating a perfect alignment of the imaging slice (SE, TR = 300 ms, TE = 15 ms, $\alpha = 90°$, resolution: 0.4×0.4×3.0 mm, averages: 5) with the scan plane defined by the tracking coils.

The comparable transmission parameters demonstrated that both transmission line setups - loop and figure-of-8-shaped - yield equivalent signal intensities during signal reception. Image artifacts were minimized due to the figure-of-8-shaped coil design and unwanted B_1-coupling during RF excitation was reduced. Using available micro-manufacturing technologies transformer coils might be directly integrated into the cables so that this new transformer design can also be used for active MR catheter tracking.

References

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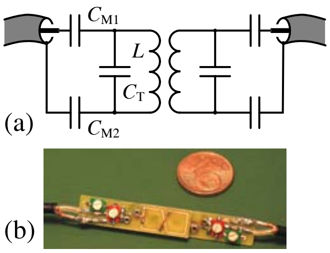

Fig.1: Schematic (a) and image (b) of a transformer device. A capacitor network was used to allow for resonant mutual inductive coupling of the transformer coils and to match the impedances of the transformer coils to the impedance of the cable (50 Ω).

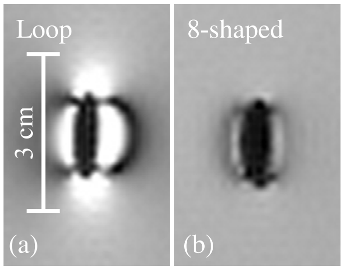

Fig. 2: Enlarged MR images of the vicinity of the loop transformer coils (a) and figure-of-8-shaped transformer coils (b). Both coils are oriented perpendicular to the imaging slice. A large artifact (≈2.0×3.0 cm²) occurs in case of the conventional loop design.

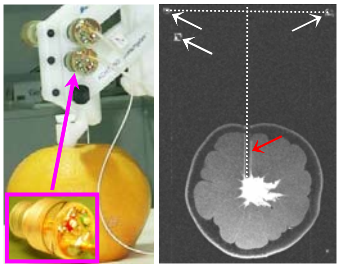

Fig. 3: (a) Active tracking coils at the instrument holder. (b) SE image acquired after puncture of the grapefruit. Marker signals and needle trajectory are clearly visible.

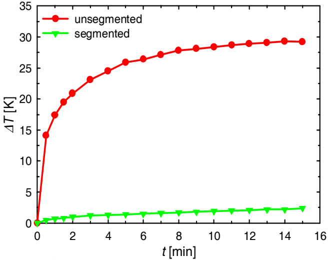

Fig. 4: Temperature-time-curves measured at the tracking coil of an unsegmented and a segmented cable after a heating period of 15 min.