Parallel transmit with toroidal transceiver for enhanced visualization and RF safety

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Introduction: Visualization of guidewires and ablation devices without causing RF-induced heating is an important concern in interventional MRI. To embed micro-coils or cable traps, typical designs require significant modification of existing devices. Such methods often sacrifice desirable device structural properties, and their performance is highly dependent on device geometry and scan plane orientation. In 2005, Hillenbrand presented a novel toroidal "bazooka balun" receiver [1] for use with standard conductive guidewires. This device also acted as a passive cable trap during transmit to improve safety. In this work, we extend this concept to a transmit-receive toroid and treat the toroid and guidewire as an additional, actively controllable element in an array of transmit coils. We demonstrate positive-contrast visualization of insulated conductive wires, contact loading effects, and show that RF safety can be actively ensured with the use of parallel transmit.

Methods: The fundamental premise of our approach is that by allowing very low levels of current to flow in a controlled manner on the conductive structure, we can achieve effective visualization of the structure, while still ensuring safety. We built a toroidal transmit-receive device (Fig. 1a) to efficiently couple to the wire. The device consists of a toroid cavity, capacitors for power-amp and pre-amp impedance matching, and a balun for isolating common mode RF. The toroid cavity inductively couples to any conductive wire fed through its center. The 1/r falloff of B1 from the inserted wire creates strong sensitivity enhancement near the wire, thus making the toroid and wire combination behave like a very sensitive, elongated coil. To show how tip visibility varies with wire insulation, we used the transceive toroid to image different wires inserted in a saline gel phantom. We imaged fully insulated wire, insulated wire with 5 mm of the conductor tip exposed, and bare wire. Imaging parameters were: 1.5T, GRE, 1^{o} flip, TR/TE = 50/15ms, 2 cm slice thickness.

To demonstrate the use of parallel transmit for RF safety, we used the setup in Fig. 2. Here, the transceive toroid is acting as an additional transmit coil in an array of surface coils. An optically-coupled toroidal current sensor [2] measures both the magnitude and phase of the current induced in the wire, without interrupting the continuity of the wire, and a separate receive coil array is used for imaging the phantom volume. The RF transmit and data receive are synchronously controlled by the MEDUSA USB console [3]. The coupling between each array element and the wire is measured by transmitting low amplitude RF pulses on each coil separately and recording the current sensor measurements. These coupling values are then used to choose transmit weights for simultaneous transmit on all coils in order to induce different levels of current in the wire. The surface coils were arranged symmetrically around the wire so that transmit weights could easily be chosen, but more generalized coil configurations and transmit weight computation methods can be used [4]. Both current sensor measurements and Bloch-Siegert B1 maps [5] (1.5T, GRE, TR/TE = 50/6ms, 40 cm FOV, 256x256, 1 cm slice) were used to verify successful current control.

Results: Figure 1b-d shows the results of the visualization experiment. The tip of the wire is clearly visible in Fig. 1c, showing that a small electrical contact between the conductor and surrounding medium, as found in EP ablation catheters, enhances visibility by allowing currents to flow all the way to the tip. This is a dielectric loading effect that extends the effective antenna length to enhance tip visibility, whereas excessive contact area (Fig. 1d) results in signal attenuation [6]. Typical SNR exceeded 100 using low (1^{o} flip) transmit power. The extremely high SNR drops as $\sim 1/r^2$, creating a very localized sensitivity that is compatible with projection imaging, since the Tx/Rx azimuthal fields maximally correlate in a partial volume.

Figure 3 shows three examples of different current levels that can be induced in the wire by different parallel transmit excitations. There is more than a 150-fold reduction in current magnitude from the maximum current case (red line) to the minimum case (black line). Figure 4 shows the images and B1 maps corresponding to the three transmit modes of Fig. 3. The very minimal deviation in B1 along the guidewire compared to the background field in the rightmost image indicates that minimal current is indeed being induced by this excitation. Note that there is still sufficient excitation for visualization of the phantom and wire, even in the minimal current, RF-safe case.

Conclusion: A toroidal transceiver enables high SNR positive-contrast visualization of conductive structures such as guidewires and EP ablation devices. Tip visibility improves if an electrode contact is present. RF safety can be ensured when this method is integrated with optical current sensors and parallel transmit using an array of surface coils.

References: [1] Hillenbrand et al., Proc. 13th ISMRM, p197, 2005. [2] Zanchi et al., IEEE Trans. Med. Imag. 29:169-178, 2010. [3] Stang et al., Proc 15th ISMRM, p925, 2007. [4] Etezadi-Amoli et al., Proc 18th ISMRM, p777, 2010. [5] Sacolick et al., MRM 63:1315-1322, 2010. [6] King, Proc IEEE 64:228-238, 1976.

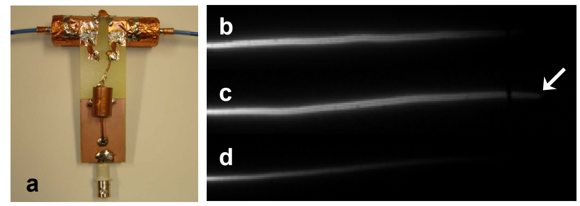

Figure 1: Wire tip visualization using transceive toroid (a) as a transmit-receive coil on a fully insulated wire (b), insulated wire with exposed tip (c), and bare copper wire (d). White arrow shows location of the wire tip, and black line is a marker in the phantom.

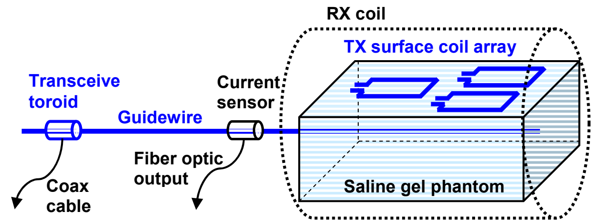

Figure 2: Setup for transmit array-based imaging and current control. The elements in blue (3 surface coils, plus the conductive guidewire and transceive toroid) form a 4-element transmit array, where each element can be individually excited.

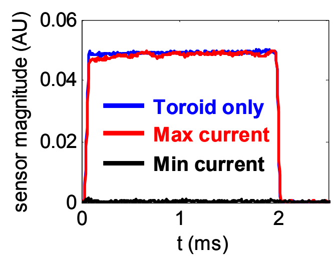

Figure 3: Current sensor measurements when transmitting with 2-ms hard pulses weighted to induce different levels of current in the wire. Maximal current (red), minimal current (black), and an excitation using only the transceive toroid are shown (blue).

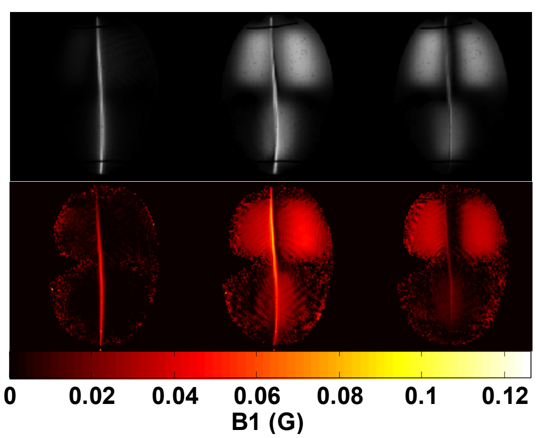

Figure 4: Coronal magnitude images (top) and B1 maps (bottom) when transmitting with weights of Fig. 3: transceive toroid only (left), maximal induced current (middle), and minimal induced current (right). In the minimum current case (right), the B1 fields near the wire show little perturbation from the background coil sensitivities, while still achieving sufficient visualization of the background volume, wire body, and wire tip (top of phantom).