Novel Multi-mode Probe for MR-guided Therapeutic Endovascular Interventions

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Introduction:

A typical minimally invasive, wholly MR guided therapeutic endovascular procedure involves accurate guidance of the catheter to the target region, performing the therapeutic procedure and monitoring the progress of the therapeutic procedure using high resolution images of the target region. Such a procedure simultaneously involves real time active tip tracking, visualization of a desired length of the catheter to enable proper orientation of the catheter and high resolution imaging. A number of active [1,2] and passive [3,4] methods have been developed and employed for the tracking and visualization of catheters and guide wires. Independent active devices have also been developed specifically for either active tracking [1] or imaging [5] as the design requirements for the two are divergent. However, such specialized devices would necessitate multiple insertions of catheters and guide-wires, thereby increasing the risk of injury to the vasculature. Therefore, it would be desirable to have a single device that is capable of performing all three functions. Recently, a phased array variant of the opposed solenoid design that demonstrates both active tracking and imaging functionalities has been reported [6]. This design however, uses multiple coaxial cables, thereby increasing complexity and mechanical rigidity of the catheter. More recently, initial prototypes of multi-mode probes that combine the functionalities of a tracking coil, a receive-only imaging coil and a wireless marker have been developed [7]. In this work, we present a novel multi-mode coil design that demonstrates a marked improvement in performance in terms of forward-looking capability, tracking, and signal-to-noise ratio, over our initial prototypes.

Methods:

The multi-mode coil was constructed on a modified 6F (2mm outer diameter) double lumen balloon catheter using 36 gauge wire. The multi-mode coil consisted of an 8-turn Helmholtz pair placed at the distal end of the catheter and connected in series with a 2-turn imaging loop as shown in figure 1. The Helmholtz pair consisted of closely placed, elongated windings and was designed to yield a high signal from a localized region to enable tip tracking, while simultaneously giving the coil the forward looking capability. The imaging loop was 20mm long, spanned the outer diameter of the catheter and was wound in a sense opposite to that of the Helmholtz pair such that there existed a region of signal cancellation between the two (figure 1(d)). This design ensured robust tip tracking capability. The inductance of the multi-mode coil was controlled using series capacitors (single layer capacitors, ATC, AZ). A π matching network was used to match the resultant loaded coil impedance to a 50Ω micro-coaxial cable (42 AWG inner conductor, Alpha Wire Company., NJ). The inductive component of the matching network consisted of a solenoid wound around the catheter. A photograph of the multi-mode coil is shown in figure 2(a).

A coaxial cable trap balun was formed by implementing 70 tightly wound turns of the coaxial cable around the catheter. The shield impedance of the balun was measured to be 510Ω. The balun was placed close to the coil terminals. Another similar coaxial trap was placed towards the proximal end of the catheter. This was done to prevent the formation of voltage standing waves induced on the coaxial cable shield due to coupling with the external coil during the transmit cycle. The cable was routed to the proximal end of the catheter through the balloon lumen of the catheter, leaving the main lumen free for guide-wire insertion, etc.

A phantom consisting of concentrically placed acrylic tubes of diameters, 43.3mm and 19mm, placed inside a plastic bottle was filled with tap water. The multi-mode coil was placed inside the inner tube such that its distal tip was aligned with the edge of the tube to enable measurement of the extent of forward-looking capability. In the imaging mode, the multi-mode coil was connected to the single channel receive-only port of a MRI scanner (Signa 1.5T, GEHC, WI) via a decoupling circuit [7]. The body coil was used as a transmit-only coil and coronal and axial images of the phantom were obtained using the multi-mode coil with an SSFP pulse sequence (TE=2.7 ms, TR=13.7 ms, FOV=160 mm). In the wireless marker mode, the body coil was used as a transmit/receive coil. An SSFP pulse sequence (TE=2.1 ms, TR=4.6 ms, FOV=340 mm pulse sequence was used to obtain wireless marker images.

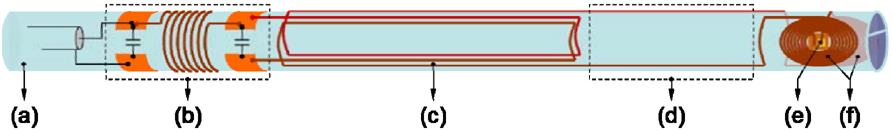

FIG. 1 Schematic drawing of the multi-mode coil showing (a) the 5F double lumen balloon catheter, (b) the π matching network, (c) the 2-turn imaging loop, (d) the region of signal cancellation, (e) the series capacitor (yellow rectangle) used to control the coil inductance and (f) the 8-turn Helmholtz pair used to provide the tip tracking peak and forward looking capability.

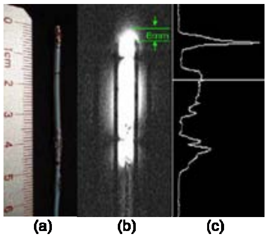

FIG. 2 (a) Photograph of multi-mode coil implementation, (b) Coronal image demonstrating forward-looking capability and (c) Signal profile showing distinct tip tracking peak

Results and Discussion:

A coronal image obtained using the multi-mode coil as a single channel receive-only coil is shown in figure 2(b). The image has been appropriately scaled to correspond to the dimensions of the multi-mode coil shown in figure 2(a). The signal intensity profile shown in figure 2(c) shows a distinct single peak corresponding to the location of the Helmholtz pair which can be used to accurately define the position of the catheter tip [8]. Coaxially wound solenoids, in contrast, demonstrate double peaks corresponding to their characteristic sensitivity pattern [7]. The Helmholtz design also demonstrates forward looking capability. As indicated in figure 2(b), the sensitivity pattern of the Helmholtz pair extends 6mm in front of the tip. This is a useful feature when performing neurological interventions. Note that, the solenoid that forms a component of the π matching network also behaves as an imaging coil, thereby extending the region of sensitivity in the axial direction.

An axial slice located at the center of the imaging loop (figure 3(a)) demonstrates that the multi-mode coil has a region of sensitivity extending beyond a tube which is 43mm in diameter with a region of very high SNR extending beyond a 19mm tube. In the wireless marker mode, a length of the catheter corresponding to the length of the coil can be visualized as seen in figure 3(b).

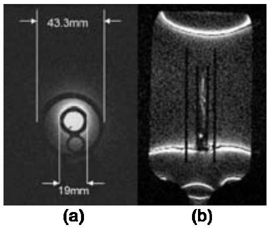

FIG. 3 (a) Axial image of tube phantom shows region of sensitivity extending beyond 43mm diameter tube and high SNR region extending beyond 19mm tube and (b) Coil behaves as wireless marker in body coil T/R mode.

Conclusions:

We have developed a novel multi-mode RF coil and presented results that represent a significant improvement in performance in three different modes (tracking, imaging and wireless marker) when compared to our initial prototypes. One weakness of the current design is that the performance of the Helmholtz pair is orientation dependent. However, this problem can be easily solved by constructing an orthogonal Helmholtz pair and is part of our ongoing work. Other ongoing work includes SAR optimization and performance studies in an animal model.

References:

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