Appendix 4

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Technical Note

Pair of Resonant Fiducial Markers for Localization of Endovascular Catheters at All Catheter Orientations

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Purpose: To test wireless resonance circuits (RC) to be used as fiducial marker of endovascular catheters during MR-guided interventions. Current markers loose their signal enhancement for certain catheter orientations. The purpose of this study was to test a marker setup which overcomes this orientation problem.

Materials and Methods: The markers were constructed from a pair of two RCs. The RCs were individually tuned and the coil axes were oriented perpendicular to each other in order to decouple the two RCs. The markers were mounted on the tip of endovascular catheters and tested in vitro and in one porcine in vivo experiment.

Results: An intense MR signal at similar signal levels was noted at all catheter orientations. In the in vivo experiment the markers allowed for fast and reliable MR guidance of the catheters.

Conclusion: A pair of two individually tuned and decoupled RCs is well suited for MR guidance of endovascular catheters.

Key Words: interventional MRI; catheter tracking; resonance circuits; patient safety; endovascular intervention
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MR GUIDANCE OF VASCULAR INTERVENTIONS has proven to be difficult. Ideally, a technique used to visualize vascular instruments would be characterized by high spatial and temporal resolution. The instrument should be directly depicted by its inherent properties without relying on additional hardware and postprocessing modification.

All passive position monitoring techniques are confronted with the challenge to generate sufficient contrast between the instrument and its surrounding anatomy (1–3). In active guidance techniques, the most common methods are MR tracking and profiling. These rely on the incorporation of a miniature radio frequency coil into the instrument or magnetically coupled MR antennas, respectively (4,5). However, all active monitoring techniques have the drawback of unsolved safety problems (6). Thus, the use of catheters comprised of radio frequency conducting components have prohibited application in patients because of potential tissue heating.

In this study, wireless resonance circuits (RC) as fiducial markers for endovascular catheters were tested as an alternative to conventional passive and active MRI position monitoring methods. RCs implemented on interventional instruments produce intense local signal enhancement on gradient and spin echo sequences after small tip excitation. The transmit coil couples to the fiducial coil, locally enhancing the B_1 field and thus substantially enhancing the excitation angle in the directly adjacent surroundings of the fiducial coil. In several in vitro studies, the use of RC for MRI guidance of interventional instruments was reported (7–9). These studies focused on the use of single-wound solenoid-shaped coils. Current markers, however, loose their signal enhancement for certain orientations. In this study, a marker setup is introduced and discussed that overcomes the orientation problem. The marker was tested in vitro and in one porcine in vivo experiment.

MATERIALS AND METHODS

Theory

The excitation of a single-wound RC depends strongly on its degree of electromagnetic coupling with the B_1 excitation field. This means that visualization of a RC depends on the orientation of the coil surface axis to the B_1 field direction. In theory, when a circularly polarized B_1 field is used and the coil axis is parallel to the x axis in the x–z plane, a small flip angle excitation pulse (i.e., 5°) results in a substantially higher excitation in the fiducial surrounding. However, at an orientation greater than approximately 45° to the x axis in the x–z plane, electromagnetic coupling between the RC and the transmit and receiver coil is substantially decreased. In the current study, we tested a fiducial marker that was comprised of a pair of decoupled RCs. Mutual inductance was minimized by orientating two

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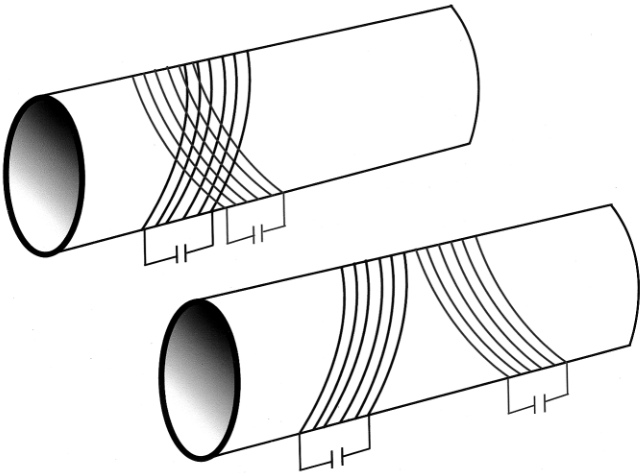

Figure 1. Illustration of fiducial markers. Each marker consists of two separate resonant circuits that are wound on the tip of a catheter at a 45° angle to the catheter axis. The two markers were positioned one atop the other (upper panel) or adjacent to each other (lower panel). In both cases, the coil axes were oriented perpendicular to each other in order to decouple the two resonance circuits.

coils perpendicular to each other. This construction allows for electromagnetic coupling of the RC with the B_1 field at any catheter orientation.

Construction of the Resonant Circuits

The fiducial marker was constructed from a pair of two RCs, each consisting of a micro-multilayer capacitor and a coil constructed from eight windings of 0.12 mm thin insulated copper wire. The coils were each wound diagonally at 45° on the tip of an endovascular catheter (Fig. 1 and 2).

The RCs were individually tuned with a network analyzer in S11 mode to 21.5 MHz in saline solution. After tuning, the two RCs were positioned (1) in series but adjacent to each other or (2) superimposed by mounting the one RC atop the second RC (Fig. 1). In both cases, the coil axes were oriented perpendicular to each other in order to electromagnetically decouple the two RCs. The coils were mounted on 7F and 8F wedge catheters (Arrow, Reading, PA) that increased their outer dimension by approximately 0.5 mm. The length of the coils was approximately 5 mm each. The diameter was approximately 2.8 mm for the inner coil and 3.0 mm for the outer coil.

MR Imaging

Interactive real-time MR imaging was performed with a quadrature transmit/receive coil on a GE 0.5T Signa SP open MRI scanner (GE, Milwaukee, WI). MR imaging was based on a multishot echo planar imaging EPI sequence. The imaging parameters were: TE/TR = 15/40, resolution 2 mm x 4 mm, 7 interleaves, acquisition frame rate = 3.5 frames/second, reconstruction and display rate = 16 frames/second, and slice thickness = 5–30 mm. Flip angle and image plane were interactively controlled during imaging.

In Vitro Experiments

The catheters with integrated RC were brought into a saline bath doped with 2.5 mmol/l Gd-DPTA (T1 = 360 msec, T2 = 280 msec). A total of four catheters were tested. Imaging of the RC was performed at different positions in the x–z plane. The catheters were tested at five different angles (0°, 22.5°, 45°, 77.5°, and 90°) with respect to the x-axis in the x–z plane. The tested catheters were fixed in a custom-made plexiglas phantom that could be turned in predefined angles. At each respective catheter angle, the catheter was rotated in 12 consecutive steps along its long axis. The catheter was rotated by 30° at each step. The ratio of the signal intensity (SI) in the vicinity of the RC over signal intensity of the background was determined at each catheter orientation. Maximal signal intensity was measured within a region of interest of four pixels. Measurements were repeated three times for each catheter. A total of four different catheters were tested. These measurements are a sufficient sampling of all possible orientations due to the symmetry of the circularly polarized B_1 field.

In Vivo Experiment

All procedures were performed in accordance with the National Institute of Health guidelines for care and use of laboratory animals and with the approval of the Committee of Animal Research of our institution. In one swine, weighing 25 kg, the feasibility of MRI-controlled guidance of endovascular catheters with an integrated pair of decoupled RCs was tested. For the procedures, the animal was given a mixture of 0.025 mg/kg i.m. telazol/ketamine/xylozine for induction of anesthesia and 2% isofluorane inhalation for maintenance of general anesthesia. After completion of the study, the animal was euthanized with sodium pentobarbital (200 mg/kg, i.v.).

For the in vivo experiment, the tip of a 7F flow directional catheter (Arrow, Reading, PA) was prepared with a pair of RCs positioned directly adjacent to each other. The catheter was introduced into the vascular system through 8F sheaths placed in the vena jugularis and vena femoralis. The catheter was then guided under interactive real-time MR imaging from the superior and inferior vena cave into the left pulmonary artery.

The SI ratio of the fiducial marker and the vascular blood pool was measured at different catheter orientations. Measurements were performed at the level of the vena cava, right atrium, and main pulmonary artery.

Data Analysis

Paired student's t-test was used to compare the SI ratio measured at each fiducial marker orientation in vitro. Data are expressed as mean ± SD where appropriate.

RESULTS

In Vitro Experiments

The quality factors of the RCs tested were 71 ± 3 when mounted on a 7F catheter (Fig. 2) and 79 ± 4 when mounted on an 8F catheter. Orthogonal orientation of

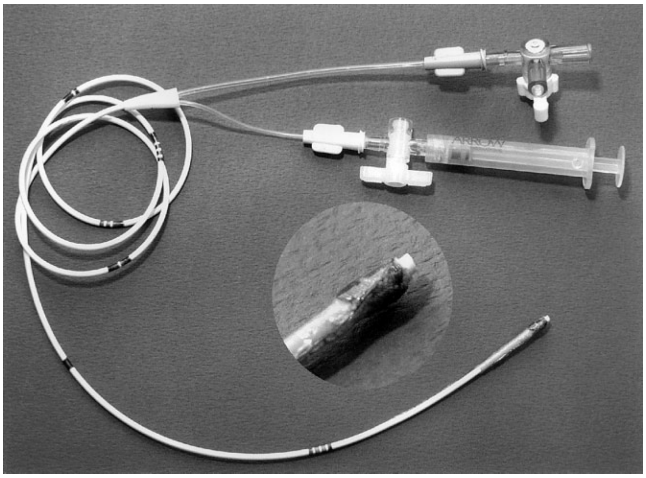

Figure 2. Photography of a pair of resonance circuits mounted on the tip of a 7F catheter.

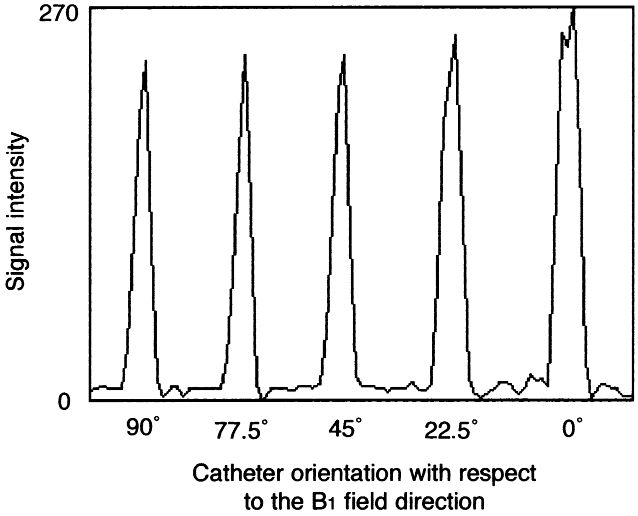

Figure 4. Graph shows representative signal intensity of the tip of a 7F catheter with integrated fiducial marker. Signal intensity was measured on gradient echo images at five different marker orientations with respect to the B_1 field direction. TE/TR = 15/40, resolution 2 mm x 4 mm, slice thickness = 20 mm. Flip angle = 5°.

the coils minimized mutual inductance when the RCs were superimposed or placed adjacent to each other. In this setting the quality factor was slightly decreased to 65 ± 4 and 67 ± 7, respectively.

During MR imaging the fiducial marker was fast and reliably identifiable against the background. A bright signal was depicted at any possible orientation of the fiducial marker with respect to the B_1 field direction. Excellent signal contrast between the fiducial marker and background was found. The SI ratio of the fiducial marker remained nearly constant at any catheter orientation (Figs. 3 and 4). The SI ratio of all measure-

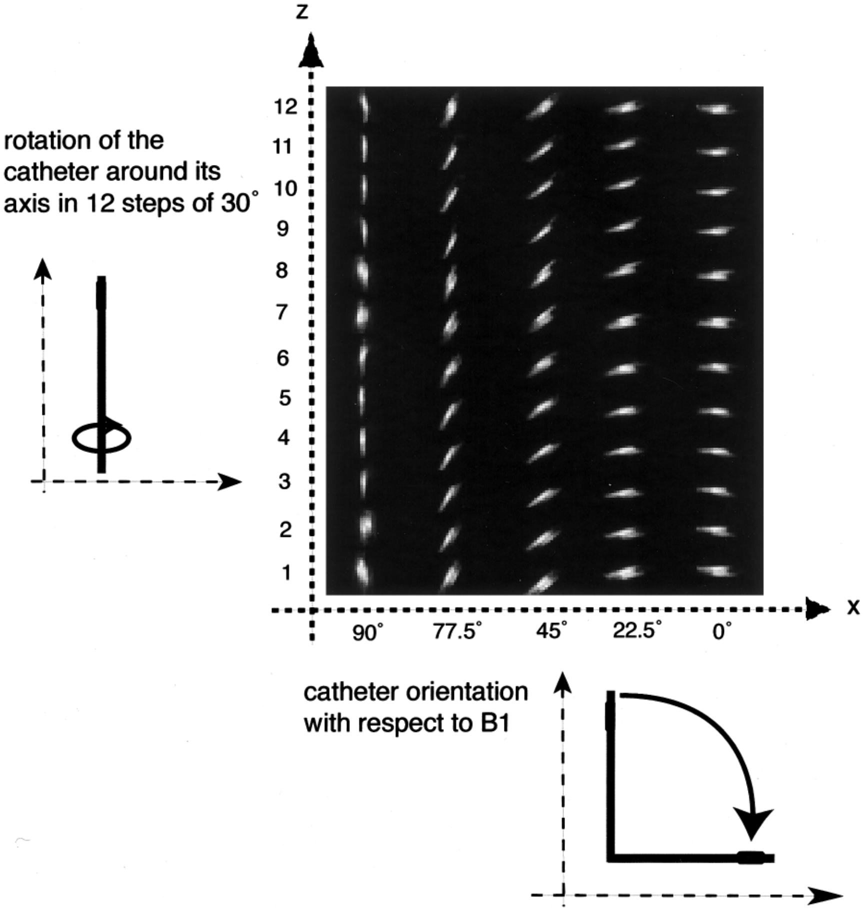

Figure 3. Gradient echo images of the tip of a 7F catheter with integrated fiducial marker. Images are acquired at different orientations of the catheter with respect to the B_1 field direction. At each orientation the catheter was rotated along its axis in 12 steps of 30°. Signal intensity of the marker was similar at any catheter orientation. TE/TR = 15/40, resolution 2 mm x 4 mm, slice thickness = 20 mm. Flip angle = 5°.

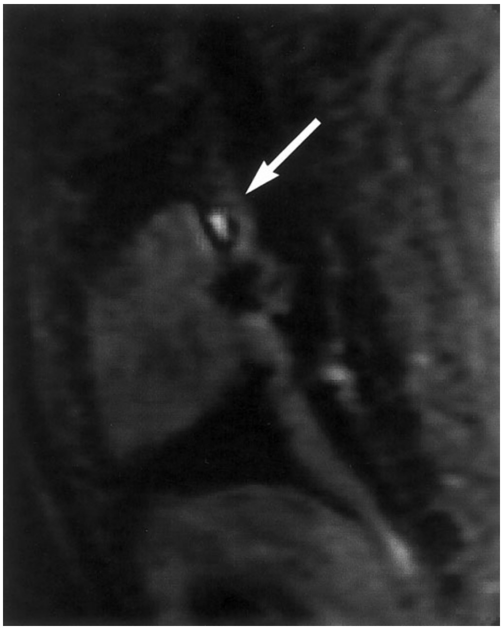

Figure 5. Oblique sagittal MR image of the heart in swine. A 7F catheter with integrated fiducial marker (arrow) is advanced from the superior vena cava into the right atrium. Note the broad susceptibility artifact below the marker due to an air-filled balloon. TE/TR = 15/40, resolution 2 mm x 4 mm, slice thickness = 20 mm. Flip angle = 5°.

ments was 14.3 ± 1.1. SI ratios measured at different catheter orientations were not statistically significant.

In Vivo Experiment

There was excellent signal contrast between the fiducial marker and the vascular blood pool (Fig. 5). SI ratio was 8.3 ± 0.4 when measured at the level of the inferior vena cava, 7.8 ± 0.5 when measured in the right atrium, and 8.6 ± 0.5 when measured in the pulmonary artery.

The good MR signal of the fiducial marker allowed unequivocal MR position monitoring of the catheter tip even when the catheter was guided through the tortuous anatomy of the right cardiac chambers and pulmonary artery. The intense signal of the catheter tip and the ability to modify the catheter signal through interactive flip angle changes allowed rapid and reliable identification of the catheter position. However, continuous monitoring of the catheter was difficult within the right cardiac chambers. This was due to the fact that in the tortuous anatomy of the right heart, the course of the catheter was not kept continuously within one imaging plane.

The signal of the anatomical background was sufficient for gross identification of all major vessels using a low flip angle of approximately 5°. Anatomic details were better visualized when using higher flip angles. However, this had a trade-off in that the signal intensity of the fiducial marker was reduced. Good signal was found using thick slices up to 20 mm. Further increasing the slice thickness had an adverse effect on the signal intensity of the fiducial marker. The option to interactively control flip angles and slice thickness was found helpful in cases where the tip of the catheter moved out of the imaging plane while advancing the catheter in tortuous anatomy. Fast definition of the catheter tip was achieved when using flip angles of 1° to 2° and thick imaging slices of 20 mm. In this setting, identification of the bright signal of the fiducial marker against a nearly black background was easy and unequivocal.

DISCUSSION

Recently, considerable research efforts have been spent on safe localization of interventional devices during MR-guided interventions. Resonance circuits (RC) as fiducial markers of endovascular catheters: 1) are readily identifiable against any background; 2) can be rapidly interrogated with minimal impact on surrounding tissue magnetization; and 3) are bioelectrically safe because they do not have any wire connections. These properties make RC attractive for position monitoring of endovascular catheters and other clinical applications, such as intravascular imaging, i.e., atherosclerotic plaques (10,11). However, the practical application of conventional solenoid-shaped RCs has been limited so far because the degree of coupling of a magnetic flux and, thus, a local flip angle excitation, depends on the orientation of the RC with respect to the transmit coil. In this study, we constructed and tested a pair of two individually tuned and uncoupled RCs as a fiducial marker of endovascular catheters. The major finding of our study was that a pair of uncoupled RCs is suited to overcome the problem of orientation dependency. The MR signal of the fiducial marker was excellent in any imaging plane and orientation with respect to the B_1 field direction. The MR signal of the fiducial marker was easy to depict as a bright spot in the in vitro and in vivo experiments. SI ratios measured at different catheter orientations were not statistically significant. An explanation for this might be that in the setting that either coil couples only partially with the B_1 field, the signal of each RC is adding up to a net signal. At the same time, contribution of noise from the coil that does not couple is little because the volume of the RC coil compared to the receiver coil is small.

The fiducial markers were difficult to manufacture when built on small catheters. In the current study, we tested catheters of 7F whose tip flexibility was affected due to the components of the fiducial markers. A decrease in flexibility was notable when the pair of RCs were superimposed. In the setting of positioning the pair of RCs directly adjacent to each other, flexibility was only slightly decreased. However, this arrangement had the drawback that each individual RC did not produce an intense signal enhancement at any time. Consequently, on the MR images there was no evidence as to which of the respective fiducial markers was coupling the most at any given moment. Though the fiducial markers had a total length of no more than 2.5 mm, this might cause a certain inaccuracy in determining the exact end of the catheter. More work is needed to further miniaturize the fiducial markers and to avoid additional stiffness of the system.

There are notable difficulties in defining the optimal imaging plane for MRI controlled guidance of endovascular catheters through the anatomy of the right atrium, right ventricle, and pulmonary artery. In such tortuous anatomic structures, it is barely possible to keep the catheter tip continuously within one imaging plane. In the current study, the ability to interactively control flip angles, and thus signal contrast between the fiducial marker and its surroundings, was found to be very helpful for fast and reliable definition of the catheter tip. In addition, the use of RCs allowed for applying thick slices of up to 20 mm without notably degrading the signal of the fiducial marker in the in vivo experiment. On the other hand, other passive MRI catheter tracking methods, based on T1 and T2* contrast, suffer partial volume effects when using thick slices and therefore show diminished contrast between the interventional instrument and the anatomic surroundings.

The attractiveness of active MR catheter tracking methods is mainly based on its ability to automatically detect the tip of the catheter. This advantage is opposed by limitations in temporal resolution and bioelectrical safety. RCs might evolve as an alternative to active tracking modalities for automated tip detection of endovascular catheters. Localization of the RC in space can be achieved by point-tracking methods as described in the RC tracking work by Dumoulin et al (8). Alternatively, the RC could be optically detuned (9). In this setup, the MR signal of the RC can be switched on and off and is thus suited for fast and safe projection-based localization. Orientation independence of the RC, as presented in the current study, would be a great advantage in preserving the robustness of such automated catheter-tip tracking techniques.

The major aim of this study was to examine the orientation dependency of the proposed coil configuration. Several aspects related to the practicability of this configuration are not addressed in this study. These limitations include: the use of RCs on small catheter such as 1F; detection of catheter kinking; and the determination of the inplane resolution at different conditions such as orientation, slice thickness, slice orientation, and other variables. These issues need to be examined in future research.

In conclusion, the results of the current study demonstrate that a constant and reliable MR signal can be obtained from a pair of two individually tuned and decoupled resonant circuits in any spatial plane. Such an arrangement of resonance circuits is well suited for passive catheter tracking methods and has the potential to be used for safe projection based catheter-tip tracking methods.

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