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MR Guided Active Catheter Tracking

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INTRODUCTION

In recent years, there has been growing interest in using magnetic resonance imaging (MRI) to provide guidance for catheter-based interventions. Traditionally, most catheter interventions are performed under X-ray fluoroscopy, which allows good visualization of the device but lacks surrounding anatomical information. Most importantly, ionizing radiation involved in X-ray fluoroscopy is harmful for both the patients and the physicians. MRI is a promising alternative to guide intervention as it provides several advantages over other imaging modalities, including excellent soft tissue contrast, the ability to provide functional information, and lack of ionizing radiation. An essential requirement for MR-guided intervention is to track and navigate the interventional devices, such as catheters, needles, and implants, to the target.

For device tracking inside an MR environment, two different approaches are commonly used: passive tracking and active tracking. Of note, there are approaches proposed that do not belong to these two categories and can be classified into a third category of hybrid techniques^{1,2}, which is beyond the scope of this review. MR-guided passive tracking is for visualizing a device within MR images based on the negative or positive contrast generated by intrinsic material characteristics. The contrast can be created and enhanced by incorporating ferromagnetic or paramagnetic materials into the device^{3,4}, or by using contrast agents⁵. Specific imaging sequences have also been proposed to improve the visualization⁶⁻⁹. In contrast, active devices with embedded RF coils, antennas, or other sensors, can generate conspicuous signals for localization. The major advantage of active tracking over passive tracking is that the unambiguous three dimensional (3D) information is generated with high temporal and spatial resolution, which potentially leads to shorter procedure times and improved procedure outcome.

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In this article, state-of-the-art MR-guided active catheter tracking techniques are reviewed, focusing on the principles and implementation in a clinical setting. Safety issues related to active tracking in MR-guided intervention are discussed, and several preclinical and clinical applications are presented.

METHODS OF MR-GUIDED ACTIVE TRACKING

Active MR Tracking with Microcoils

Active MR tracking can be achieved using a MR-tracking pulse sequence with small radiofrequency (RF) receive coils (“microcoils”) that are incorporated into interventional instruments^{10,11} (**Fig. 1**). The sequence begins with a spatially non-selective RF pulse to excite all the spins within a large volume inside the RF transmit coil (e.g. body coil). Then, a magnetic field gradient is applied along one spatial direction making the magnetic field vary monotonically with the position along that direction. Hence, the frequency of the spins at different locations, which is also the frequency of MR signal received, linearly depends on the spins’ location. Different from conventional MR receive coil, microcoil has a limited receive sensitivity profile. In other words, it can only detect MR signals from the spins in the immediate vicinity of the microcoil. As a consequence, the MR signal received by a microcoil is shown as a sharp peak in the frequency spectrum (**Fig. 1C**). The location of the signal peak in the frequency domain indicates the microcoil’s spatial location along the axis of the applied gradient. If this process is performed with the magnetic gradient applied along three orthogonal directions, respectively, the three-dimensional coordinates of the coil can be obtained. By integrating different coils connected to individual receive channels, this approach is capable of tracking multiple coils simultaneously for visualizing the trajectory of a catheter rather than only its tip position.

For robust tracking with microcoils, several strategies can be applied. First, any variation to the static magnetic field (B_0) will distort the linear relationship between the MR tracking signal frequency and the microcoil’s location. This resonance frequency offset may be due to the transmitter and receiver frequency offset, or B_0 inhomogeneities created by the device. In active tracking, the microcoils are usually at or near the interface between the tissue and the device where the magnetic susceptibility difference between the two greatly distorts the local magnetic field. This will lead to either loss of the received tracking signal or imprecise calculation of the device location. Several multiplexing acquisition schemes have been proposed to eliminate the resonance offset errors¹¹. In these schemes, four excitations are usually required with certain modulation of the gradients’ appearance and polarity along x, y, and z axes. Another important strategy is phase field dithering, which is especially useful in low signal-to-noise ratio conditions¹². It employs dephasing gradients in a rotating fashion on the orthogonal plane to the frequency-encoding gradient. This would dramatically improve the tracking quality by reducing the undesirable coupling with the body coils or other conducting devices.

Active MR Tracking with Antennas

To enable the whole-shaft visibility of the catheter, active visualization methods using antennas connected to MR receiver were proposed. Different from passive tracking, the

active visualization (profiling) of the device is based on the conspicuous signal received by tracking antennas on separate channels other than conventional imaging channels. There are mainly two types of antennas: magnetically coupled loop antennas (coils)¹³⁻¹⁵ and electrically coupled loopless (rod) antennas^{16,17}.

A loop antenna is a loop coil wound thin and extended along a certain length of the interventional instrument (e.g., catheters). Due to limited receive sensitivity of the coil, the conventional MR imaging with the loop antenna can outline the instrument. Different coil geometries could be used so long as the coil's sensitivity can be highly localized.

A loopless antenna is essentially a wire that can be easily integrated into more flexible and thinner interventional instruments. Similar to a loop antenna, it also serves as a receive-only antenna that can detect signals from its surroundings, and the resultant MR image delineates the instrument. The difference is that such an antenna has extremely high sensitivity in a cylindrical volume with a significantly greater size than that of the catheter. This hinders sharp delineation of the instrument, while on the other hand it can reveal the anatomic surrounding around the instrument.

Active Tracking with Measurement of Gradients

Another active tracking technique that does not rely on visualization with MR imaging is using the spatially varying gradients of the MR system. Robin Medical, Inc. (Baltimore, MD) developed a miniature tracking sensor that has three orthogonal pick-up coils to measure the induced voltages by the changing magnetic fields (gradients) inside the MR scanner. By comparing the measured signals to the gradient field map of the scanner that is acquired in advance, the current location and orientation of the sensor (6 degrees of freedom) can be immediately determined. Specifically, for catheter-based applications, such sensors were integrated into the tip of MRI-compatible catheters (CathScout, Robin Medical, Baltimore, MD) (**Fig. 2**). Another mechanism for measuring the gradient fields is to employ an optical sensor using the Faraday effect, which can also generate position and orientation information in the MR scanner¹⁸.

VISUALIZATION OF MR-GUIDED ACTIVE TRACKING

Visualization on MR images

In MR-guided active tracking with microcoils, the calculated coil positions is with reference to the same MR scanner coordinate system as MR imaging because the same frequency encoding principle of MR tracking also applies to MR imaging. As a consequence, virtual markers representing microcoil positions from MR tracking can be directly overlaid on the pre-acquired MR images for visualization without time-consuming registration (**Fig. 3A, B**).

In MR-guided active tracking with antennas, the catheter-related signal is intrinsically visualized as part of the MR image. In addition, for better identification, the signals from the active device channels can be depicted in color and displayed with the conventional grayscale images acquired by the body coil (**Fig. 3C, D**). The visualization of the whole device requires the full length of the device contained within the imaging slice. Therefore, a

relatively thick imaging slice is usually prescribed and the slice may need to be manually repositioned when the catheter is moving.

Combining Active Tracking with Real-time Imaging

For the active tracking methods with numeric output of locational information (e.g., tracking with microcoil and tracking with sensors measuring magnetic field), tracking sequence can be interleaved with a fast MR imaging sequence so that the 3D spatial coordinates of the device can be used by a subsequent imaging sequence to automatically shift the imaging plane with movement of the device. This allows 2D images of the surrounding anatomy update in real time at the location of the device.

For active tracking with antennas, the real-time imaging plane needs to be adjusted interactively in real-time to contain the device in the image plane. Sometimes, this may cause delays and inaccuracies, which make this approach less ideal for real-time tracking. One solution to this problem is to perform device-only projection imaging that allows the entire device to be seen even if the portion is outside the conventional imaging slice^{19,20}. A further improvement is an iterative predication correction algorithm that can reconstruct the 3D trajectory of the catheter based on the projection images in a fraction of a second²¹.

Visualization Interface of Active Catheter Tracking

The development of graphical interfaces is one of the key components of applying active catheter tracking into a clinical setting. It should allow clear and real-time visualization of both the catheters and the surrounding anatomic and functional information revealed by imaging with an easy-to-operate interactive user interface.

All the major MR scanner vendors have developed interactive graphical interfaces that support active catheter tracking. Siemens introduced the Interactive Front End (Siemens Corporate Research, Baltimore, MD, USA) that can provide flexible control over the scan plane orientation and imaging parameters²². The signals from the catheter coil channels can be color coded and visualized as part of the real-time MR images. For active catheter tracking with microcoils, graphical representations of catheters are displayed based on the curve fitting of the tracked coil positions and superimposed on the incoming real-time MR images (**Fig. 4**). Similarly, Philips Healthcare developed the iSuite real-time interactive interface that integrated active catheter visualization and real-time imaging options (**Fig. 5**). Besides these vendor-specific applications, in-house solutions for visualization of active catheter tracking were developed under open-source software, for example, VURTIGO²³, which is focusing on electrophysiology applications, and 3D Slicer^{24,25}, a more generic platform for image-guided device tracking.

SAFETY

The primary concern when performing any intervention is ensuring the safety of the patient. All the potential safety problems of MR-guided intervention techniques need to be addressed prior to clinical usage. The most basic requirement is that all of the devices used in the MR environment should be non-magnetic so that their normal functionality would not

be affected inside the magnetic field. However, the focus of this section is on the safety issues associated with active catheter tracking, which is beyond the scope of MR safety.

The major safety risk of active catheter tracking is the possible localized increases in the RF specific absorption rate (SAR) near the catheter. This is, in fact, a general problem for MR-guided intervention involving metallic devices (needles, guidewires, etc.). Although metallic devices have no ferromagnetic components and are safe to use in an MR environment, they are electrically conductive. The RF pulses applied in the MR scanner can induce electric currents in and around these conductors resulting in the so-called RF heating. In particular, when using microcoils or RF antennas for active catheter tracking, long cables need to be incorporated along the full length of the catheter to transport electrical signals from active tracking coils to the MR receiver system. Under certain conditions, these long conductive transmission lines could cause significant heating because of the high electric fields induced by the RF pulses²⁶⁻²⁸.

One approach that can significantly reduce the heating near the tip of the cable/coil combination is to avoid a resonant length of the cable and place coaxial chokes on the cables to disrupt the standing wave pattern on the outer conducting surface of the cable²⁹.

However, the chokes themselves resonate at Larmor frequency so that the local heating generated by the high electric fields are not eliminated, but are confined to the choke region. A different method for modifying the transmission line is to employ miniature transformers to segment the line, which can suppress common mode current associated with RF heating by shifting the lowest common-mode resonance of the device far beyond the Larmor frequency^{30,31}. Another strategy for safe active catheter tracking is to use non-conductive transmission lines such as optical fibers that are inherently RF safe. A miniaturized optical link needs to be integrated into the catheter to convert the electric signal into an optical signal^{32,33}.

APPLICATIONS

Cardiac Electrophysiology

Catheter ablation, a treatment of choice for cardiac arrhythmias, is generally performed under functional guidance using electrophysiologic mapping in conjunction with x-ray fluoroscopy or ultrasound. However, the sub-optimal success rate, the risk of significant complication, and prolonged radiation exposure have motivated MR-guided electrophysiology (EP) to develop toward the goal of improving ablation efficacy and safety. Compared to other imaging modalities, MRI can offer complex 3-D cardiovascular anatomic information with improved soft-tissue resolution, allow visualization of myocardial scar and ablation lesion, permit catheter visualization relative to soft tissue structure, and reduce radiation exposure. MR-guided active catheter tracking techniques along with passive tracking techniques have been developed as important advances towards fully MR guided EP procedures. In the first study to report the feasibility of real-time MRI-guided EP procedures, an active catheter with a loop antenna extending along the entire shaft was successfully positioned at the right ventricular target sites of a canine model³⁴. Later, active tracking using microcoils were demonstrated in swine to navigate catheters to the left atrium and atrioventricular node, followed by electroanatomic mapping and RF ablation^{35,36}. The

tracked catheter and coil locations were superimposed on time-resolved high-resolution MR image roadmaps to provide real-time guidance during in vivo manipulation (**Fig. 6**).

Recently, an MR-guided actively-tracked electroanatomical mapping and ablation system was used in a human for ablation of typical right atrial flutter³⁷. Deflectable MR-EP RF Vision catheters (Imricor, Burnsville, MN) were guided into the coronary sinus and right atrium using active MR tracking alone. The catheters were shown as a virtual catheter icon displayed in real-time in a previously generated 3D model created from MR images. RF ablation of a cavotricuspid isthmus was also performed under active MR-guidance.

Other Intravascular Interventions

In addition to cardiac applications, active catheter tracking techniques have been successfully applied to a number of different MR-guided endovascular interventions. These interventions generally require precise and fast localization of catheters in the complex and moving anatomy in which MR-guided active tracking may offer some benefits. Studies using active MR catheter tracking have been reported for angioplasty³⁸, stenting of aortic aneurysms³⁹, renal arteries^{40,41}, and carotid arteries⁴², renal embolization^{43,44}, and creation of a transcatheter shunt⁴⁵. Due to the lack of clinically approved instruments to date, these are all limited to animal studies.

Cell Therapy Delivery

The hybrid cell therapy delivery procedure combining transvascular and percutaneous approaches could benefit from MR guidance because therapeutics can be precisely targeted to the desired location with MR guidance and the results can be evaluated by MRI. Their feasibility was first demonstrated in swine for targeted left ventricular mural injection under MR guidance⁴⁶. A commercially available guiding catheter (Stiletto, Boston-scientific, Natick, MA) was converted to an active receive coil that was easily localized in the interactive real-time MR images for targeted left ventricular (LV) mural injection. Based on this work, the injection catheter was further modified to incorporate two receive coils to precisely deliver regenerative cellular treatments to the infarcted myocardium⁴⁷. In addition to the active antenna along the guiding catheter allowing for the visualization of the entire shaft, the new design added a microcoil at the tip of the injection needle to enhance the precision of positioning. Modifying commercially available injection catheters, which are usually designed specifically for X-ray fluoroscopy, has limitations in becoming fully optimized for MR-guided procedures. Dedicated devices need to be designed and built for MR-guided procedures. A steerable intramyocardial injection catheter was developed with a deflectable distal section by utilizing the components of the catheter to form a loopless antenna for active tracking. This prototype was used under MR guidance to deliver labeled stem cells to the infarcted myocardium⁴⁸. Another active tracking method using loop antennas was also adapted to steerable catheter therapeutic interventional MRI procedures⁴⁹.

Interstitial Tumor Therapy

Interstitial therapy delivered directly to the tumor can be achieved with radiation, chemicals, or thermal coagulation. MRI has been increasingly used to guide and monitor therapy

deliveries because of its excellent anatomical and functional imaging capabilities. Recently, an active MR-tracking system was developed to facilitate accurate and time-efficient catheter placement in interstitial brachytherapy for radiation delivery to treat gynecological cancer²⁴ (**Fig. 7**). The active catheter tracking was achieved by attaching flexible printed-circuit microcoils to the inner metallic stylet that fits into the catheter. The tracking system, including an active device, an advanced MR tracking sequence, and a visualization interface has been successfully applied in clinical cases.

For thermal therapy, MRI has frequently been used to monitor the therapy progress as multiple MRI techniques are suitable for thermometry. Active MR tracking can be added to guide the therapy delivery catheter and improve the monitoring. The catheter positional information provided by active catheter tracking could be used to prescribe thermometry slice position⁵⁰. For improved MR thermometry, continuous tracking can also provide motion information on the therapy probe to compensate motion⁵¹.

SUMMARY

Within the last two decades, tremendous effort has been made in developing robust active catheter tracking techniques for MR-guided interventions. Active tracking can provide accurate and rapid localization of catheters in an MR environment. It requires less manpower during intervention procedures than image-based passive tracking approaches and may result in more efficient intervention procedures. To date, numerous MR-guided active catheter tracking techniques have been applied in many preclinical applications and they may soon be applicable in clinical routines. To facilitate MRI becoming mainstream for image-guided intervention, further research on active device tracking is needed, together with other MR imaging techniques, to fully exploit the unique strengths of MR and to thoroughly address the practical and safety issues in clinical settings.

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SYNOPSIS

Several advantages of magnetic resonance (MR) imaging over other imaging modalities have provided the rationale for increased attention to MR-guided interventions, including its excellent soft tissue contrast, its capability to show both anatomical and functional information, and no use of ionizing radiation. An important aspect of MR-guided intervention is to provide visualization and navigation of interventional devices (e.g. catheters) relative to the surrounding tissues. The multiple approaches that have been developed to achieve this in an MR environment can generally be categorized into active tracking, passive tracking, and hybrid techniques¹. This article focuses on the methods for MR-guided active tracking in catheter-based interventions. Practical issues about implementation of active catheter tracking in a clinical setting are discussed and several current application examples are highlighted.

KEYPOINTS

- MRI shows great promise as a tool for guiding interventions as it provides three-dimensional imaging capabilities with excellent soft-tissue contrast and functional information without ionizing radiation.
- MR-guided active catheter tracking can provide rapid and robust catheter visualization.
- Combined with MR imaging, it allows simultaneous visualization of the device and the surrounding anatomy.
- Active catheter tracking provides several features that may prove valuable for clinical applications.
- The development of active catheter tracking is an indispensable step towards fully MR-guided clinical interventions.

Fig. 1.

Active MR tracking with microcoils. **(A)** The basic MR tracking sequence. A non-selective RF pulse is applied followed by frequency encoding gradient along one axis during data acquisition. Three-dimensional position of a microcoil can be acquired by playing the tracking sequence three times with the gradients applied along x, y and z axis respectively. **(B)** A catheter equipped with two tracking solenoid microcoils (arrows). **(C)** MR signal received by the microcoil is shown as a sharp peak in the frequency domain. The frequency at which the peak is located is proportional to the microcoil's position along the applied gradient direction.

Fig. 2.

CatheScout developed by Robin Medical, Inc. (Baltimore, MD). **A.** Two CatheScout tracking modules with a transmission wire. Each module includes three orthogonal coils and can generate 6 degree of freedom information. **B.** An x-ray image of an MR-compatible ablation catheter with two CatheScout tracking modules embedded near the tip of the catheter (Courtesy of Erez Nevo, Robin Medical, Inc. Baltimore, MD; Atsushi Yamada, Tohru Tani, Shigehiro Morikawa, and Shigeyuki Naka, Shiga University of Medical Science, Japan.)

Fig. 3.

(A) Two microcoils (arrows) affixed to a guidewire inside a catheter. (B) The microcoils' positions (red square and blue dot corresponding to the two microcoils shown in A) acquired by active tracking are superimposed on a pre-acquired MR image during renal catheterization. (C) Photograph of a 6-French catheter and guidewire with integrated loopless antennas for active tracking. Two individual RF-shielded boxes at the proximal end contain the antenna tuning, matching, and decoupling electronics, and can be connected to separate receive channels of the MR scanner. (D) Tracking of an active catheter shown in (C) inside the aortic arch with a fast real-time imaging sequence (balanced SSFP). A hot-metal color table was used to coat the signal from the tracking antenna's channel for visualization. This allows a simultaneous visualization and tracking of the intravascular catheter and the anatomy despite cardiac and respiratory motion. (A,B Courtesy of E. J. Schmidt, Ph. D., Brigham and Women's Hospital, Boston, MA, and C. L. Dumoulin, Ph.D. Cincinnati Children's Hospital Medical Center, Cincinnati, OH. C,D Adapted from Quick HH, Kuehl H, Kaiser G, et al. Interventional MRA using actively visualized catheters, TrueFISP, and real-time image fusion. *Magnetic resonance in medicine* 2003;49(1):129-137; with permission.)

Fig. 4.

A screen shot of the Siemens Interactive Front End (IFE) interface acquired during a cardiac RF ablation procedure. Two active tracked catheters are displayed as colored geometric models by curve fitting of the detected microcoils' positions, and overlaid on a set of incoming real-time MR images, together with a 3D model built from pre-acquired MRA images. User-placed ablation markers are shown as magenta spheres. (Courtesy of L. Pan, Siemens Healthcare, Baltimore, MD.)

Fig. 5.

A screenshot of the iSuite real-time interactive interface (Philips Healthcare, Best, the Netherlands) acquired during an atrial flutter ablation study. Actively tracked ablation catheter (red cylinder) and reference catheter in coronary sinus (green cylinder) are displayed in real-time in the auto-segmented/auto-registered 3D model of right atrium (blue) and left atrium (orange) (central window) and in MR images (three small windows on the right). The red spheres are the ablation sites. (Courtesy of S. Weiss, Philips GmbH Innovative Technologies, Hamburg, Germany.)

Fig. 6.

Navigation to and within the atrium. **A**, Data Handler 3D surface display, showing MR-tracked EP catheter and torqueable sheath passing through the transseptal hole. **B**, Endoluminal Data Handler display, taken at the time of A, showing the anterior portion of the LA with the EP catheter inside. **C**, Three of the MR-tracking in-room displays used by the clinicians showing (left column) axial (S/I) cine wall motion, (middle column) sagittal (L/R) MRA and (right column) coronal (A/P) MRA, during atrial mapping. The real-time displays can be appreciated from the image in the left column, 2nd row, where the catheter is close to the coronary trifurcation, whose ablation could have serious repercussions. (From Schmidt EJ, Mallozzi RP, Thiagalingam A, et al. Electroanatomic mapping and radiofrequency ablation of porcine left atria and atrioventricular nodes using magnetic resonance catheter tracking. *Circulation. Arrhythmia and electrophysiology*. 2009;2(6): 695-704, with permission.)

Fig. 7.

MR-guided active catheter tracking in a gynecological cancer patient. **(A)** Photograph of an active MR-tracked brachytherapy catheter that consists of a plastic hollow catheter and inner metallic stylet. The dashed window shows an enlarged view of the inner stylet with two printed-circuit tracking coils attached at the distal end. 3D rendering **(B)** and axial, sagittal and coronal views **(C)** of one catheter trajectory (red dot) were reconstructed by actively tracking the stylet's tip position during the stylet withdrawal from the catheter and fitting to a smooth curve.