Intravascular MR imaging and intravascular MR-guided interventions

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Intravascular MR technology, using an intravascularly placed MR receiver probe to acquire high-resolution angiographic MR images (i.e. intravascular MR imaging) and to guide cardiovascular interventional therapies (i.e. intravascular MR-guided interventions), is a new, very attractive development in the field of MR imaging. The new technology offers unique advantages for cardiovascular imaging and interventions, including superior contrast capability and multiplanar imaging capabilities without the use of contrast agents and with no risk of ionizing radiation. The combination of intravascular MR techniques with other advanced MR imaging techniques, such as functional MR imaging, will open new avenues for the future comprehensive management of cardiovascular atherosclerotic disease. Further improvements in intravascular MR fluoroscopy with true real-time display, analogous to X-ray fluoroscopy, will dramatically establish the role of intravascular MR technology in modern medicine.

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Introduction

Conventional X-ray angiography is the primary means for detecting and characterizing atherosclerotic disease. However, conventional angiography displays only the lumen of the vessel without providing direct data about the vascular wall or the atherosclerotic plaque. This disadvantage led to the exploration of alternative imaging modalities such as angioscopy, 1 high-frequency intravascular ultrasound (IVUS), 2 laser spectroscopy, 3 computed tomography (CT), 4 and magnetic resonance (MR) imaging 5 for cardiovascular examinations. Among these techniques, MR imaging has provided superior contrast and resolution of the vessels and the vessel wall. 6 The technical improvements during the last decade have resulted in several advantages for MR imaging compared with conventional X-ray fluoroscopy. Cardiovascular MR imaging, which provides high-resolution angiographic images of vessels (especially superior soft-tissue contrast of the vessel wall and its adjacent area) without the need for contrast agents, functional examination of organs and free selection of multiple images planes with no risk of ionizing radiation, has made several new applications possible in the management of cardiovascular diseases.

In current clinical practice for cardiovascular MR imaging, external body or surface coils are used. Despite considerable efforts, the spatial resolution of MR imaging, which needs to be improved in order to resolve vascular wall structure, is low. 7 This is because the upperbound of the signal-to-noise ratio (SNR), when using external coils, is limited. 8 With external surface coils, it is difficult to increase adequately the data validity to deep-level vessels such as aorta, coronary arteries and renal arteries, which are primary target sites of atherosclerosis. 9 When using external coils for imaging deeply located targets inside the body, the coil must be large enough to obtain sufficient sensitivity to the region-of-interest (ROI). A large external coil will, however, pick up noise from undesired regions of the body and therefore limit the SNR. Thus, to improve SNR and resolution of the images of the vasculature, especially of the deeply located vessels, it appears that the only alternative is to acquire MR images using coils placed inside the vessels, called 'inside-out MR imaging', in which an internally placed 'surface' or 'local coil' is set close to the target tissues of the vessels, such as atherosclerotic plaques. 10-13 This 'inside-out' imaging was initially tested by Kantor and his colleagues, who developed an intravascular MR receiver probe. 14 Several other types of probe were reported by other investigators. Recently, after developmental refinements, intravascular MR imaging (IVMRI) has been recognized not only as a powerful tool for examining the vessel wall, but also as a useful method for guiding cardiovascular interventional therapies under MR fluoroscopy.
Common abbreviations

2D = two-dimensional, 3D = three-dimensional, CT = computed tomography, FOV = field-of-view, IVMRI = intravascular magnetic resonance imaging, IVMRRP = intravascular magnetic resonance receiver probe, IVUS = intravascular ultrasound, MR = magnetic resonance, MRIG = MR-imaging guidewire, RF = radio frequency, ROI = region-of-interest, SNR = signal-to-noise ratio, SPGR = spoiled gradient echo, TE = echo time, TEMRI = transesophageal MR imaging, TELUS = transesophageal ultrasound, TR = repetition time.

Intravascular MR instruments

Currently, different types of intravascular MR instruments are under investigation. Based on their design and function, intravascular MR instruments can be categorized into three major groups: (a) intravascular MR receiver probes, primarily designed for intravascular MR imaging; (b) intravascular MR tracking devices, produced for cardiovascular interventional MR imaging; and (c) intravascular MR-imaging guidewires, developed for both intravascular MR imaging and interventional MR imaging.

Intravascular MR receiver probes (IVMRRPs)

The first IVMRRP was developed to obtain high resolution $^3$P nuclear MR spectra from a canine heart by passing an intravascularly used probe through the external jugular vein or the common carotid artery into the right or left ventricle. This probe consisted of a two-turn elliptical transceiver coil, fashioned from copper magnet wire and insulated with polystyrene. Subsequently, different types of IVMRRPs have been developed with continuous refinement. These IVMRRPs can be classified as catheter coils and built-in catheters.

Catheter coils

Early intravascular MR receiver probes, including single-loop, crossed-loop (birdcage), multipole, center-return and opposed solenoids, were constructed using coaxial cables with their configured radio-frequency (RF) coil tips at different geometries (Figure 1). The single-loop coil is modeled with an oval-shaped tip. The crossed-loop coil consists of a cylindrical array of two loops with current flowing up and down at evenly spaced intervals on the outer surface of the cylinder. The central return design has a geometry similar to that of the crossed-loop designs but with current flowing in one direction along the central axis of the cylinder. The opposed-solenoids design is based on two coaxial solenoids separated by a gap region and with current driven in opposite directions. These probes were covered with shrink tubing or Teflon and connected to tuning and coupling components, which have a general circuit resonance at 64 MHz in a 1.5 Tesla (T) MR imager. The circuit resonance was obtained by adding one or two miniature chip capacitors in parallel with the coils. The tuning and coupling components were then linked to the MR scanner via the coaxial cable.

Early investigations have confirmed a substantial improvement in sensitivity for these intravascular coils relative to externalized coils. These studies also indicated that the solenoid coil holds the most promise, with a cylindrical region of high sensitivity that offers a 10-fold improvement in SNR over that of an external coil and is best suited for cross-sectional imaging of vessels. Since the rapidly changing sensitivity profile of a solenoid coil can lead to significant motion artifacts, some investigators modified the coil by adding a ‘bullet tip’ to its end, which maintains the coil at the center of the vessel and therefore restricts coil motion relative to the vessel wall. An expandable, intravenously placed RF coil was later developed for arterial wall imaging. It is constructed of Cu-Be loops, demonstrating a potential 15- to 20-fold increase in SNR compared with an external coil.

Early catheter coils were too rigid and large to place into small tortuous vessels, such as coronary arteries, because the tuning and coupling components were placed at the neck of the probe (i.e. between the coils and the long coaxial cables), and thus limited the ability to construct the IVMRRP with a thin distal portion. Subsequently, a new flexible, long and narrow catheter coil was developed (Figure 1). This catheter coil has very small tuning and coupling components, which allows the distal portion of the coil to be thin and therefore flexible. This coil, 1.5 mm in diameter, is composed of two parallel conductors with a shortened end, and its decoupling is achieved by using a diode-placed shunt to the coaxial cable at a critical distance from the matching capacitor. It enables high-resolution multi-slice MR imaging and high-resolution one-dimensional chemical shift imaging of small or tortuous vessels in any orientation relative to the main
magnetic field. Using this catheter coil, investigators have characterized atherosclerotic plaque composition and size.18

**Built-in catheters**

A built-in instrument is made by incorporating one or more miniature RF coils or copper wires into the commercially available interventional devices, such as embolization catheters and balloon catheters (Figure 2).13,19,20 The miniature coils are connected, though a bulky insulated coaxial cable embedded in the catheter wall, onto the surface coil reception port for signal reception. The improved SNR characteristics of these miniature coils permit not only visualization of microscopic anatomic details of the vessels but also allow fast high-resolution imaging.13 The development of built-in catheters makes possible the performance of cardiovascular interventions under MR-imaging guidance, since these built-in RF coils can be actively visualized under MR imaging. Built-in catheters, primarily coil-tipped catheters, have been used for intravascular MR-guided interventions (Figure 2).

Coil-tipped catheters are made by winding the miniature coils, which are copper wire spirals, around the tips of interventional devices to identify actively their position.19,22 The miniature coil detects MR signals only from those spins near the coil, so that a single sharp peak is observed in the power spectrum and is indicative of the location of the coil in real space.21 The coil-tipped catheter allows both real-time imaging and active tip localization within a single fluoroscopic mode sequence, and provides adequate temporal resolution.22 The drawbacks with this catheter are (a) reduced maneuverability of the device, (b) the safety risk of RF heating and (c) the fact that only the tip of the device can be seen on the MR imaging.23,24 Meanwhile, visualization of only a single point may not be sufficient for steering devices in complex vascular territory.25

All the IVMRP designs can be operated at either receive-only mode or at transmit/receive mode. In receive-only mode, the probe detects signals arising from the surrounding tissue of interest, while the tissue signals are excited from an external radiofrequency (RF) source, such as a body coil.13 The principle of receive-only mode is primarily applied for the purpose of intravascular MR imaging. In this mode, since the RF pulse is transmitted by an external coil, the uniformity of the flip angle can be obtained within the ROI and desired image contrast can be obtained using standard MR-imaging techniques. At transmit/receive mode, the probe receives the surrounding tissue signals that are excited by the same probe. This principle is used primarily to localize the MR signal in interventional MR imaging such as intravascular MR fluoroscopy for tracking interventional devices.26

**Intravascular MR tracking device**

MR tracking, the accurate visualization of the delivery process of interventional devices into targets under MR fluoroscopy, is one of the basic techniques for cardiovascular interventional MR imaging. Intravascular MR tracking devices are designed for either passive MR tracking or active MR tracking. The passive-tracking technique is based on visualization of the signal void and susceptibility artifacts caused by the interventional instruments themselves under MR imaging. The active-tracking technique is achieved by visualizing a signal from a miniature RF coil that is part of the interventional instrument.

**Passive tracking devices**

Currently, several different passive-tracking devices are available, including the field inhomogeneity catheter and the susceptibility-based catheter (Figure 2).

The field inhomogeneity catheter is produced by mounting a copper wire onto the entire length of the device to electrically induce local-field image artifacts for directly visualizing the device.27,28 The thin copper wire (50–80 μm in diameter) is attached to the catheter and is connected to a battery. When direct current is passed into the wire, local field inhomogeneity is induced, leading to intravoxel spin dephasing and therefore to a signal loss around the catheter. Through this, the entire catheter can be visualized. Increasing the current increases the effect, making the catheter blacker and larger.27 The strength of the current varies between 50 and 150 mA.28 The movement of the catheter in the main magnetic field due to the forces on the wires is a drawback, which can be minimized by an antiparallel configuration of the wires.27 When using this adjustable, locally induced field-inhomogeneity catheter, the visualization of the catheter in small and tortuous vessels remains a major problem, and the electrical safety of this type of catheter has not been determined.28

The susceptibility-based catheter is designed by constructing paramagnetic materials, such as dysprosium oxide or Gd14 ions, into the wall or onto the surface of conventional interventional devices, which then can be passively tracked under MR imaging.23,29 The dysprosium
oxide rings are locally impregnated into a conventional nonbraided polyethylene catheter, which causes local signal losses with increased susceptibility, and therefore the impregnated part of the catheter can be depicted without steering problems. The major weakness of this catheter is its poor contrast. Coating the surface of interventional devices with Gd ions has recently been reported; this can produce signal enhancement for passive MR tracking.

Some investigators have also demonstrated a passive-tracking guidewire, called a fiberglass-based guidewire (Figure 3). A conventional guidewire was impregnated with five dysprosium oxide rings near the tip for passive MR tracking.

Active-tracking devices

Built-in guidewires are currently the representative devices for active MR tracking. In conventional cardiovascular interventional procedures, a guidewire is usually placed first either to guide interventional devices or to recanalize directly severely stenotic or occluded vessels. There have been attempts to make the guidewire visible under MR fluoroscopy. Investigators initially tested electrically coupled antennas with either loop or stub shapes, which offered the potential to incorporate these antennas into conventional sterile guidewires. Efforts also have been made to build miniature coils with different geometries onto the tips of commercially available guidewires (Figure 3). The miniature coils are attached to a coaxial cable running through the center of the guidewire, and the entire assembly is enclosed in a sheath of fluorooctylpolypropylene (FEP) to protect the coil and make the guidewire smooth. The built-in RF coil delivers a high-contrast signal over its full length, enabling visualization of the position and curvature of the tip of the guidewire.

Since a guidewire has limited space to place a tuning and coupling component at the distal (neck) portion (between the coil and the long coaxial cable), the built-in guidewire is tuned and matched at its proximal end (at the interface between the coaxial cable and the surface coil input of the scanner). MR tracking of a guidewire is a challenge because the SNR decreases as the size of the RF coil is decreased. The problems with the built-in guidewire are that the signal is limited to the coil at the guidewire tip, and that there is a possible local heating risk from the coils attached to the tip.

**Loopless antenna (MR-imaging guidewire)**

Recently, a loopless antenna has been developed (Figure 4). Unlike the built-in guidewire, in which only the signal from the miniature RF coil can be visualized, the entire body of the loopless antenna can be observed under MR imaging. The loopless antenna is made from coaxial cable, consisting of a conducting wire that is an extended inner conductor from the coaxial cable. The tip of the loopless antenna is essentially a dipole and loopless, which makes possible a very thin diameter antenna. The characteristics of the loopless antenna include: (a) high sensitivity to the MR signal along the entire length of the catheter; (b) sensitivity inversely proportional to the distance from the antenna; (c) production of very high signal around the antenna when it is used as a transmitter/receiver probe; and (d) creation of a projection image because the antenna localizes the MR signal around itself does not require slice selection.

In addition, since the electronic circuits are placed at the proximal end of the coaxial cable (and therefore outside the vessels), the physical dimensions of the loopless antenna can be constructed without limitations. Currently, the thinnest loopless antenna that can be manufactured
easily is 0.6 mm in diameter (Figure 5). Analogous to a conventional guidewire, the thin antenna can either be directly inserted into small or tortuous vessels, or be placed into the central channel of interventional devices. Since the loopless antenna is expected to function not only as an intravascular MR receiver probe for intravascular MR imaging and for creation of intravascular MR fluoroscopy, but also as a conventional guidewire for interventional MR imaging, it is called an MR-imaging guidewire (MRIG). Indeed, for reasons of safety and for technical purposes, such as torque control and subselective placement as well as negotiation of hard atherosclerotic lesions, this guidewire must also function as an imaging receiver probe when performing intravascular MR-guided interventional procedures. The MRIG has been tested in vivo, and found to be useful for both intravascular MR imaging and cardiovascular interventional MR imaging. A recent study also demonstrated the possibility of three-dimensional (3D) visualization of the MRIG by depth reconstruction from projection MR images.

**Intravascular MR imaging**

Atherosclerotic cardiovascular disease is the leading cause of mortality in economically developed countries. Its evolution, risk manifestations and inconsistent response to therapy remain poorly understood. Using conventional X-ray angiography, one can image only the lumen of the vessel of interest without direct observation of the vessel wall and the atherosclerotic plaque.

Attempts have been made to apply MR imaging to overcome this limitation. Although early studies indicated the usefulness of MR imaging for characterization of plaque structure, the low SNR associated with external surface coils in these studies could not provide the spatial resolution necessary to resolve vascular wall structure. This subsequently led to the innovative development of intravascular MR imaging. Intravascular MR imaging can be used for: (a) delineating vascular layers and characterizing plaque structure; (b) monitoring the behavior of the atherosclerotic plaque, such as its progress and/or regression; and (c) pre-operatively selecting cardiovascular interventional procedures based on plaque analysis.

**IVMRI of the arterial wall and atherosclerotic plaque**

The intravascular MR technique was preliminarily developed for vessel wall imaging, i.e. delineating vascular layers and characterizing plaque structure. Significant efforts to evaluate intraarterial MR imaging of vessel walls and atherosclerotic plaques have been made using different types of IVMRPUs, such as catheter coils, a built-in catheter or a loopless antenna. These studies demonstrate excellent correlation between MR imaging and histopathology for measuring the thickness and size of the vessels and plaques, as well as for differentiating the vessel wall layers and plaque components. Some studies demonstrate that on T2-weighted images, vessel wall layers can be discriminated, with the adventitia seen as an outer ring of reduced signal intensity and the media as a ring of brighter signal intensity. Plaque characterization is also possible on T2-weighted images, with calcified plaque readily identified as an area of low signal intensity.
and fibrous tissue showing a higher signal intensity due to fibrous structures containing collagen. Fat components had a mean signal intensity on T2-weighted images.18,19

**IVMRI for monitoring atherosclerotic behavior**

Intraarterial MR imaging may not be a good choice for serial studies in which the progress and/or regression of an atherosclerotic plaque are being monitored, since insertion of an intraarterial MR probe may induce endothelial damage in the artery wall and thereby affect the evaluation of atherosclerotic lesions. In order to resolve this problem, alternative methods have been attempted. One study demonstrated MR imaging of the arterial wall by placing a catheter coil into the venous system, thereby depicting the artery parallel to the vein.17 Recent studies also describe transesophageal MR imaging (TEMRI) of the aortic wall by placing the loopless antenna into the esophagus.40 In this technique, the antenna, which is placed within a standard nasogastric tube, is inserted into the esophagus rather than the vasculature. The image SNR and resolution associated with this technique are higher than those associated with the surface coil technique, but lower than those associated with the intravascular MR technique. TEMRI has been used successfully in humans, demonstrating contrast resolution images of the aortic wall that are superior to those obtained with transesophageal ultrasound (TEUS)11 (Figure 6).

**IVMRI for selecting interventional procedures**

Currently, various cardiovascular interventional techniques, e.g. balloon angioplasty and endovascular stenting, are widely used in clinical practice. The classification of atherosclerotic plaques using IVMRI (called analytic IVMRI) before an interventional procedure may provide predictive indicators for the most appropriate clinical methodology.15,19,38 For example, balloon angioplasty is most often indicated in cases where the plaque is 'soft' (as in fibromuscular dysplasia and in fatty atheromas), and endovascular stenting is most often indicated in cases where the plaque is 'hard' (as in calcified atheromas).42

**IVMRI technology**

Many ex vivo and in vivo studies have demonstrated the use of catheter coils to image vessels, confirming that IVMRI in-plane resolution was better with a 1.5 T imager than a 0.5 T imager. In addition, T2-weighted images provide the best discrimination of the vessel wall and characterization of plaques.10,12,13,15,38 Different pulse sequences, such as two-dimensional (2D) or 3D standard or fast spin-echo pulse sequences, and gradient-echo pulse sequences, have been used in IVMRI.17,38 One study also describes the use of the loopless antenna for in vivo observation of the aortic wall, with a fast spoiled gradient echo (SPGR) pulse sequence with short repetition-time (TR) and echo-time (TE) parameters (Figure 7).18 For the purpose of IVMRI, the IVMRRPs are usually operated at the receive-only mode.10,13,16,38

One of the important requirements in IVMRI is to obtain high-resolution images without degradation from motion artifacts. Ghosting artifacts in IVMRI probably arise from small motions of the IVMRRP within the artery due to hemodynamics.12,17 Artifacts can be minimized either by saturating the blood signal and restricting the probes to the center of the artery by constructing them with a 'bullet' tip,10 a balloon tip47 or an expandable coil,17 or by ECG-gated and breath-hold MR imaging techniques.10

**Intravascular MR-guided interventions**

Early studies have proved the valuable role of IVMRI in the diagnosis of cardiovascular atherosclerotic diseases. The next question is how to deliver percutaneously the intravascular MR instruments into the target vessel. This

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**Figure 6**

(A) Transesophageal MR image of human aorta compared with (B) a transesophageal ultrasound image of the aorta in the same patient. The arrow indicates an intrasosophageally placed loopless antenna with a high signal surrounding it. (Images courtesy of Dr Kendrick A Shunk.)

**Figure 7**

Intravascular cross-sectional MR image of normal rabbit aorta. Ao = aorta, IVC = inferior vena cava. The aortic wall appears as a non-signal ring surrounding the aorta lumen that presents as a high signal circle. In the aortic lumen, there is a round non-signal area (arrow), which represents the position of the loopless antenna. (Image courtesy of Mr Bradley D Bolster, Jr.)
question has motivated investigators to explore techniques for cardiovascular interventions performed under MR imaging guidance. These techniques include visualization of vascular interventional devices using an MR tracking technique and monitoring an entire interventional process under MR fluoroscopy, similar to X-ray fluoroscopy.

MR tracking

Accurate visualization of the interventional devices relative to the surrounding anatomy is crucial to a successful and safe image-guided interventional procedure. Also important is the ability to identify easily interventional devices, obtain a high positional accuracy with the imaging system and achieve real-time imaging for good maneuverability. Two fundamental approaches for real-time MR imaging, passive tracking and active tracking, have been advocated, as well as an alternative approach, loopless antenna tracking, which have been developed recently.

Passive MR tracking

As mentioned earlier, the passive-tracking technique is based on visualization of the signal void and susceptibility artifacts caused by the interventional instruments themselves. The susceptibility artifact must be small enough not to obscure the surrounding anatomy, and therefore not to compromise the ability to perform the intervention. Passive tracking offers some advantages, such as allowing visualization of the entire device as well as safety and maneuverability problems with the catheters. Some authors tested different commercially available interventional devices, such as guidewires, catheters, balloon catheters and stents, using passive MR tracking with four different pulse sequences. They found that cobalt/nickel/steel alloy wires present the best and most consistent results. However, owing to the dependence of the passive-tracking technique on field strength, device orientation and particular pulse sequence parameters, the passively visualized susceptibility artifacts are often inconsistent and the temporal resolution is usually inadequate. These problems can be overcome by modifying the magnetic properties of the catheters and by designing susceptibility-based tracking techniques.

MR tracking of field inhomogeneity catheters and susceptibility-based catheters represents two alternative techniques to passive tracking. As mentioned earlier, these techniques suffer from limited use in small or tortuous vessels and poor contrast during MR tracking.

Active MR tracking

In the active-tracking technique, the position of the device is derived from the signal received by a miniature RF coil that is attached to the instrument itself (e.g. built-in catheters and built-in guidewires). The position of the coil is used to control the motion of a cursor over a scout (roadmap) image. Active MR tracking provides a high-contrast signal and robust determination of device position and higher tracking speeds, but is much more technical and seems to be limited to roadmap techniques. Built-in coils and electric wires present a safety risk and may reduce the maneuverability of an interventional device, which makes the active approach less suitable for MR tracking of microcatheters and guidewires. In addition, active tracking of built-in guidewires and microcatheters remains challenging because the SNR decreases as the size of the miniature RF coil is decreased.

Loopless antenna MR tracking

Recently, a new MR tracking technique, loopless-antenna-tracking FOV MR fluoroscopy, has been presented. In this study, by using a very narrow rectangular field of view (FOV) combined with roadmap 3D image data, the authors acquired a movie of the percutaneous placement procedure of the loopless antenna at a rate of 7.3 frames/s. The advantage of this tracking technique is that not only the antenna but also the surrounding tissue is visible during the tracking procedure, and therefore a stenotic vessel can be located under MR fluoroscopy. Also, the same tracking result can be achieved with a flexible, long and narrow catheter coil. Using this tracking technique, investigators have successfully performed the entire procedure of MR-guided balloon angioplasty in an animal model (figures 8 and 9).

Monitoring of an interventional procedure

One study demonstrates the feasibility of performing intravascular MR-guided balloon angioplasty in vivo, providing adequate monitoring of the entire process of balloon dilation of the stenotic vessels when inflating the balloon with an MR contrast agent. Another study also

Figure 8
Illustration of in vivo experimental design for intravascular MR-guided balloon angioplasty in the rabbit aorta. (A) An artificial aortic stenosis is created by binding a plastic cable tie at the upper abdominal aorta, while a 7-Fr introducer is inserted into the lower abdominal aorta. (B) The stenosis is located by tracking an MRG under intravascular MR fluoroscopy. (C) Along with the MRG, a balloon catheter is tracked into the stenosis. (D) The stenosis is dilated by inflating the balloon with an MR contrast agent. (E) The stenosis is completely opened.
workstations connected via high-speed data link to MR scanners. The MR images can be reconstructed on-the-fly at a rate of 10 frames/s and displayed on a monitor in the scan room within 0.5 s for acquisition. Using a 2D gradient echo-pulse sequence, a frame rate of 2 images/s can be achieved by limiting the acquisition to a rectangular portion of the FOV. The choice of pulse sequences and imaging parameters has a strong influence on the visibility of the individual devices. Different pulse sequences, such as 2D Fourier-transformed SPGR pulse sequences, fast spin-echo pulse sequences, and 2D phase-contrast sequences, have been used for creation of MR fluoroscopy. The keyhole technique has been shown to be effective in monitoring the insertion of the device, and for tracking device-induced signal intensity changes, which permits a reduction in imaging time by a factor of about 4.

During intravascular MR-guided intervention with an IVMRPP, a nonselective RF pulse is applied with the external body coil (at the receive-only mode) or the internal RF coil (at the transmit/receive mode) to excite all spins within the field of view. A pulse sequence, such as a gradient-recalled echo sequence, is then generated with read-out gradient pulses along an axis. The location of the IVMRPP on that axis is obtained by Fourier transforming the acquired data and finding the peak signal corresponding to the location of the IVMRPP. During MR tracking, ghost artifacts may be suppressed effectively using flow compensation and small flip-angle excitation. For the purpose of interventional MR imaging, the IVMRPPs are usually operated at a transmit/receive mode.

Safety

An important concern for performing IVMRI or IVMR-guided interventions is the thermal effects that might result from either the RF-conductive parts of the devices, such as miniature coils and copper wires attached to the catheters or guidewires, or the entice coaxial cable of the loopless antenna. The thermal effect is produced by the electric field of the RF excitation of the body coil. If the transmit coil couples with the receiver probe or with the cables of the probe, the electric field around the probe increases and may cause excessive heating. The temperature rises due to currents flowing in the coil and could lead to patient burns, especially when using RF-intense imaging sequences, such as fast spin-echo. Even when a conventionally used Terumo guidewire (with a titanium core) is inappropriately placed into the vessel during MR scanning, heating may occur, with evidence of increased signal around the titanium core (Figure 10).

In order to avoid the RF heating problem, a decoupling circuitry is frequently used. With appropriate imaging sequence restrictions (for instance, no fast spin-echo, limited flip-angle and longer TRs), the temperature can be limited and therefore the tissue damage could be avoided. Some investigators find that when operating the built-in guidewires at a transmit/receive mode, no temperature rise can be detected.

described the in vivo placement of a temporary vena cava filter using a passive-tracking technique, which is preferred in pregnant patients with deep vein thrombosis before Cesarean section. The alloy (e.g. tantalum) rings on the surface of balloon catheters, dilators and Wallstents produce significant image artifacts, which function as excellent markers for monitoring the delivery of these devices. Some investigators have demonstrated the feasibility of monitoring different intravascular interventions, including embolization, balloon occlusion and transjugular intrahepatic puncture of the portal system, under MR fluoroscopy. Others have reported the feasibility of nitinol stent insertion into a vessel under MR guidance.

MR fluoroscopy

Currently, commercial MR Scanners are not equipped with tracking software. Some experimental programs run on
imaging of the cardiovascular system has some prominent advantages, cardiovascular interventional MR imaging is still in its developmental phase. During the last decade, most of the investigations on IVMRI and IVMR-guided interventions have been carried out either in vitro using phantoms or in vivo using animals, primarily rabbits, dogs and pigs. Recently, however, the application of intravascular MR technology in humans has been initiated.23,53

One study demonstrated the safe intravascular MR tracking of a susceptibility-based catheter within the basilic vein in a 47-year-old healthy male volunteer with no complications.23 A recent report demonstrated the successful monitoring of balloon dilation of an iliac and femoral artery stenosis in six patients, using built-in catheters under MR guidance.51 In addition, an alternative method for imaging the aortic wall using an intrasophageal placed loopless antenna has been also performed in ten human cases, without abnormal manifestations to date.41

IVMRI use in conjunction with other MR techniques

MR imaging is capable of providing useful functional information, such as quantification of flow data and capillary perfusion, pressure-gradient calculations using appropriate phase-contrast pulse sequences, and tissue metabolism. Functional MR imaging, pre- and post-therapeutic interventions, is a current reality. The online monitoring of the effectiveness of such interventions as a guide to the next therapeutic step promises more effective patient care. Advanced MR techniques, such as MR perfusion imaging and MR angiography as well as interventional MR imaging, may become essential imaging modalities for the online management (the early diagnosis followed by the prompt treatment and immediate post-operative evaluation at the same facility) of vascular ischemic diseases. For example, one may use the MR perfusion technique to evaluate functionally early vascular insufficiency of organs, and MR angiography to locate the diseased arteries. Then, the MR-guided interventional therapy could be carried out in the same MR facility without moving the patient. After treatment, post-operative MR perfusion imaging and MR angiography could be performed to confirm immediately the reperfusion status of the organs, to assess the effectiveness of the interventions and to determine the next steps necessary for further treatment.

It is time to apply fully these advantages of MR technology in patient care. Investigators are exploring a new methodology for the on-line management of ischemia in a single MR scanning session. The development of an intravascular MR-guided interventional technique is an important step toward to the success of this exploration. Using an animal model with aortic stenosis, some authors have successfully tested the idea of using only MR techniques to manage renovascular insufficiency on-line.15

Clinical applications

To date, MR-guided therapies have been clinically limited to non-vascular interventions, such as disectomy, laser ablation of breast cancer, laser or radio-frequency ablation of head and neck tumors, monitoring of prostate cancer therapy, interstitial cryotherapy, interstitial focused ultrasound surgery and needle biopsies.49-52 Although MR
Comparison with other imaging modalities

X-ray angiography has been considered the standard imaging technique for the diagnosis and interventional treatment of cardiovascular diseases. However, there are several concerns about X-ray fluoroscopy, including limited tissue characterization, adverse reaction to contrast agents, no multiplane images and patients’ exposure to ionizing radiation. For the purpose of visualization of atherosclerotic plaques, conventional X-ray angiography does not provide direct image data about the vessel wall and the plaques. In addition, X-ray angiography is unable to assess accurately the predisposition of a given plaque to rupture, owing to the limited capability to determine plaque composition using this method. Although modern X-ray fluoroscopy delivers relatively low X-ray doses, some procedures, such as interventional therapies, can be very long, and the accumulated X-ray dose to the patient can become significant. The long-term exposure of the medical staff is also a concern because they participate in these procedures as often as several times a day.

Several catheter-based modalities have been developed in an attempt to provide the clinician with a better understanding of atherosclerosis. Angiography and laser spectroscopy permit viewing of only the superficial vascular features rather than the layers and atheromas inside the arterial wall. IVUS is useful for determining luminal dimensions and percentage stenosis. IVUS has real-time imaging capability and is considered well-suited for routine use in clinical applications that require catheterization. Visualization of atherosclerosis is significantly improved by using a high-frequency (42 MHz) focused transducer. However, IVUS suffers from several drawbacks: limitation in the evaluation of plaque composition owing to poor contrast resolution between different intraplaque components; inability to reliably detect thrombus (new or organized) superimposed on soft, lipid-laden plaques; artifacts related to transducer angle relative to the wall; an imaging plane limited to the aperture of the transducer; and variable resolution at different depths of view.

Compared with other imaging modalities, MR imaging, including IVMR, offers unique advantages, such as multiplanar imaging capabilities, 3D reformating, more versatile contrast capability and the absence of ionizing radiation and risk of allergy to contrast agents. However, MR imaging in clinical applications requires enhanced gradient capabilities and specialized radio-frequency coils with high sensitivity to arterial tissue. For IVMR techniques, the biologic and operative safety requires further investigation.

Conclusions

Intravascular MR technology, including intravascular MR imaging and intravascular MR-guided interventions, represents a new, very attractive imaging modality, with unique properties for characterizing atherosclerotic plaque structures and thus for guiding cardiovascular interventional therapies. As a new technical development, intravascular MR technology still requires further refinement and testing before it can be used in humans. Undoubtedly, the use of intravascular MR techniques combined with other advanced MR imaging techniques, such as MR angiography and functional MR imaging, will open up new avenues for the future comprehensive management of cardiovascular atherosclerotic disease. The further improvement of MR fluoroscopy with true real-time display, analogous to X-ray fluoroscopy, will dramatically establish the role of intravascular MR technology in modern medicine.

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