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Development of a 0.014-in., anti-solenoid loop MR imaging guidewire for intravascular 3.0-T MR imaging☆

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Abstract

Purpose: This study aimed to develop a 0.014-in., anti-solenoid loop (ASL) magnetic resonance imaging guidewire (MRIG) for intravascular 3.0-T MR imaging.

Materials and Methods: We first designed the ASL MRIG, which was made of a coaxial cable with its extended inner conductor and outer conductor connected to two micro-anti-solenoids. We then evaluated in vitro the functionality of the ASL MRIG by imaging a "vessel" in a phantom and achieving signal-to-noise ratio (SNR) and SNR contour map of the new 0.014-in. ASL MRIG. Subsequently, we validated in vivo the feasibility of using the ASL MRIG to generate intravenous 3.0-T MR images of parallel iliofemoral arteries of near-human-sized living pigs.

Results: In vitro evaluation showed that the 0.014-in. ASL MRIG functioned well as a receiver coil with the 3.0-T MR scanner, clearly displaying the vessel wall with even distribution of MR signals and SNR contours from the ASL MRIG. Of the in vivo studies, the new ASL MRIG enabled us to successfully generate intravenous 3.0-T MR imaging of the iliofemoral arteries.

Conclusion: This study confirms that it is possible to build such small-looped MRIG at 0.014 in. for intravascular 3.0-T MR imaging.

Keywords: Arteries; Intravascular MR imaging; MRIG

1. Introduction

Atherosclerotic cardiovascular disease remains the leading cause of death in developed countries. To date, X-ray technology has been used as a primary imaging modality for diagnosis and treatment of atherosclerotic cardiovascular disease. This imaging technique can only outline the stenotic vessel lumen, with minimal capability of visualizing the atherosclerotic plaques of the vessel walls. Magnetic resonance (MR) imaging has become a promising tool for characterizing atherosclerotic plaques of vessel walls, achieving optimal visualization in multiple planes without the risk of radiation exposure [1–3]. However, with surface coil-mediated MR imaging, the signal-to-noise ratio (SNR) dramatically decreases as the distance between a target and the surface coil increases. Thus, the advantage of vessel wall MR imaging is limited to more superficial arteries, such as carotid arteries, when using surface MR coils. For those deep-seated arteries, such as the abdominal aorta, as well as iliac and renal arteries, surface coil-mediated MR imaging is usually not optimal [4].

To solve this problem, different intravascular MR receiver coils have been developed [5–7]. One of the intravascular MR coils is a dipolar loopless antenna, which could be manufactured as thin as 0.014 in. in diameter [6]. Such thin intravascular MR antenna, also called an MR imaging guidewire (MRIG), provides two primary functions as (a) an intravascular MR receiver probe to generate high-resolution MR images of vessel walls and plaques of deep-seated arteries and (b) a conventional guidewire to guide endovascular interventions, such as balloon angioplasty and endovascular gene delivery [8–10].

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It is difficult to build a 0.014-in. loopless antenna with its tip mechanically strong enough to withstand the forces of endovascular interventional manipulation. A loop design of intravascular MRIG may overcome this problem. An MRIG with a looped tip can create additional mechanical strength and thereby reinforce its practical use for endovascular interventions. In addition, some studies have demonstrated additional advantages of looped MR coils, including their low imaging distortion and high signal intensity generated at the targets [11–13].

To date, all of the reported looped MR receiver coils are built larger than 0.032 in. in diameter, which is not preferred for intravascular MR imaging of small-sized arteries, such as coronary arteries [14,15]. In this study, we attempted to fill this gap by developing a 0.014-in. loop-designed MRIG.

2. Materials and methods

2.1. Study design

This study was divided into three components, including (i) designing and manufacturing a 0.014-in., anti-solenoid loop (ASL) MRIG; (ii) evaluating its functionality via serial in vitro experiments with comparison of MR signal distributions or SNR contour maps between the 0.014-in. ASL MRIG and a 0.014-in. loopless MRIG; and (iii) validating the feasibility of using the new ASL MRIG to generate intravascular 3.0-T MR images in near-human-sized living pigs.

2.2. Configuration and production of the ASL MRIG

The ASL MRIG was made of a 0.014-in. coaxial cable (Microstock, West Point, PA, USA), with extension of its inner conductor up to 4.0 cm. The tip of the coaxial cable was equipped with two microsolenoid inductors. Each of the solenoid inductors was 1.2 cm long and made with 20 turns of a 50-AWG enameled copper wire and wound at opposite directions with approximately 0.5-mm interturn spacing. The two microsolenoid springs were linked at 1-cm interval, with one solenoid connected to the outer conductor and the other one connected to the inner conductor (Fig. 1A). The total length of the ASL MRIG from the tip to the MMCX connector was 40.0 cm.

For the comparison, we also manufactured a 0.014-in. loopless MRIG. The loopless MRIG had the same characteristics as the ASL MRIG: made of the same 0.014-in. coaxial cable (Microstock), with its entire length at 40 cm, and a 4-cm extension of the inner conductor with 100 Q-factor that was tuned using a network analyzer (Agilent Technologies, Santa Clara, CA, USA). In addition, the tuning/matching boxes of the 0.014-in. ASL MRIG and the 0.014-in. loopless MRIG were made using the same circuit structure, including a balun and a coaxial cable trap for reducing interference between the MRIG and MR imaging (Fig. 1B). The boxes were then connected through a custom-designed preamp to a clinical 3-T MR imaging scanner (Achieva, Philips Healthcare, Best, Netherlands). For MR imaging, both the ASL and loopless MRIGs were operated in a receiving mode only, to collect the proton decay signals excited by the MR body coil.

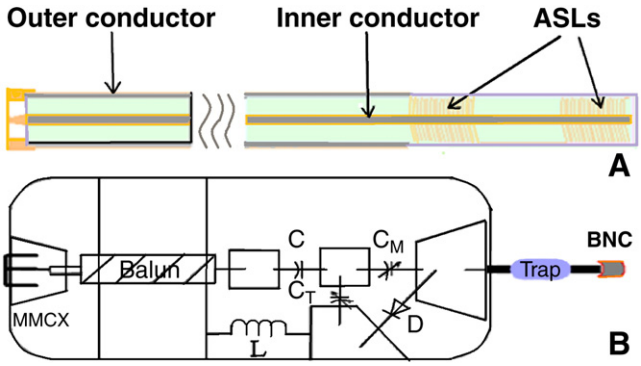

Fig. 1. (A) Design of the 0.014-in. ASL MRIG. The extended inner conductor and the outer connector are connected to each of two ASLs that are circulated at opposite directions. (B) Diagram of the balun/tuning/matching box. MMCX is used to connect the ASL coil to the tuning box, then to a MR imaging preamp through a BNC connector. C_T is a variable capacitor for tuning the S11 factor of MRIG to −30 dB at 127.72 MHz and C_M is a capacitor for matching the resistance to 50 Ω. D is a pin diode for active protection. C is a capacitor and L is an inductor.

2.3. In vitro evaluation

To test the functionality of the new ASL MRIG, we performed serial in vitro experiments to compare the 0.014-in. ASL MRIG with the 0.014-in. loopless MRIG. We placed the ASL or loopless MRIG into a plastic tube that mimics a "vessel." The vessel was positioned in a plastic box filled with 0.9% sodium chloride solution (Fig. 2). Axial T2-weighted MR imaging of the vessel was then performed by using a turbo spin-echo (TSE) sequence with TR=4000 ms, TE=60 ms, echo train length=6, FOV=60×60 mm, slice thickness=1 mm, slice gap=1 mm, matrix=120×114 and NSA=4. To further measure the SNR, the vessel was removed from the plastic box and axial T2 images with either the ASL or loopless MRIG were acquired again using the same MR parameters. Subsequently, we compared the SNR contour maps between the ASL and loopless MRIGs by calculating the MR signal intensities divided by the standard deviations of the background noises using a correction method [16].

2.4. In vivo validation

To validate in vivo the feasibility of using the new 0.014-in. ASL MRIG to intravascularly image vessel walls, we used three pigs, approximately 50 kg in weight with iliofemoral arteries at approximately 4–6 mm in diameter (Q-Bar Farm SPF, Dayton, OR, USA). Animals were treated according to the Principles of Laboratory Animal Care of the National Society for Medical Research and the Guide for the Care and Use of Laboratory Animals (NIH

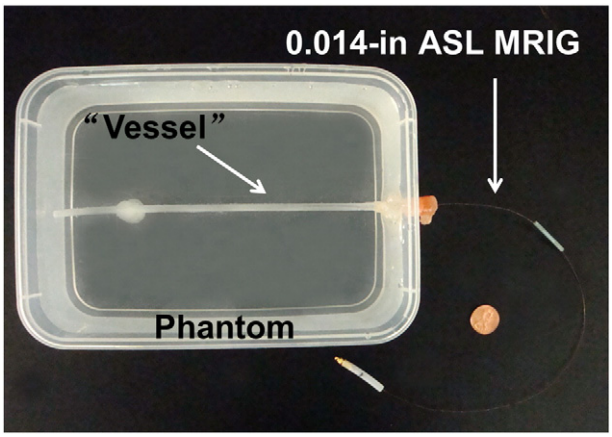

Fig. 2. In vitro experimental setup for 3.0-T MR imaging of the "vessel" using the 0.014-in. ASL MRIG.

publication no. 80-23, revised 1985). The animal experiments were approved by the Institutional Animal Care and Use Committee.

Through a surgical cut-down, we first positioned a 7- to 9-F introducer into the iliofemoral vein, through which a 0.014-in. conventional guidewire was advanced into the inferior vena cava. Then, a balloon catheter, with its balloon size at 5–7 mm in diameter and 4.0 cm in length (Boston Scientific, Boston, MA, USA), was positioned into the iliofemoral vein over the guidewire. The conventional guidewire was then replaced by the 0.014-in. ASL MRIG. Intravenous MR imaging of parallel iliofemoral arteries was subsequently performed on the Philips 3.0-T MR scanner. We first acquired three-dimensional (3D) time-of-flight (TOF) bright blood images by using two-channeled surface coils (GP Flex M coils, Philips Healthcare) to localize the anatomic structures and the location of the ASL MRIG tip. For 3D TOF imaging, one surface coil was placed under the back and another one placed on the abdomen of each pig. The parameters for 3D TOF imaging were TR=21.3 ms, TE=3.0 ms, FOV=100×100 mm, slice thickness=5 mm, slice gap=0.5 mm, matrix=280×182, NSA=1 and flip angle=60°.

After adjusting the position of the ASL MRIG to be in the center of the balloon, we fully inflated the balloon with saline. The inflated balloon not only stopped the blood flow disturbance, but also kept the MRIG in the center of the iliofemoral vein lumen. We then performed intravenous T2-weighted, axial MR imaging of the parallel iliofemoral arteries using TSE sequence with TR=3000 ms, TE=80 ms, echo train length factor=10, FOV=100×100 mm, slice thickness=3 mm, slice gap=1 mm, matrix=288×288 and NSA=8. After obtaining satisfactory intravascular MR images, the animals were euthanized with intravenous injection of sodium pentobarbital at a dosage of 100 mg/kg.

3. Results

Of the in vitro experiments, both the 0.014-in. ASL and loopless MRIGs functioned well as receiver coils with the 3.0-T MR scanner, clearly displaying the vessel wall (Fig. 3A and B). Fig. 3C presents the SNR curves of the two MRIGs, showing the Q point (the intersection of the lines of two MRIGs) that indicates higher SNR within a 1-mm radius with the ASL MRIG than that with the loopless MRIG. However, the loopless MRIG had greater

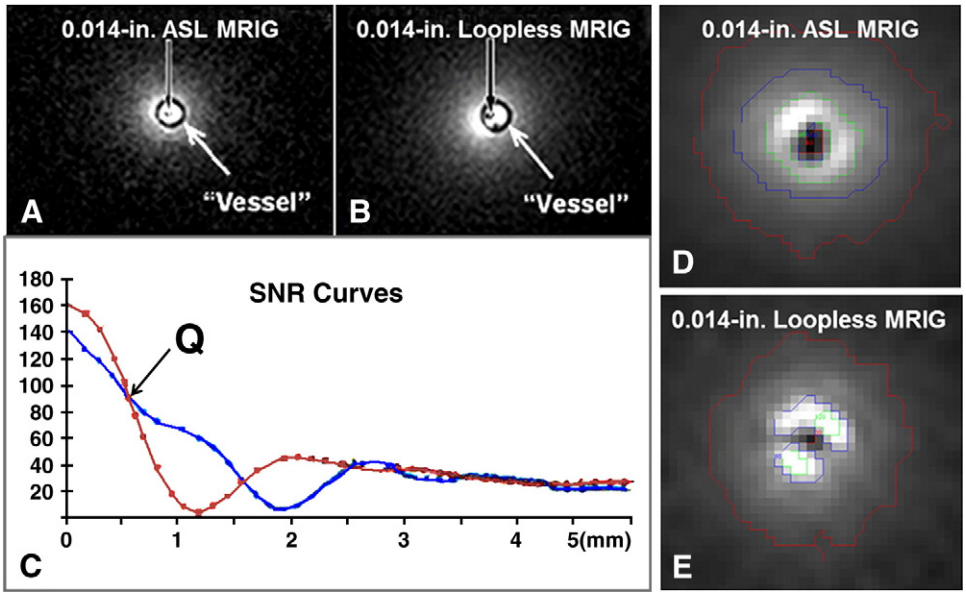

Fig. 3. In vitro axial T2-weighted MR images with the ASL MRIG (A) compared to the loopless MRIG (B). Both MRIGs could clearly demonstrate the vessel walls. (C) The Q point (the intersection of the lines of two MRIGs) is shown in the SNR curves for the ASL MRIG within the vessel (red line) and the loopless MRIG within the vessel (blue line). (D and E) SNR contour maps of T2-MR imaging for the ASL MRIG (D) and the 0.014-in. loopless MRIG (E), showing more even distribution of MR signals and higher SNR with the ASL MRIG (D) than those with the 0.014-in. loopless MRIG (E).

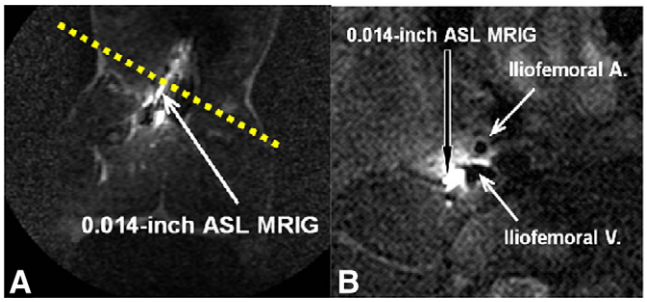

Fig. 4. Intravenous MR imaging of parallel iliofemoral arteries in a pig. (A) Scout 3D TOF MR image with a body coil at the coronal view was used to localize and adjust the position of the intravenously placed ASL MRIG (arrow), based on which an axial intravenous 3.0-T T2-weighted MR imaging of the parallel iliofemoral artery was achieved, demonstrating clearly the wall of the iliofemoral artery (B).

penetration than the ASL MRIG. The comparison of SNR contour maps between two MRIGs demonstrated more even distribution of MR signals and higher SNR with the 0.014-in. loop MRIG than those with the 0.014-in. loopless MRIG (Fig. 3D and E).

Of the in vivo studies, all three pigs survived the surgeries and imaging procedures. After achieving satisfactory 3D TOF images, we could precisely localize and adjust the position of the 0.014-in. ASL MRIG (Fig. 4A). The intravenous T2-weighted MR images using the ASL MRIG displayed both the iliofemoral veins and arteries, clearly depicting the walls of the parallel iliofemoral arteries (Fig. 4B).

4. Discussion

Intravascular MR receiver coils provide a unique tool to generate vessel wall images at higher resolution in comparison to the surface coils. With MR imaging of the vessel walls using an intravascular coil at 3.5 mm in diameter, some authors demonstrated a cylindric region of high sensitivity that offered a 10-fold improvement in SNR over that using an external coil [14,15]. However, to date, all of the loop-designed intravascular MR receiver coils have been produced with a diameter larger than 0.032 in. These intravascular MR coils provided high-quality MR imaging of the vessel walls of deep-seated middle- to large-sized vessels, such as iliac and renal arteries, as well as the aorta. For small-sized vessels, such as coronary arteries, a 0.032-in. or larger intravascular coil is too big to be practical. It is essential to make these endovascular coils as thin as 0.014-in. in diameter, which is the standard size of clinically used guidewire for intracoronary interventions. To the best of our knowledge, there is no report on production of a 0.014-in., loop-designed intravascular MR coil. In this study, we attempted to fill this gap.

We have designed and manufactured a new 0.014-in. ASL MRIG. The results of our in vitro evaluation and in vivo validation studies initially confirm that (i) it is possible to build such small-sized intravascular MRIG with two micro-ASLs; (ii) the new 0.014-in. ASL MRIG functions well, as a receiver, with a 3.0-T MR scanner; and (iii) it is feasible to use the 0.014-in. ASL MRIG to generate intravascular MR images of deeply seated vessel structures, such as the walls of iliac arteries. Manufacturing such tiny-looped intravascular MRIG is a challenging task. Further efforts are warranted to refine the design of such tiny-looped coils to be strong enough with excellent mechanical properties for guiding endovascular interventional procedures. Since this study primarily focused on designing and manufacturing the new 0.014 in. ASL MRIG, we did not compare it with a standard surface coil.

In conclusion, we report our development of a 0.014-in., loop-designed MRIG for intravascular 3.0-T MR imaging, which may provide high-quality MR imaging to guide intracoronary interventional therapies.

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