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Simultaneous Bilateral Magnetic Resonance Imaging of the Femoral Arteries in Peripheral Arterial Disease Patients

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Abstract

Purpose—To image the femoral arteries in peripheral arterial disease (PAD) patients using a bilateral receive coil.

Materials and Methods—An eight-channel surface coil array for bilateral MRI of the femoral arteries at 3T was constructed and evaluated.

Results—The bilateral array enabled imaging of a 25-cm segment of the superficial femoral arteries (SFA) from the profunda to the popliteal. The array provided improved the signal-to-noise ratio (SNR) at the periphery and similar SNR in the middle of a phantom compared to three other commercially available coils (4-channel torso, quadrature head, whole body). Multicontrast bilateral images of the in vivo SFA with 1 mm inplane resolution made it possible to directly compare lesions in the index SFA to the corresponding anatomical site in the contralateral vessel without repositioning the patient or coil. A set of bilateral time-of-flight, T1-weighted, T2-weighted, and proton density-weighted images was acquired in a clinically acceptable exam time of ≈ 45 minutes.

Conclusion—The developed bilateral coil is well suited for monitoring dimensional changes in atherosclerotic lesions of the SFA.

Keywords

vessel wall imaging; peripheral arteries; femoral arteries; RF coil array; peripheral arterial occlusive disease

Introduction

Peripheral arterial disease (PAD), a manifestation of systemic atherosclerosis, occurs in about 12% of the adult population, affecting 8–10 million people in the United States (1,2).

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The most common symptomatic manifestation of mild to moderate lower extremity PAD is intermittent claudication, which occurs at an annual incidence of 2% in people over age 65 (3) and is a frequent problem in those who smoke or develop obesity and/or diabetes. These patients are at significantly higher risk of death compared to age-matched healthy controls (4) and may be less likely to receive appropriate treatment for their atherosclerotic risk factors than are those with coronary or carotid artery disease (5,6). Functional status is often severely impaired in patients with intermittent claudication. Peak exercise performance in the claudicating patient is about 50% that of age-matched controls, an impairment equivalent to moderate to severe heart failure (7). The limited capacity to ambulate leads to disability that is particularly detrimental to quality of life, because both leisure and work activities are often severely curtailed. Improvement in the absence of intervention is rare in this disabling disease.

The superficial femoral arteries (SFA) are the main arterial conduits carrying blood to the lower limbs. Stenosis of these vessels leads to intermittent claudication and ultimately to loss of limb. A number of endovascular interventions have been used to revascularize the SFA including angioplasty, stenting, atherectomy, and bypassing (8–10). Medical interventions have also been used to reduce stenosis and increase perfusion (11–13). Accordingly, an effective method to monitor the efficacy of these interventions and to track the state of atherosclerotic lesions in these vessels is highly desirable. During the past 5 years, magnetic resonance imaging (MRI) has become a leading method for determining the dimensions and composition of lesions in the carotid arteries (14–24). MRI of the SFA vasculature has been less developed (25–28) due in part to limited availability of high sensitivity phased array coils customized for the lower extremities.

Coil performance is critical for vessel wall imaging due to the high signal-to-noise ratio (SNR) required to resolve the thin wall structure (≈ 0.74 mm for the healthy femoral artery (29)). For clinical examination of the lower extremity vessel walls, coverage in the head-foot direction on the order of 20–30 cm is preferred. Bilateral coverage reduces examination time by a factor of two and eliminates the need for positional registration of the left and right arteries for postimaging comparisons. These lower extremity vessel wall imaging requirements are congruent with a multielement phased array receiver where a multitude of surface coils operate in unison to provide large coverage that is typically associated with a volume coil and improved local SNR that is associated with a surface coil (30). This report describes the construction and performance of an eight-channel phased array coil for bilateral SFA imaging. This custom coil was used to image the SFAs of PAD patients; the images were used to delineate plaque, to determine the patency of a stent, and to evaluate the condition of a surgically repaired SFA.

Material and Methods

Fabrication of the Receiver Coil

The bilateral receiver coil consisted of eight rectangular elements wrapped around two acrylic cylinders of 17.8 cm diameter; four coils were distributed azimuthally around each cylinder (Fig. 1). The cylinders were divided into separate anterior and posterior semicylinders to make patient leg entry more convenient. Each element was laid out using copper tape with 1.2 cm width, 25 cm length, and an arc length of ≈ 16 cm. This arc length extended slightly beyond 90° to accommodate partial coil overlapping of 1.3 cm to reduce mutual inductance between adjacent coils (for example, coils 1 and 2, 2 and 3, 3 and 4, 4 and 1, etc. in Fig. 1) (30). Additionally, the roughly orthogonal relationship reduced coupling between adjacent opposing coils (coils 1 and 8, and 4 and 5). A shared inductor was introduced to reduce coupling between diagonal coil pairs (coils 1 and 5, and 4 and 8). Each coil was tuned to 127 MHz using six distributed capacitors (three 20 pF capacitors,

two 30 pF capacitors, and one trimmer of ≈ 20 pF) and capacitively matched to 50V while loaded with a 3 L phantom doped with 60 mM NaCl and 10 mM CuSO₄ to mimic leg loading. Network analyzer measurements showed that the unloaded quality factor was ≈ 180 , which reduced to 20 with phantom loading. MR signal was transferred to eight system-integrated preamplifiers through shielded baluns and coaxial cable with appropriate electrical length for preamplifier decoupling (30). Active detuning circuits, consisting of a 30 pF capacitor in parallel with a pin diode and ≈ 52 nH inductor at the drivepoints were used to deactivate the coils during radiofrequency (RF) excitation provided by the body coil.

Phantom Imaging

Imaging was performed on a 3 T MR scanner (GE Medical Systems, Excite, Milwaukee, WI). For SNR comparison, phantom images were acquired using the eight-channel bilateral coil, and three commercially available GE coils (4-channel torso array, quadrature head coil, and body coil). Data were acquired using a gradient echo pulse sequence with TR/TE = 100/6.8 msec, flip angle = 60°, field of view (FOV) = 42×21 cm², slice thickness = 4 mm, acquisition matrix = 256×128 , and receiver bandwidth = ± 31 kHz. Signal was measured in the sum-of-squares magnitude image. Rayleigh noise was measured as the standard deviation of pixel intensities in the sum-of-squares magnitude image acquired without RF excitation. This Rayleigh noise was corrected to Gaussian noise according to Constantinides et al (31).

Human Imaging

In vivo imaging was performed using the bilateral coil on five volunteers with PAD and one volunteer with no indication of peripheral disease. The study was approved by the local Institutional Review Board and written informed consent was obtained from all subjects prior to imaging. Time of flight (TOF) images in the transverse plane were collected over a 25-cm span from the profunda to the popliteal to localize the femoral vasculature and guide the prescription of spin echo images. TOF images were acquired using the following imaging parameters: TR/TE = 25/6 msec, flip angle = 40°, FOV = 26×18 cm², slice thickness = 2mm, acquisition matrix = 256×180 (interpolated to 512×512), and receiver bandwidth = 122 Hz/pixel. The 26-cm frequency encode FOV reduced scan time by cropping the peripheral region of the legs while still capturing the SFA in the medial portion of the legs. Transverse spin echo images were collected using identical acquisition matrix, FOV, slice thickness, and receiver bandwidth as those in the TOF acquisition. Proton density-weighted (PDw) images were collected with the following parameters: TR/TE = 1800/13 msec, echo train length (ETL) = 10, number of excitations (NEX) = 2, yielding 30 slices in 6.7 minutes. For T1-weighted (T1w) images: TR/TE/ETL/NEX = 400/10 msec/2/2, yielding 30 slices in 9.3 minutes. For T2-weighted images: TR/TE/ETL/NEX = 1800/80 msec/10/2, yielding 30 slices in 6.6 minutes. Spatial saturation pulses were applied to inflowing blood to improve contrast between the lumen and vessel wall in all spin echo acquisitions.

In three PAD patients, SNR for the bilateral was measured in magnitude sum-of-squares PDw images in three regions: the gracilis muscle, the Sartorius muscle, and the femur. The SNR was defined as the mean signal within the manually outlined ROI divided by the mean of the standard deviations in three background regions free of artifacts. SNR was scaled according to Ref. (31). The shortest distance from the center of the outlined region to the leg periphery was also recorded. SNR was not measured in the SFA due to subject-dependent variability in vessel composition and blood saturation.

The same three PAD patients had also been previously scanned using a commercially available four channel receive array with 6-cm loops (Pathway MRI, Seattle, WA). This coil

was intended to be utilized for bilateral imaging of the carotid arteries and was adapted for unilateral SFA imaging in this study. SNR was measured in manually matched slices in the distal thigh in the same manner as described above in spin echo images with the following parameters: TR/TE/ETL/NEX = 3000/10.4 msec/8/2, slice thickness = 2 mm, pixel size = $0.39 \times 0.39 \text{ mm}^2$, and receiver bandwidth $\frac{1}{4}$ 122 Hz/pixel.

SFA depth was measured in 13 patients referred for peripheral MRA using Advantage Workstation 4.2 software (GE Healthcare). The minimum distance between the vessel and leg periphery was recorded at five positions between the inferior edge of the femoral condyle and the superior edge of the femoral head.

Results

Phantom Imaging

Figure 2 shows a phantom image collected using the bilateral coil and SNR profiles through the image center from the four coils tested. Due to an increased number of coil elements with reduced dimension, the 8-channel bilateral coil provided a substantial SNR increase at the periphery and similar SNR in the middle of the phantoms compared to other coils tested. The proximity of the bilateral coils to the phantoms, or the increased filling factor, also contributed the SNR improvement over the all-purpose coils which have more remote conductors.

Human Imaging

SFA depth varied with position along the leg: the vessel was most shallow at the knee joint ($25 \pm 6 \text{ mm}$ deep), deepest $\approx 140 \text{ mm}$ superior to the knee joint ($55 \pm 9 \text{ mm}$ deep), and $42 \pm 7 \text{ mm}$ deep in the upper thigh.

Figure 3 shows images of the distal thigh used for in vivo SNR acquired with the developed bilateral SFA array and the commercially available unilateral SFA array in the same PAD patient. SNR measured in three PAD patients with both arrays is given in Table 1. Although differing pulse sequence parameters make direct SNR comparison difficult, the unilateral array may outperform the bilateral array in superficial regions, whereas the situation may be reversed in deep tissue.

A TOF image covering 25 cm of both legs in a healthy subject is shown in Fig. 4. The superficial femoral arteries appear hyperintense and localize near the veins, which exhibit ladder-like bands. Tissue surrounding a stent can be seen in the right SFA with hypointense bands at the proximal and distal ends. The smaller deep femoral arteries are also visible.

Figure 5 shows images from a patient with a subintimal atherectomy, a surgical procedure in which blood flow is restored to the SFA by creating a new lumen between the intimal and medial layers of the arterial wall. Spin echo images reveal the division between the new and former lumens, while the TOF image suggests blood flows through both lumens. For comparison, images from the same position in the contralateral leg indicate a patent SFA.

The PDw image of a patient with an eccentric lesion in the left SFA is shown in Figure 6. The corresponding TOF image shows reduced flow in this region. Despite applying a saturation pulse, the T1w images were susceptible to flow artifacts, making it difficult to visualize the vessel walls. The right PDw image indicates a concentric lesion with detectable heterogeneity.

The appearance of SFA tissue near a stent depends on the stent composition and architecture (32). In the present study the tissue surrounding a stent can be visualized as a rosette in spin

echo images, while the TOF image implies blood flow through the stent (Fig. 7). Poor blood suppression hindered the delineation of the left SFA vessel wall in T1w and PDw, while the TOF and T2w images indicate SFA patency.

Images of a partially blocked right SFA are shown in Fig. 8. The PDw image indicates the presence of a necrotic core (isointense) surrounded by a fibrous cap (hyperintense).

Discussion

Visualization and quantitation of atherosclerotic plaque in the lower extremities is a relatively new area of MRI investigation (9,13,25–27,33). The diameter of the leg is much less than that of the body trunk, making smaller, more efficient coils conducive to improved signal detection in the legs. The legs can also be immobilized and are less likely to generate motion artifacts compared to other vessels, such as the carotids. Correspondingly, in vivo imaging of the lower extremity vessels can have advantages of high SNR and image quality, allowing reliable measurements of atherosclerotic lesions. This study has focused on developing fast and reliable peripheral vessel imaging technology.

A major challenge in clinically relevant SFA atherosclerosis imaging is sampling an adequately large FOV in the head–foot direction. Since there may be multiple lesions dispersed throughout the SFA, it is desirable to cover the area from the profunda to the popliteal. Our early studies utilized a single channel loop coil with 6 cm diameter for signal reception; although the images obtained with this coil were of good quality, it lacked the desired coverage in the head–foot direction and did not offer bilateral imaging. We have overcome both of these deficiencies by fabricating a custom coil that covers the full length of the right and left SFA. This affords the advantage of directly comparing an atheroma in the index SFA with the corresponding site on the contralateral artery, whereas image registration required for two unilateral images make such a comparison inconvenient. Although the bilateral coil affords these important benefits, its 18 cm diameter can accommodate the legs of a patient of average size and weight (<200 lbs), but can be restrictive for larger patients. This confinement can lead to involuntary leg muscle twitching during an extended imaging session (>45 min) which may generate image artifacts.

In this work, conventional spatial saturation provided only marginal blood suppression, and in some cases compromised the delineation of the vessel wall. While spatial saturation may provide adequate suppression of blood signal in arteries with fast-moving blood such as the aorta, slower blood flow in the lower extremities (34) may limit its effectiveness, especially during a multislice or volumetric acquisition. SFA vessel wall delineation may be improved by implementing advanced blood suppression techniques such as T2 prepared inversion recovery (35,36) or motion-sensitizing magnetization preparation (37–40).

In conclusion, the clinical utility of the new bilateral coil was demonstrated by addressing three specific aims: 1) to resolve the relatively small SFA vessel wall structure over an FOV extending from the profunda to the popliteal; 2) to acquire a complete set of TOF, T1w, T2w, and PDw images from both legs in a reasonable examination time; and 3) to compare diseased and contralateral vessels in the same patient. Each of these aims has been addressed, indicating the potential of this coil for noninvasive detection of atherosclerotic lesions and for the monitoring of their progression, stabilization, and regression over time in multiple arterial sites.

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Figure 1. (a) Eight-channel bilateral coil schematic diagram in the transverse plane, (b) photograph on the workbench, and (c) photograph with a patient on the scanner table.

Figure 2.

a: Phantom image acquired in the transverse plane using the bilateral coil. **b:** SNR profiles across the anterior-posterior center in (a) from the 8-channel bilateral, 4-channel torso, quadrature head, and body coils.

Figure 3. Image of the distal thigh acquired using the developed bilateral array(**a**) and a commercially available unilateral array (**b**).

Figure 4.

TOF image acquired to localize the femoral vasculature. The 25-cm long head-foot coil coverage enabled localization of the disease site. The SFA are located in the medial portion of the legs, allowing a reduced FOV in the frequency encoding direction (left-right). FV: femoral vein.

Figure 5.

Images from a patient with a left subintimal atherectomy, a surgical procedure in which blood flow is restored to the artery by creating a new lumen between the intimal and medial layers of the arterial wall. Top row: spin echo images of the left SFA reveal a division between the new (arrows) and former (arrowheads) lumens, while the TOF images suggest blood flow through both lumens. For comparison, images from the same position in the right leg suggest a patent SFA (bottom row).

Figure 6.

SFA eccentric plaque in the left SFA in T2w and PDw images, corresponding to reduced patency shown in the TOF image (top row, arrows). Despite the application of a saturation pulse, the T1w images were susceptible to flow artifacts, making it difficult to visualize the vessel walls (arrowheads).

Figure 7.

Images of the right SFA illustrate tissue surrounding a stent (top row, arrows). Bottom row: patent left SFA is suggested by the TOF and T2w images (arrowheads), while the wall is obscured by poor blood suppression in T1w and PDw images.

Figure 8. Images of the right SFA indicate partial blockage (top row, arrows). The right PDw image shows a hypointense residual lumen, a hyperintense fibrous cap, and an isointense necrotic core. Images of the left SFA also show signs of reduced lumen area (bottom row, arrowheads).

Table 1

Bilateral and Unilateral Coil SNR From Three PAD Patients

Region	4-ch unilateral SFA array	8-ch bilateral SFA array	Depth (mm)
Femur	6.7 ± 1.9	10.1 ± 2.4	58.6 ± 10.2
SM	66.9 ± 16.4	24.4 ± 5.5	23.7 ± 3.3
GM	88.4 ± 14.1	24.7 ± 6.9	20.8 ± 3.3

SM: sartorius muscle; GM: gracilis muscle.