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Clinical advances in cardiovascular magnetic resonance imaging and angiography

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Chapter 5

Peripheral Arterial Disease: Sensitivity-encoded Multiposition MR Angiography Compared with Intraarterial Angiography and Conventional Multiposition MR Angiography

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Abstract

A sensitivity-encoded magnetic resonance (MR) angiography protocol was developed in which imaging times in the pelvic and upper-leg positions were reduced and isotropic submillimeter voxel volumes were acquired in the lower-leg position. To achieve this, sensitivity encoding and random central-k-space segmentation in a centric filling order were applied. Results with this technique were compared with those with midstream aortic digital subtraction angiography (DSA) (as the reference standard) and conventional MR angiography in 15 patients with peripheral vascular disease. The results show that sensitivity-encoded MR angiography demonstrates increased diagnostic accuracy in comparison to that with conventional MR angiography and depicts more open infragenuous arterial segments compared with both midstream aortic DSA.

Introduction

Contrast material-enhanced magnetic resonance (MR) angiography has evolved in only a few years to be a safe, fast, reproducible, and reliable imaging technique.¹⁻⁹ With the increasing availability of high-field-strength (1.5-T) MR imaging systems, MR angiography is now widely used for the detection of stenosis in patients with peripheral arterial disease. In MR angiography, the length of the imaged volume in one acquisition is limited to approximately 40–50 cm. Thus, more than one acquisition is required to image the entire vascular tree from the abdominal aorta down to the infragenual arteries.

In general, two MR angiography protocols are used: single-injection multiposition^{4-6,10} or multi-injection multiposition.^{7-9,11} Compared with the single-injection protocol, the multi-injection protocol has the following advantages: It has almost no limitation of imaging duration for each volume, which allows higher spatial resolution, and it can be performed with any system without the need for special hardware. However, the contrast material volume for each position is limited. More important, by the time the lower-leg arteries are imaged, contrast material from previous acquisitions will cause both venous and tissue enhancement. Although subtraction techniques are used in the multi-injection protocol, venous and tissue enhancement might lead to a lower contrast (or vessel)-to-noise ratio.

In a single-injection multi-position protocol, all three positions (pelvis, upper leg, and lower leg) should be acquired while contrast material is confined to the lower-limb arteries. In MR angiography, the contrast material bolus travels down the arterial tree at an average of 6 seconds per position, and venous enhancement at the ankle occurs approximately 68 seconds after the start of contrast material injection into a decubital vein.¹² The infragenual arteries of a healthy person would be completely filled with contrast material at approximately 18 seconds after the start of the acquisition of the first (pelvic) position. This clearly indicates the limited length of the arterial window despite the large range in venous arrival times and the fact that contrast material travels more slowly in men and the elderly and in patients with aortic aneurysm, arterial occlusive disease, and cardiac disease.¹² Therefore, contrast material may arrive in the venous system while images are being acquired at the most distal position. This venous enhancement can cause non-diagnostic MR images of infragenual arteries. Hence, imaging of the abdomen and upper-leg arteries must become faster to prevent venous enhancement. To better detect and evaluate infragenual arteries, spatial resolution should be increased. An increase in spatial resolution is possible, however, only at the cost of prolonged acquisition times. Current single-injection multi-position contrast-enhanced MR angiography protocols are designed to acquire images as quickly as possible with an acceptable spatial resolution.

New MR imaging techniques have become available. Sensitivity encoding (SENSE; Philips Medical Systems, Best, the Netherlands)^{13–15} increases imaging speed without the loss of spatial resolution or reduction of spatial coverage. Random central-k-space segmentation in a centric filling order, a variant of centric k-space filling (CENTRA [contrast-enhanced timing robust angiography]; Philips Medical Systems), allows longer acquisition times without venous enhancement.

The purpose of this prospective study was to compare a single-injection multiposition contrast-enhanced MR angiography protocol with sensitivity encoding and random central-k-space segmentation in a centric filling order (hereafter, sensitivity-encoded MR angiography) with a conventional single-injection multiposition contrast-enhanced MR angiography protocol (hereafter, conventional MR angiography) in patients with peripheral arterial disease. Midstream aortic intra-arterial digital subtraction angiography (DSA) was used as the standard of reference.

Materials and Methods

From March 15 to April 30, 2001, 19 consecutive patients referred to undergo DSA to evaluate symptoms of peripheral arterial disease were asked to participate. One patient was excluded because of a pacemaker, and two patients refused participation. One patient refused to undergo conventional MR angiography and was excluded from the analysis. Therefore, 15 patients were included in the study (13 men and two women; mean age, 66 years; age range, 52–77 years). Patients participated on a voluntary basis, and written informed consent was obtained. Approval was obtained from the institutional review board of the hospital. DSA, conventional MR angiography, and sensitivity-encoded MR angiography were performed within a 1-week interval (mean, 3.5 days). There were no statistically significant differences between the age distributions by sex ($p=.171$, nonparametric Mann-Whitney U test). Twelve of the 15 patients had mild to severe claudication, two patients had rest pain, and one patient was referred for evaluation of ulcerations in a diabetic foot. No adverse reactions or complications were encountered during or after any of the imaging examinations.

Conventional MR Angiography

Conventional MR angiography (Mobi-Trak; Philips Medical Systems) was performed with a 1.5-T MR system (Gyrosan NT Intera, release 7.1.1; Philips Medical Systems). Patients were positioned feetfirst. For immobilization and alignment of the arteries from the abdominal aorta to the lower-leg arteries, the patients' legs were strapped and fixed in a leg support. A quadrature body coil was used for signal transmission and reception. A survey image was obtained with a two-dimensional multisection turbo

field-echo sequence (image matrix, 256x128; 30 transverse sections; section thickness, 3.3 mm; section gap, 11 mm) in three positions. Automatically generated coronal and sagittal maximum intensity projection images were used for volume planning at conventional MR angiography. The time delay between the start of contrast material injection and the start of the acquisition was determined by means of bolus timing in a thick section with automatic complex subtraction (BolusTrak; Philips Medical Systems). The conventional MR angiography protocol included automated table movement, image reconstruction, and generation of subtraction and maximum intensity projection images. The imaging parameters are presented in Table 5.1.

A biphasic contrast material injection protocol was used: 39 mL of gadoteridol (Prohance; Bracco-Byk Gulden, Konstanz, Germany) was injected by using an MR imaging-compatible injector (Spectris MR injector; Medrad, Indianola, Pa): injection of volume 1, 20 mL at a flow rate of 0.6 mL/sec; injection of volume 2, 19 mL at 0.3 mL/sec with a subsequent saline flush. Total injection duration was 96.6 seconds. Total examination time (patient in and out of the MR unit) ranged from 20 to 30 minutes. After automatic postprocessing at the console of the MR system, the subtracted data were sent to a remote work position (Easy Vision; Philips Medical Systems) for reconstruction and interpretation of the images. No subtraction artifacts were encountered.

Sensitivity-encoded MR Angiography

Sensitivity-encoded MR angiography was performed with the same 1.5-T MR system by using a prerelease version of 8.1 software. For more accurate planning, some parameters in the survey protocol were adjusted (image matrix, 184x256; reconstruction matrix, 256x512; 60 transverse sections; section thickness, 3 mm; section gap, 4 mm). Acquisition of a reference MR image to determine the sensitivity of each element in a four-element synergy (phased-array) body coil is mandatory for application of sensitivity encoding. The abdominal reference MR image was obtained in continuity with the survey acquisition, and after an automated table movement, the lower-leg reference image was obtained. For optimal correlation, both the reference image and the dynamic MR image of the abdomen (aorto-iliac position) were obtained at end expiration. The bolus timing protocol was identical to that in conventional MR angiography.

Table 5.1 Comparison of Imaging Parameters for Standard and Sensitivity-encoded MR Angiography.

Parameter	Station		
	All Volumes	Abdomen	Upper legs
Repetition time msec/echo time msec	6.1 / 1.55	4.8 / 1.36	4.2 / 1.27
Flip angle (degrees)	35	20	20
No. of sections	35	40	30
Thickness (mm)	3.0	2.2	2.0
Zero interpolation	To 7.0 1.5-mm-thick sections	To 80 1.1-mm-thick sections	To 60 1.0-mm-thick sections
Volume thickness (cm)	10.5	8.8	6.0
Field of view (mm)	430	430	430
Matrix			
Size (pixel)	512 x 180	384 x 192	416 x 208
Imaging percentage	NA	50 (384 x 384)	50 (416 x 416)
Voxel volume (mm ³)			
Acquired	6.0	5.3	4.3
Interpolated	1.06	0.76	0.71
Coll	Quadrature body	Four-element synergy	Quadrature body
Application in sensitivity-encoded MR angiography	NA	Sensitivity encoding (SENSE factor 2)	NA
k-Space filling	Abdomen, linear, upper leg, low to high; lower leg, low to high	Linear	Random segmentation of k space
Imaging time (sec)	31	18	19
Table movement	Automatic	Manual during imaging of contrast material	Manual during imaging of contrast material

NA = not applicable.

MR imaging protocols were used for the abdominal arteries (repetition time msec/echo time msec, 4.8/1.36; section thickness, 2.2 mm; field of view, 430 mm; image matrix, 384x192; acquired voxel volume, 5.3 mm³), upper-leg arteries (4.2/1.27; section thickness, 2.0 mm; field of view, 430 mm; image matrix, 416x208; acquired voxel volume, 4.3 mm³), and lower-leg arteries (4.3/1.4; section thickness, 1.0 mm; field of view, 430 mm; image matrix, 432x432; acquired voxel volume, 0.98 mm³). These sequences were repeated in reverse order after administration of contrast material (Table 5.1). Some further adjustments were made. In the upper- and lower-leg positions, random central-k space segmentation in a centric filling order was applied. The center of k space was written 4 seconds after volume acquisition started, and the central region of k space was filled during the first 4 seconds of volume acquisition in random order (as opposed to centric or elliptic centric orders). Thus, central k space, which provides image contrast, was filled during the arterial imaging window. If venous enhancement occurred, it would be during peripheral k space filling, which provides image resolution. The writing of the exact center of k space 4 seconds after the start of volume acquisition makes this technique less sensitive for early timing errors (Figure 5.1). In the abdomen and lower-leg positions, constant level appearance (CLEAR; Philips Medical Systems) was applied, and a reference MR image was obtained to measure B₁ inhomogeneity and thus non-uniform coil sensitivity. CLEAR is a software tool that compensates for non-uniform coil sensitivity and provides a more homogeneous image comparable to that acquired with a quadrature body coil.

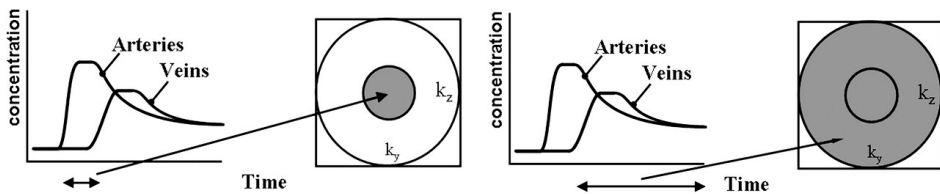


Figure 5.1 Left: During the arterial window, the three-dimensional center of k space is written, which provides image contrast. Right: By the time contrast material arrives in the veins, the periphery of k space is written, which provides image detail.

In the abdomen position, sensitivity encoding was applied in the phase-encoding (left-to-right) direction. Two coil elements were positioned beside each other (two in front and two in back), which led to reduced signal at the borders of the field of view in the feet-to-head direction in comparison to that with a quadrature body coil. Constant level appearance was applied to compensate for the reduced signal. Furthermore, the overlap between the abdomen and upper-leg volume was increased to 8 cm, which reduced total image coverage from 128 to 123 cm. To improve the contrast-to-noise

ratio, the flow rate of contrast material was increased. A biphasic injection was applied to ensure that central k space of the lower-leg position was acquired during passage of the arterial bolus: injection of volume 1, 15 mL at a flow rate of 0.8 mL/sec; injection of volume 2, 25 mL at 0.4 mL/sec. Owing to the changed parameters, central k space of the lower-leg position was filled 49 seconds after the start of the acquisition of the abdomen position. Reduced imaging time, by means of sensitivity encoding, and increased spatial resolution would lead to a reduction of the signal-to-noise ratio. To compensate for this reduction, we used a phased-array coil instead of the quadrature body coil and we increased the contrast material injection rate to improve the signal-to-noise ratio. Furthermore, we reduced the flip angle to 20° because, according to the hardware automated estimation of the signal-to-noise ratio, this was the optimal flip angle for the given MR imaging parameters. This value is also near the theoretic optimum of 25° to 55°¹⁶. Total examination time ranged from 45 to 55 minutes. No subtraction artifacts were encountered.

DSA Imaging

DSA was performed with a dedicated angiography system (Multistar T.O.P.; Siemens Medical Engineering, Forchheim, Germany) with non-ionic contrast material (iomeprol, Iomeron 350; Bracco-Byk Gulden, Konstanz, Germany). Contrast material was injected at variable flow rates and volumes depending on the catheter tip location and segment imaged. DSA was performed by means of puncture of the common femoral artery. The tip of a 4-F pigtail or straight catheter was positioned in the infrarenal abdominal aorta. The conventional imaging protocol included acquisition of overlapping images from the distal abdominal aorta down to the dorsal pedal artery of both legs. Magnification images and views of suspected stenoses were obtained in two orthogonal directions. When the original images of the infragenual arteries did not have good quality, an intra-arterial vasodilator was administered (slow manual injection of 25 mg of Papaverin [Pharma Chemie, Haarlem, the Netherlands]) to optimize contrast material delivery. An experienced vascular radiologist (A.V.T. or L.E.M.D.) supervised all procedures.

Image Evaluation

The arterial tree in each patient was divided into 29 segments, including the infrarenal aorta, common iliac arteries, external iliac arteries, common femoral arteries, superficial femoral arteries above the abductor canal, superficial femoral arteries below the abductor canal, supragenual popliteal arteries, and infragenual popliteal arteries, as well as the tibiofibular trunk, proximal and distal halves of the anterior tibial arteries, proximal and distal halves of the posterior tibial arteries, and proximal and distal halves of the peroneal arteries.

The most severe stenosis in each arterial segment was chosen for classification. Stenoses were graded by using the following equation: percentage stenosis = $(1 - [D/N]) \times 100$, where D is the measured diameter of the residual lumen at the point of maximal narrowing in a segment, and N is the measured diameter at a normal point in that arterial segment. Stenoses were graded on enlarged maximum intensity projection and source MR angiographic images or DSA images by using the digital ruler on a workstation. For segments from the aorta to the popliteal arteries, categories of percentage stenosis were 0%-24%, 25%-49%, 50%-74%, 75%-99%, and 100% (occlusion). Since the diameter of infragenual arteries is 2-3 mm and section thickness in conventional MR angiography is 3 mm, we chose the following categories for stenoses in the infragenual arteries: 0%-49% stenosis, 50%-99% stenosis of one segment, 50%-99% diffuse stenosis in one segment, and 100% stenosis (occlusion). In case a segment could not be scored reliably as a result of poor contrast material delivery at DSA, poor contrast resolution at MR angiography, or an artifact, no grade was assigned. The occurrence of venous enhancement in a segment and the degree of evaluation impairment were scored as grade 0, no venous enhancement; grade 1, venous enhancement present, grading not difficult; grade 2, venous enhancement present, grading suboptimal; or grade 3, venous enhancement present, grading not possible.

MR angiographic images were read by two MR angiography radiologists (H.C.M.v.d.B., J.W., both with 4 years of experience in MR angiography) independently and unaware of the results of other and prior investigations. At least 6 weeks separated the readings of conventional and sensitivity-encoded MR angiographic images. DSA images were read by two vascular radiologists (A.V.T., L.E.M.D.) independently and unaware of the results of other and prior investigations. Final MR angiography and DSA classifications were reached by consensus. If the two readers could not reach consensus, the opinion of an independent radiologist was conclusive.

Statistical Analysis

For the statistical analysis, we considered only segments that were graded on the basis of all three modalities. With DSA as the standard of reference, sensitivity and specificity were calculated with the following categories for disease severity: 50% or more stenosis, 50% or more diffuse stenosis (only infragenual segments), 75% or more stenosis (only non-infragenual segments), and occlusion (100% stenosis). The 95% CIs were constructed for both sensitivity and specificity.¹⁷ A McNemar test was used to determine the statistical significance of differences in sensitivity and specificity between conventional and sensitivity-encoded MR angiography. Furthermore, the number of open infragenual segments was determined at DSA, conventional MR angiography, and sensitivity-encoded MR angiography. Open was defined as not occluded and visible on images of sufficient diagnostic image quality

(ie, sufficient contrast, evaluation not compromised by venous enhancement). A McNemar test was used to compare the number of open infragenual segments between DSA, conventional MR angiography, and sensitivity-encoded MR angiography. A p value less than .05 was considered to indicate a statistically significant difference. In the statistical analysis, interdependence between the diagnostic interpretation of arterial segments was not taken into account. The disease severity of arterial segments is correlated within a patient, but this does not necessarily mean that the diagnostic interpretation is also correlated. Therefore, we did not consider the possible correlation between diagnostic interpretation of arterial segments in our analysis.

Results

Owing to a technical error, constant level appearance could not be applied in one patient. In another patient, movement caused artifacts in both conventional and sensitivity-encoded MR angiographic images, but the three images had sufficient image quality for evaluation, and none of these segments were excluded from the analysis. At conventional MR angiography in five patients, venous enhancement occurred in 70 segments of the infragenual arteries, and 15 of the segments could not be evaluated (grade 3 venous enhancement). In three of these five patients at sensitivity-encoded MR angiography, venous enhancement occurred but it did not result in any segments that could not be graded ($p < .01$) (Table 5.2).

Table 5.2 Occurrence of Venous Enhancement in Infragenual Arterial Segments at Conventional Compared with Sensitivity-encoded MR Angiography.

Grade with Sensitivity-encoded MR Angiography	Grade with Conventional MR Angiography				Total
	0	1	2	3	
0	126	25	20	10	181 [*]
1	0	0	10	5	15 [†]
2	0	0	0	0	0 [*]
3	0	0	0	0	0 [‡]
Total	126	25	30	15	

Data are the number of segments. Grade 0, no venous enhancement; grade 1, venous enhancement present, grading not difficult; grade 2, venous enhancement present, grading suboptimal; grade 3, venous enhancement present, grading not possible. ^{*} $p < .001$; [†] $p < .16$; [‡] $P < .01$.

In all, 381 arterial segments were evaluated with the three imaging techniques; 207 segments were imaged from the aorta to the popliteal artery, and 174 were imaged in the infragenual arteries (Tables 5.3-5.6).

Table 5.3 Stenosis at Standard MR Angiography and DSA.

Stenosis at Conventional MR Angiography	Stenosis at DSA				
	<25%	25%-49%	50%-74%	75%-99%	Occlusion (100%)
<25%	152	4	3	0	0
25%-49%	10	7	3	0	0
50%-74%	1	5	8	1	0
75%-99%	0	0	0	0	1
Occlusion (100%)	0	0	0	0	12

Data are the number of segments. Imaging was performed from the aorto-iliac arteries to the femoropopliteal arteries.

Table 5.4 Stenosis at Sensitivity-encoded MR Angiography and DSA.

Stenosis at Sensitivity- encoded MR Angiography	Stenosis at DSA				
	<25%	25%-49%	50%-74%	75%-99%	Occlusion (100%)
<25%	159	2	1	0	0
25%-49%	3	14	2	0	0
50%-74%	1	1	10	0	0
75%-99%	0	0	1	1	1
Occlusion (100%)	0	0	0	0	13

Data are the number of segments. Imaging was performed from the aorto-iliac arteries to the femoropopliteal arteries.

Table 5.5 Stenosis at Conventional MR Angiography and DSA.

Stenosis at Conventional MR Angiography	Stenosis at DSA			Occlusion (100%)
	<50%	One Stenosis 50%-99%	Diffuse Stenosis 50%-74%	
<50%	94	4	1	30
One stenosis, 50%-99%	5	2	1	0
Diffuse stenosis, 50%-99%	6	3	6	9
Occlusion (100%)	7	1	1	31

Data are the number of segments. Imaging was performed in the infragenual arteries.

Table 5.6 Stenosis at Sensitivity-encoded MR Angiography and DSA.

Stenosis Sensitivity- encoded MR Angiography	Stenosis at DSA			Occlusion (100%)
	<50%	One Stenosis 50%-99%	Diffuse Stenosis 50%-74%	
<50%	105	4	1	3
One stenosis, 50%-99%	7	6	0	0
Diffuse stenosis, 50%-99%	0	0	7	7
Occlusion (100%)	0	0	1	33

Data are the number of segments of the infragenual arteries.

In the aortic to popliteal arteries, the sensitivity of sensitivity-encoded MR angiography for detection of stenosis of 50% or more (89%, 25 of 28 segments; 95% CI: 73%, 96%) was higher than that of conventional MR angiography (79%, 22 of 28 segments; 95% CI: 60%, 90%) (Figure 5.2).

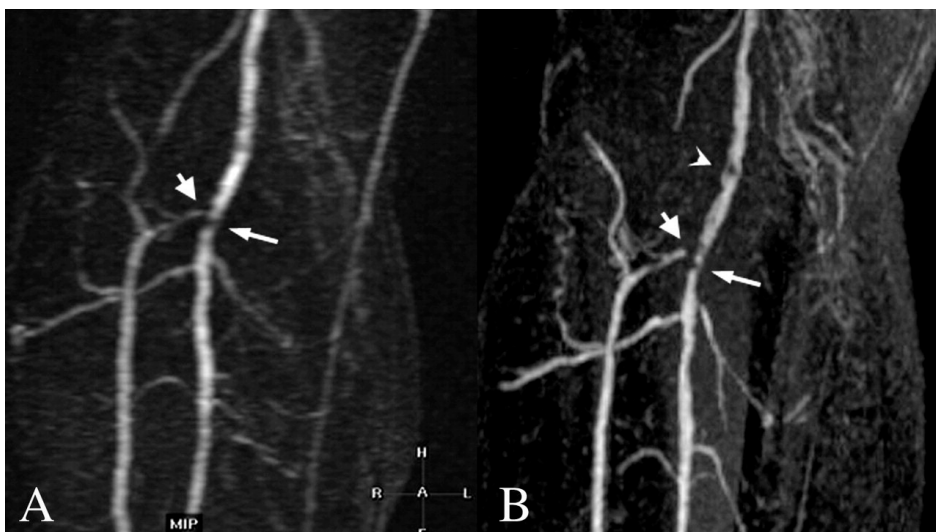


Figure 5.2 Coronal MR angiographic images in the proximal left lower leg of a 65-year-old man with moderate to severe claudication. **(A)** Conventional maximum intensity projection image (6.1/1.55; section thickness, 3 mm; field of view, 430 mm; image matrix, 512x180; acquired voxel volume, 6.0 mm³) shows a subtotal stenosis at the origin of the anterior tibial artery (short arrow) and a significant stenosis in the tibiofibular trunk (long arrow). **(B)** Sensitivity-encoded maximum intensity projection image (4.3/1.4; section thickness, 1 mm; field of view, 430 mm; image matrix, 432x432; acquired voxel, 0.98 mm³) of the proximal left lower leg. There is good correlation with the findings in **A**. As a result of the sixfold increase in spatial resolution in **B**, much better detail is seen. Diffuse arterial wall irregularity and a large plaque that causes a significant stenosis in the popliteal artery (arrowhead) are visible in **B** but not in **A**.

The specificity of sensitivity-encoded MR angiography (99%, 177 of 179 segments; 95% CI: 96%, 100%) was similar to that of conventional MR angiography (97%, 173 of 179 segments; 95% CI: 93%, 98%) (Figure 5.3). The sensitivity of sensitivity-encoded MR angiography for detection of occlusions and stenoses of 75% or more was also higher than that for conventional MR angiography. Specificities were equal (Table 5.7).

In the infragenual arteries, the sensitivity for the detection of one significant stenosis was 87% (54 of 62 segments; 95% CI: 77%, 93%) with both conventional and sensitivity-encoded MR angiography. The specificity showed a statistically significant increase from 84% (94 of 112 segments; 95% CI: 76%, 90%) with conventional MR angiography to 93% (104 of 112 segments; 95% CI: 88%, 97%; $p=.013$) with sensitivity-encoded MR angiography. For the detection of diffuse stenosis in arterial segments, the specificity was significantly higher with sensitivity-encoded MR angiography than

that with conventional MR angiography. However, sensitivities were similar for sensitivity-encoded MR angiography and conventional-MR-angiography (Table 5.8).



Figure 5.3 Coronal MR images in a 54-year-old woman show excellent agreement for a short arterial occlusion in the distal two-thirds of the superficial femoral artery on the left (arrow). **(A)** Anteroposterior DSA image. **(B)** Conventional maximum intensity projection image. **(C)** Sensitivity-encoded maximum intensity projection image. Images in **A** and **B** were obtained with the same parameters in all three positions (6.1/1.55; section thickness, 3 mm; field of view, 430 mm; image matrix, 512x180; acquired voxel volume, 6.0 mm³). Image in **C** was obtained with the following imaging parameters in the abdomen (4.8/1.36; section thickness, 2.2 mm; field of view, 430 mm; image matrix, 384x192; acquired voxel volume, 5.3 mm³), upper legs (4.2/1.27; section thickness, 2.0 mm; field of view, 430 mm; image matrix, 416x208; acquired voxel volume, 4.3 mm³), and lower legs (4.3/1.4; section thickness, 1.0 mm; field of view, 430 mm; image matrix, 432x432; acquired voxel volume, 0.98 mm³).

Table 5.7 Sensitivity and Specificity of Standard and Sensitivity-encoded MR Angiography for Stenosis from Aorta to Popliteal Arteries.

Measurement	Standard MR Angiography			Sensitivity-encoded MR Angiography		
	≥50% Stenosis	≥75% Stenosis	Occlusion (100%)	≥50% Stenosis	≥75% Stenosis	Occlusion (100%)
Sensitivity	79 (60,90)	93 (69, 99)	92 (67,99)	89 (73, 96)	100 (78,100)	100 (77, 100)
Specificity	97 (93, 98)	100 (98, 100)	100 (98, 100)	99 (96, 100)	100 (97, 100)	100 (98, 100)

Data are percentages. Numbers in parentheses are the 95% CI.

Table 5.8 Sensitivity and Specificity of Standard and Sensitivity-encoded MR Angiography for Stenosis in Infragenual Arteries.

Measurement	Standard MR Angiography			Sensitivity-encoded MR Angiography		
	One Stenosis 50%-99%	Diffuse Stenosis 50%-99%	Occlusion (100%)	One Stenosis 50%-99%	Diffuse Stenosis 50%-99%	Occlusion (100%)
Sensitivity	87 (77, 93)	90 (79, 96)	72 (57,83)	87 (77, 93)	92 (82,97)	78 (61, 85)
Specificity	84 (76, 90)	86 (79, 91)	93 (87, 96)	94 (88, 97)*	100 (97, 100)†	99 (96, 100)

Data are percentages. Numbers in parentheses are the 95% CI.

* Compared with standard MR angiography, $p=.013$; † Compared with standard MR angiography, $p<.01$.

Sensitivity-encoded MR angiography depicted significantly more open infragenual arterial segments ($n=162$) than were depicted at midstream aortic DSA ($n=145$, $p<.001$) and conventional MR angiography ($n=143$, $p<.001$) (Figures 5.4, 5.5).

Discussion

In this study, we compared an optimized single-injection multi-position contrast-enhanced MR angiography protocol (sensitivity-encoded MR angiography) with DSA and a conventional single-injection multi-position contrast-enhanced MR angiography protocol (conventional MR angiography) in patients with peripheral arterial disease. We found that the application of sensitivity encoding and random central-k-space segmentation in a centric filling order and the acquisition of submillimeter isotropic voxels in the lower legs in a single-injection multi-position contrast-enhanced MR angiography protocol improve diagnostic performance and increase the number of open infragenual arterial segments that are detected.

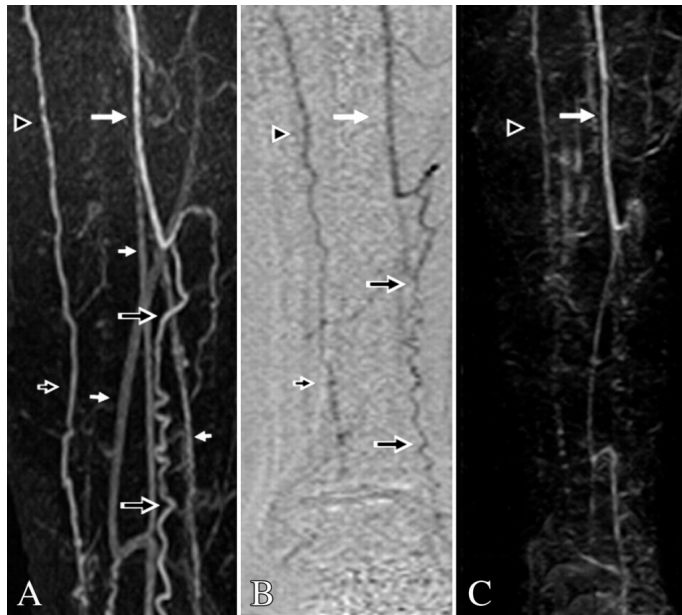


Figure 5.4 Coronal images in the right lower leg in a 66-year-old man with extensive small vessel disease. **(A)** Sensitivity-encoded maximum intensity projection image was obtained with the following parameters: 4.3/1.4; section thickness, 1 mm; field of view, 430 mm; image matrix, 432x432; acquired voxel volume, 0.98 mm³. Posterior tibial artery and distal half of the peroneal artery are occluded. Venous enhancement is visible (short solid arrows) but, because of the increased spatial resolution, does not cause diagnostic difficulty. Tortuous collateral vessel (large open arrows) from peroneal artery (large solid arrow) is clearly seen, as is a collateral vessel (short open arrow) from anterior tibial artery (arrowhead). **(B)** DSA image shows excellent agreement with **A**. **(C)** Conventional maximum intensity projection image (6.1/1.55; section thickness, 3 mm; field of view, 430 mm; image matrix, 512x180; acquired voxel volume, 6.0 mm³) in right lower leg. Collateral vessels from peroneal (solid arrow) and anterior tibial (open arrowhead) arteries are not visible because of limited spatial resolution.

A common drawback of single-injection multi-position contrast-enhanced MR angiography protocols is the difficult evaluation of infragenual arteries because of small vessel diameter and venous enhancement. With sensitivity-encoded MR angiography, the sixfold increase in spatial resolution and isotropic voxels and prevention of venous enhancement enabled more accurate measurement of stenoses, better distinction between occlusion and stenosis, and better delineation between arteries and veins. Thus, we achieved statistically significant increases in specificity for the detection of significant stenoses and the number of open infragenual segments in a comparison between sensitivity-encoded MR angiography and conventional MR angiography.

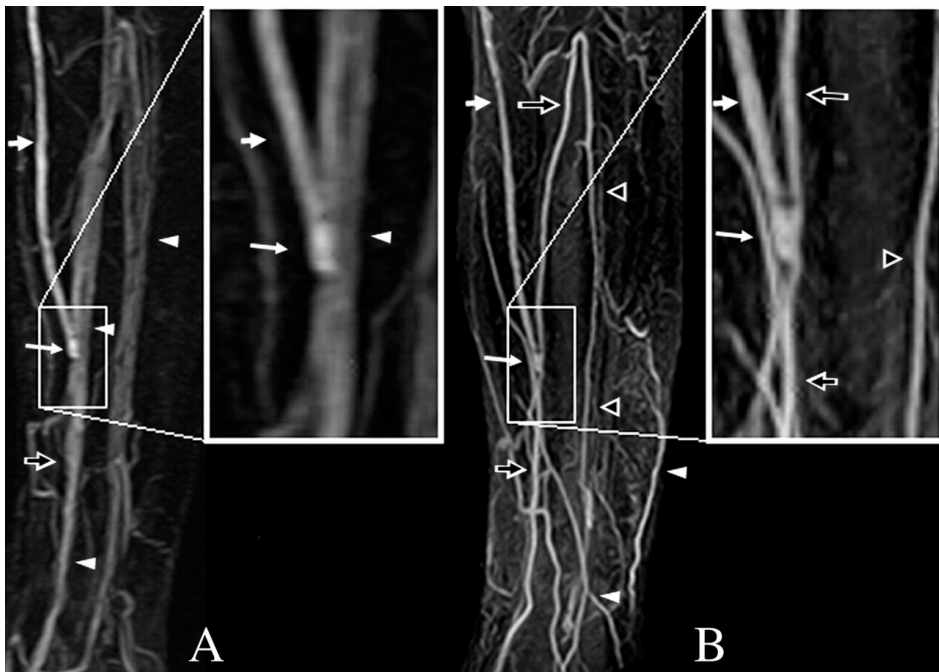


Figure 5.5 Coronal MR images in the left lower leg of a 76-year-old man. **(A)** Conventional maximum intensity projection image (6.1/1.55; section thickness, 3 mm; field of view, 430 mm; image matrix, 512x180; acquired voxel volume, 6.0 mm³) and detail image show bypass graft (short solid arrows) from common femoral artery to distal posterior tibial artery (open arrow). Owing to venous enhancement (arrowheads) and relatively large voxels, distal anastomosis (long solid arrow) and outflow arteries cannot be evaluated. **(B)** Sensitivity-encoded maximum intensity projection image (4.3/1.4; section thickness, 1 mm; field of view, 430 mm; image matrix, 432x432; acquired voxel volume, 0.98mm³) and detail image show clearly the bypass graft (short solid arrows), distal anastomosis (long solid arrow) and outflow arteries, posterior tibial artery (short open arrow), backflow through posterior tibial artery (long open arrows) to peroneal artery (open arrowheads). There is some venous enhancement in the superficial venous system (solid arrowheads) that does not hamper image evaluation.

Review of the literature showed a wide range of sensitivity and specificity values for three-dimensional contrast-enhanced MR angiography. Sensitivity varied from 81% to 100% and specificity from 83% to 99%.^{18–20} For segments from the aorta to popliteal segments, these values ranged from 92% to 100% for sensitivity and 91% to 99% for specificity. In the current study, we compared sensitivity-encoded MR angiography directly with conventional MR angiography and found better diagnostic performance with the former. In a comparison of our results to those in the literature for conventional MR angiography protocols, sensitivity and specificity for both conventional and sensitivity-encoded MR angiography were in the same range,

although sensitivity of conventional MR angiography in segments from the aorta to popliteal arteries was slightly lower. Still, it is difficult to compare the results of different studies because of differences in study population, study design, and MR angiography protocols.

Time-of-flight MR angiography has higher sensitivity than that for midstream aortic DSA²¹ and conventional angiography^{22,23} for detection of open infragenual arteries in the diagnostic work-up for bypass surgery. Findings in our study showed equivalent results: Sensitivity-encoded MR angiography depicted significantly more open infragenual segments than were depicted with midstream aortic DSA. This explains the relatively low sensitivity of sensitivity-encoded MR angiography for the detection of occlusions in the infragenual arteries. A drawback in our study design is that highly selective DSA was not performed in the infragenual arteries. Selective DSA is considered the investigation of choice in patients with severe peripheral vascular disease.²⁴ Although an intra-arterial vasodilator was administered to optimize contrast material delivery at midstream aortic DSA, it was not injected selectively; therefore, the effect is less. Use of midstream aortic DSA as the standard of reference can produce a bias in favor of sensitivity-encoded MR angiography. No power analysis for sample size was calculated in the current study; therefore, further study to compare sensitivity-encoded MR angiography with highly selective DSA in a larger population is needed.

Compared with conventional single-injection multi-position MR angiography, sensitivity-encoded MR angiography depicts more diagnostic vessel segments and less venous enhancement. Comparable results were achieved with multi-injection time-resolved MR angiography.²⁵ Compared with multi-injection time-resolved MR angiography, sensitivity-encoded MR angiography provides higher spatial resolution and isotropic voxel volumes. Furthermore, in sensitivity-encoded MR angiography, conventional phased-array surface coils are used instead of a dedicated coil for the lower-leg position. This makes sensitivity-encoded MR angiography feasible in any clinical setting.

Application of sensitivity encoding (SENSE factor 2) in the pelvic position reduced acquisition time by a factor of 2. Shorter repetition time (reduced flip angle) and decreased volume thickness reduced acquisition time even more. Instead of merely reducing acquisition time, we accepted a time loss to improve spatial resolution. Compared with that in conventional MR angiography, total acquisition time of the pelvic and upper-leg position was reduced by 25 seconds in sensitivity encoded MR angiography. In contrast to that with conventional MR angiography, venous enhancement occurred only occasionally in sensitivity-encoded MR angiography. Further reduction in imaging time may lead to (central) k-space filling before the arterial contrast material bolus has arrived, which would result in artifacts and/or nondiagnostic findings.

Recently, a study was performed to apply sensitivity encoding in peripheral MR angiography.²⁶ The authors demonstrate that the technique is robust, and high-spatial-resolution images are acquired in the below-knee vessels. In sensitivity-encoded MR angiography, imaging times in the abdomen and upper-leg positions were 18 and 19 seconds compared with 11 and 12 seconds, respectively, with the WakiTrak protocol. The slightly longer imaging times in sensitivity-encoded MR angiography decrease the risk of acquisitions that are faster than the travel time of the contrast material bolus. Patients often have one or more of the characteristics for decreased speed of an arterial contrast material bolus. The acquired volumes were larger with sensitivity-encoded MR angiography (abdomen, 8.8 cm; upper leg, 6.0 cm; lower leg, 6.0 cm) than those with the Wakitrak protocol (abdomen, 8.1 cm; upper leg, 5.1 cm; lower leg, 3.8 cm), which makes planning easier and allows inclusion of elongated arteries. In sensitivity-encoded MR angiography, patients' legs were fixed in the conventional leg support to provide a venous pool in the calf to reduce contrast enhancement in the deep venous system and prevent movement. These features seem to make sensitivity-encoded MR angiography more robust. Furthermore, results with the Wakitrak protocol have not been compared with those with conventional MR angiography or DSA.

In the future, use of a higher SENSE factor and the development of a dedicated lower-extremity coil with the possibility of application of the sensitivity-encoded technique in all the positions might lead to faster acquisition, increasing spatial resolution, or the possibility of adding an extra position to the MR angiography protocol. A 3.0-T MR system is now commercially available. The higher signal obtained at the higher field strength will allow even faster acquisition or higher spatial resolution, while the signal-to-noise ratio and the contrast-to-noise ratio at the levels in a 1.5-T MR system are maintained. In addition, the development of new contrast agents with a shorter T1 will allow increased speed and spatial resolution.

For adequate therapy planning in patients with peripheral arterial disease, accurate images of the arteries are essential. In patients with extensive small-vessel disease and in those who have undergone bypass graft surgery, venous enhancement at MR angiography occurs more often. The clinical implication of findings in the current study is that sensitivity-encoded MR angiography can provide more accurate and detailed three-dimensional images of the infraglenal arteries without venous enhancement, because random central- k-space segmentation in a centric filling order is applied and isotropic submillimeter voxel volumes are acquired. Sensitivity-encoded MR angiography depicts more open infraglenal segments than are depicted with either midstream aortic DSA or conventional MR angiography, which provides the surgeon with more arteries for possible distal graft anastomosis. Conventional MR angiography shows good diagnostic performance in the aorta and iliac, femoral, and popliteal arteries and has some advantages over sensitivity-encoded MR angiography. These advantages are that no coils have to be set up and that it is easy to plan, is fully

automated, can be performed by one technician, and takes less time. Because the number of MR examinations that can be performed is limited and, in clinical practice, the number of referrals for MR angiography of the peripheral arteries is increasing, we now perform sensitivity-encoded MR angiography in patients referred for evaluation of small-vessel disease, infragenual arterial disease, or necrosis of the foot or for imaging before or after bypass graft surgery. The importance of high-spatial-resolution MR angiography images without venous enhancement, as provided with sensitivity-encoded MR angiography, is greatest in these selected patients.

In conclusion, application of sensitivity encoding and random central-k-space segmentation in a centric filling order and acquisition of submillimeter isotropic voxel volumes in the lower leg increase the diagnostic accuracy of single-injection multiposition contrast-enhanced MR angiography.

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