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Abbreviations:
ECG = electrocardiography
MIP = maximum intensity projection
3D = three-dimensional

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Peripheral MR Angiography: Separation of Arteries from Veins with Flow-spoiled Gradient Pulses in Electrocardiography-triggered Three-dimensional Half-Fourier Fast Spin-Echo Imaging[1]

The authors evaluated a nonenhanced magnetic resonance (MR) angiographic technique that allows separation of arteries from veins. In 15 healthy subjects, peripheral MR angiography was performed with readout flow-spoiled gradient pulses in electrocardiography-triggered three-dimensional half-Fourier fast spin-echo MR imaging. Appropriate flow-spoiled gradient pulses were measured and applied in the three-dimensional acquisition to differentiate arteries and veins in the peripheral vasculature. Subtraction of the diastolic bright-blood arteries from the systolic black-blood arteries allowed visualization of the arteries by cancelling the veins, which are constantly depicted as bright blood throughout the cardiac cycle. Stronger flow-spoiled gradient pulses improved the depiction of slow-flow arteries even in the distal foot and hand vessels.

Peripheral moving-bed three-dimensional (3D) contrast material–enhanced magnetic resonance (MR) angiographic techniques have become widely established and are used in routine clinical examinations (1,2). However, overlap of the arterial and venous phases is still problematic in the lower extremities. Optimization of artery-vein separation in terms of the amount of contrast material and injection rate remains an area of ongoing research (3,4).

In nonenhanced MR angiography, fresh-blood imaging with electrocardiography (ECG)-triggered 3D half-Fourier fast spin-echo imaging has been reported (5,6), and its clinical application to thoracic and abdominal MR angiography has been evaluated in patients with aortic disease (7). The fresh-blood imaging technique permits the depiction of slow-flow vessels in T2-weighted MR images and of fast-flow vessels by acquiring data during the slow-flow cardiac phase (6). Diastolic and systolic subtraction was demonstrated with ECG-gated spin-echo imaging in the middle 1980s (8,9). In this method, the pulsatile flow signal difference effect on the diastolic signals and flow void signals during systole are used in the readout direction. However, the constant depiction of bright blood has been limited depending on the flow velocity in the vessels even with acquisition during diastole. This is because a long echo time was applied. In addition, the technique requires a long acquisition time because of spin-echo acquisition.

The purpose of our study was to evaluate a nonenhanced MR angiographic technique, flow-spoiled fresh-blood imaging, which permits the separation of peripheral arteries from veins by using readout flow-spoiled pulses in ECG-triggered 3D half-Fourier fast spin-echo MR imaging.

Materials and Methods

Theory

In fast-flow vessels, the fresh-blood imaging technique, ECG-triggered 3D half-Fourier fast spin-echo MR imaging with short echo train spacing, shows both arteries and veins as bright blood in diastole-triggered images, whereas the technique shows black-blood arteries and bright-blood veins in systole-triggered images (6). In general, the technique has been applied with the phase-encode direction parallel to the orientation of the vessel (6,10). Therefore, it is straightforward to obtain images of only the arteries by subtracting the systolic image from the diastolic image of fast-flow vessels. On the contrary, in peripheral or slow-flow vessels, the technique provides bright-blood arteries even in systole-triggered images because of the slow flow, which makes it difficult to separate arteries from veins. By applying the readout direction in parallel with the vessel orientation, an intrinsic dephasing effect can be obtained compared with the phase-encode direction, which is acquired from near the center or low frequencies of the k space in half-Fourier fast spin-echo imaging (6). Furthermore, by applying flow-spoiled gradient pulses in the readout direction, a greater flow-dephasing effect can be obtained.

Figure 1 shows sequence diagrams of *(a)* the original readout gradient and *(b)* the readout gradient with flow-spoiled gradient pulses. The effect of flow-spoiled pulses on slow-flow vessels is presented in systolic triggering (Fig 2a) and in diastolic triggering (Fig 2b). The flow-spoiled gradient pulses cause the pulsatile flow blood to further dephase or become a flow void during systole but not during diastole as a result of reduced flow. In other words, the flow-spoiled gradient pulses do not affect the signal intensities of relatively immobile blood during diastole or stationary background tissues. Therefore, subtraction of these two sets of diastolic and systolic images provides arterial images.

Subjects

Fifteen consecutive healthy subjects (nine men and six women; age range, 25–42 years; mean age, 32.25 years) underwent flow-spoiled fresh-blood imaging in 22 peripheral arterial regions (iliac in seven cases, femoral in seven cases, calf in six cases, foot in one case, and hand in one case). Fifteen healthy subjects were recruited among personnel working in the MR imaging unit (ie, physicists, technologists, and physicians). They had no personal or family history of arterial diseases and had normal imaging results. In addition, a 69-year-old female patient suspected of having arteriosclerosis obliterans underwent flow-spoiled fresh-blood imaging before contrast-enhanced MR angiography. The institutional review board at the Diagnostic Imaging Center approved the study, and informed consent was obtained from all subjects.

Imaging Technique

MR angiography was performed with a 1.5-T silent MR imager (Pianissimo; Exelart/Prestige, Toshiba, Tokyo, Japan). A whole- body quadrature-detected coil was used for iliac, femoral, and calf studies, while a quadrature-detected brain coil was used for foot and hand studies. Before 3D acquisition, ECG preparation images (single sections in multiple phases) were acquired to determine the appropriate diastolic and systolic ECG delay times (6). Next, flow preparation images, single-shot MR images obtained with flow-spoiled gradients of varying strength, were acquired during systole and diastole. A sequence diagram of the flow preparation image is shown in Figure 3. To observe the flow-dephasing effect in each single-shot acquisition, the strength of the readout flow-spoiled pulses was varied from −10% to 40% in increments of 10%. The strength of a flow-spoiled pulse is a percentage of one-half the area of the readout gradient, which is equivalent to the area from the ramp up to the echo center of the readout gradient.

Flow preparation images were acquired during both diastole and systole with the following parameters: repetition time

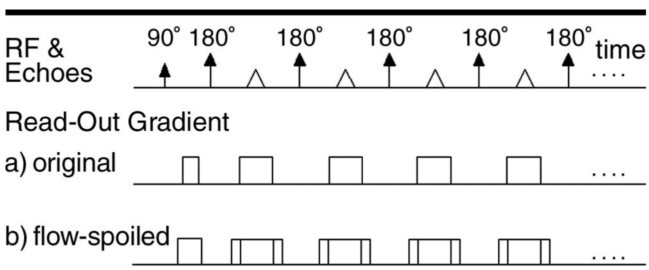

Figure 1. Sequence diagram of the readout gradient for the original readout and flow-spoiled gradients. *RF* = radio frequency.

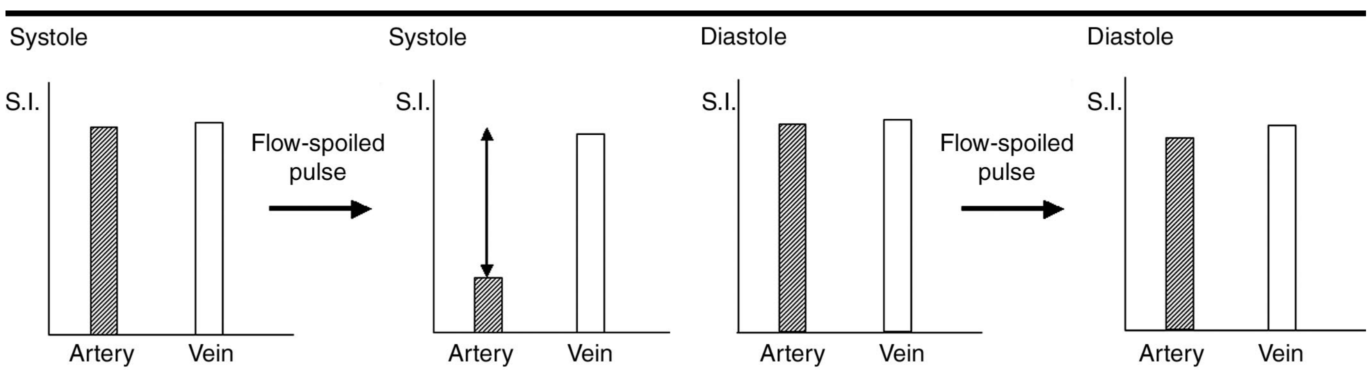

Figure 2. Schematic shows the effect of flow-spoiled gradient pulses on the signal intensity of slow-flow blood during **(a)** systole and **(b)** diastole.

msec/echo time msec/inversion time msec of 3 RR intervals/30 (effective)/190, echo train spacing of 5 msec, matrix of 128 × 256, one signal acquired, section thickness of 30–40 mm, field of view of 37 × 37 cm, six single-shot images with varying flow-spoiled gradient pulses, and a total acquisition time of about 15 seconds depending on the cardiac rate. After flow preparation images were acquired in diastole and systole, the appropriate strength for the flow-spoiled gradient pulses was determined on the basis of findings on the subtraction images obtained between diastole and systole. This pulse strength was applied in 3D acquisition to trigger every section encoding (Fig 4). Typical parameters for 3D acquisition were the following: 3 RR intervals/30/190, echo time spacing of 5 msec, matrix of 256 × 256, one signal acquired, section thickness of 3–5 mm, field of view of 37 × 37 cm, two shots, 15–30 section encodings, and a total acquisition time of 1.5–3.0 minutes. Both diastolic and systolic ECG-triggered 3D data were acquired with the same conditions. Interpolation in the section direction was performed to improve the spatial resolution.

After acquisition, the systolic source images were subtracted from the diastolic source images, and the subtracted images then underwent maximum intensity projection (MIP) processing. The total acquisition time was about 15 minutes, including acquisition of the scout, ECG preparation, flow preparation, and 3D images.

In contrast-enhanced MR angiography, 3D images were acquired after administration of 0.2 mL per kilogram of body weight of gadopentetate dimeglumine (Magnevist; Berlex Laboratories, Wayne, NJ) with the following parameters: 3.4/1.2, flip angle of 20°, 25 4.0-mm-thick sections, 128 × 256 matrix, and field of view of 30 × 30 cm. Flow-spoiled fresh-blood imaging was performed before contrast-enhanced MR angiography.

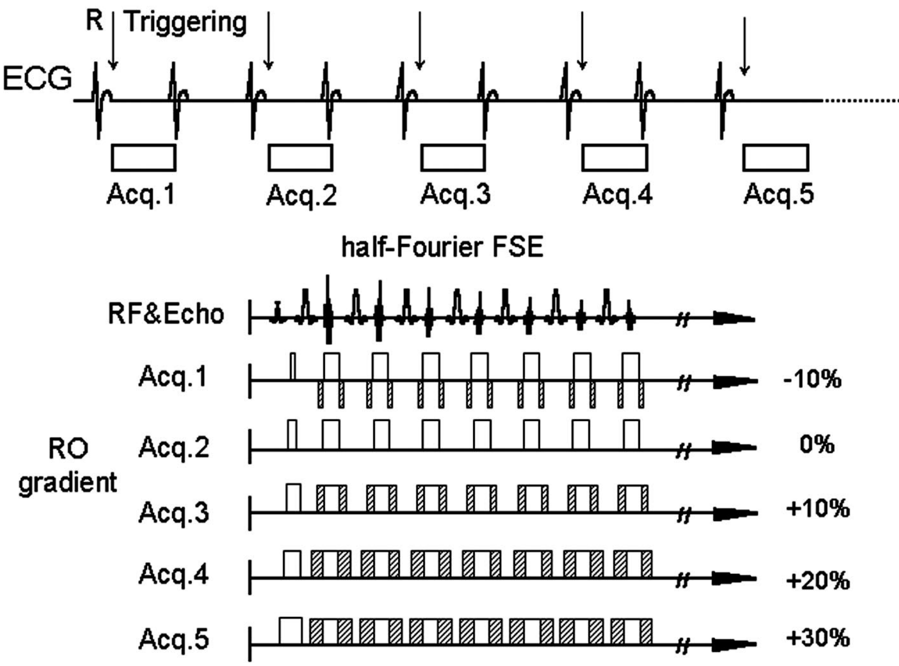

Figure 3. Sequence diagram of flow preparation imaging. To acquire six images with different flow-dephasing effects in each single-shot acquisition, flow-spoiled gradient strength in the readout direction was varied from −10% to 40% in increments of 10%.

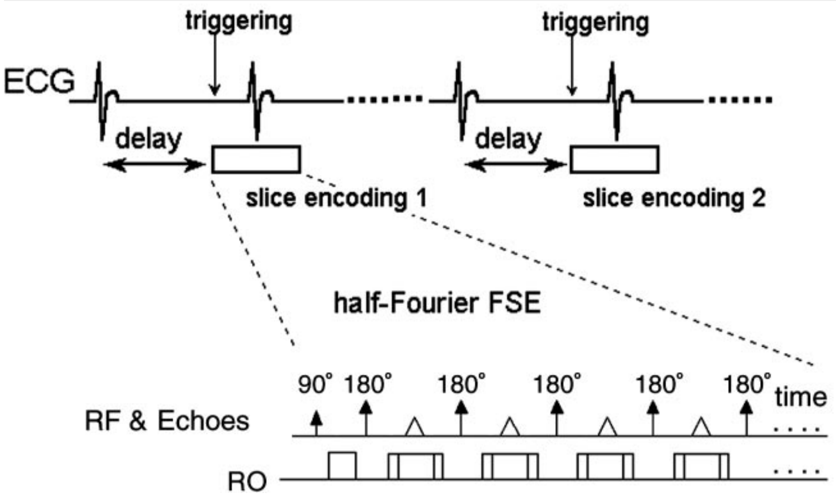

Figure 4. Sequence diagram of 3D acquisition with an appropriate flow-spoiled gradient strength. *FSE* = fast spin echo, *RF* = radio frequency, *RO* = readout.

Image Analysis

The strength of a flow-spoiled gradient pulse was determined on the basis of findings on subtracted projection images, as determined by three operators (M.M., H.W., R.K.). All 3D images were reviewed by one experienced radiologist (J.U.) and two radiology technologists (H.W., R.K.). In each case, the three readers independently evaluated the image quality of arteries in iliac, femoral, popliteal, tibial, foot, and hand images. They used a three-grade scoring system: good, no venous overlap and depiction of major arteries with good continuation; fair, some venous overlap or less depiction of major arteries; or poor, severe venous overlap, poor depiction of major arteries, or both. Final MIP images processed after subtraction were reviewed in terms of visualiza-

Image Quality of 22 Regions in 15 Subjects

Region	Score*			
	Poor	Fair	Good	Total
Iliac	0	1	6	7
Femoral	0	0	7	7
Calf	0	0	6	6
Foot	0	0	1	1
Hand	0	0	1	1
Total	0	1	21	22

Note.—Data are the number of cases.
* Good = no venous overlap and depiction of major arteries with good continuation. Fair = some venous overlap or less depiction of major arteries. Poor = severe venous overlap, poor depiction of major arteries, or both.

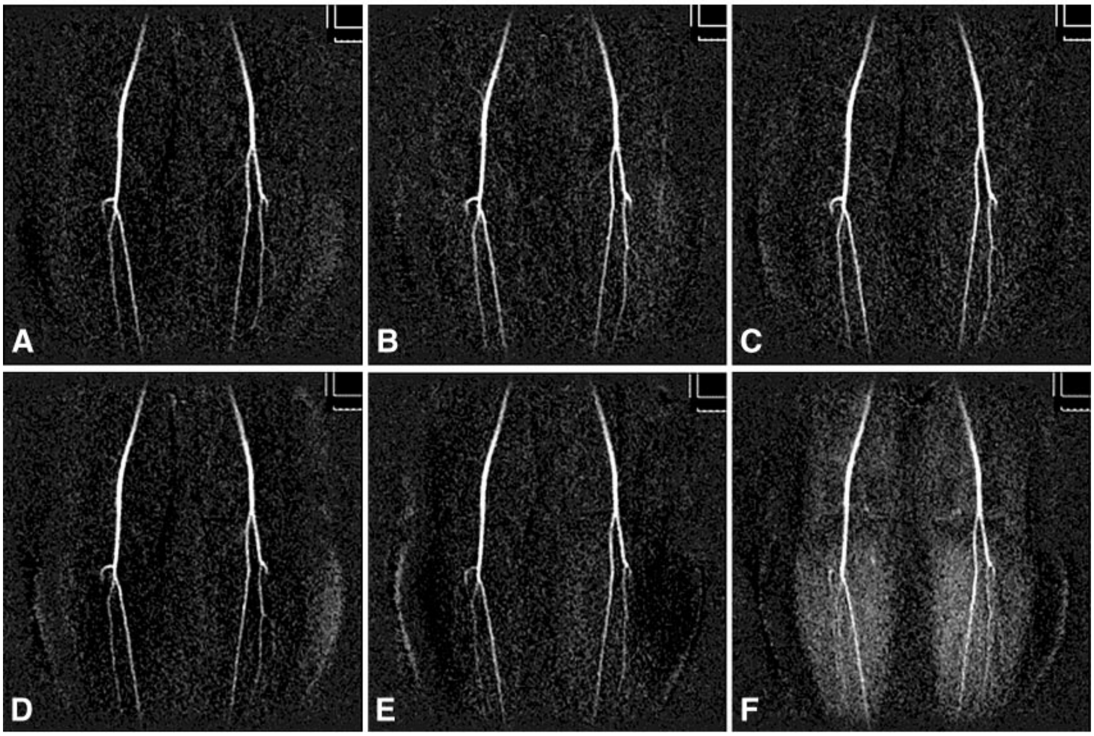

Figure 5. Flow preparation images obtained after diastolic and systolic subtraction were acquired with the following flow-spoiled gradient pulses: *A,* −10%; *B,* 0%; *C,* 10%; *D,* 20%; *E,* 30%; and *F,* 40%. The two-dimensional projection images were acquired with the following parameters: 3 RR intervals/30 (effective)/190, echo train spacing of 5 msec, matrix of 128 × 256, one signal acquired, section thickness of 30–40 mm, field of view of 37 × 37 cm, six single-shot images with varying flow-spoiled gradient pulses, and a total acquisition time of about 15 seconds. Note that an entire arterial tree of the femoral artery (faster inflow vessel) to the popliteal trifurcation is delineated most clearly in *B* and *C*.

tion of major arteries, venous overlap, and overall image quality. If a discrepancy occurred between the three readers, consensus was reached with discussion.

Results

Flow preparation images obtained after diastolic and systolic subtraction are shown in Figure 5. The femoral to popliteal trifurcation image was obtained with flow-spoiled gradient pulses from −10% to 40% in increments of 10%. The diastolic and systolic subtraction images of the flow preparation image are shown with flow-spoiled gradient pulses of −10%, 0%, 10%, 20%, 30%, and 40%. The signal intensity of the femoral region is high with a flow-spoiled gradient of 0%, but the popliteal trifurcation area is most clearly depicted at 10%. Images with stronger flow-spoiled pulses, such as 30% and 40%, show reduced signal intensity. A suitable flow-spoiled gradient strength of 0% or 10% was selected on the basis of the delineation of an entire arterial tree from the femoral artery to the popliteal trifurcation. In this case, the 5% flow-spoiled gradient was selected and applied in 3D acquisition. Three-dimensional source images obtained with a 5% gradient are shown in Figure 6. The diastolic images (Fig 6, *A, B*) show bright blood for both arteries and veins, whereas the systolic images (Fig 6, *C, D*) show bright-blood veins and black-blood arteries. Subtraction of the diastolic source images from the systolic source images followed by MIP processing provide an image that shows bright-blood arteries (Fig 6, *E*).

Results of the evaluation of flow-spoiled fresh-blood images obtained in the 22 regions in the 15 healthy volunteers are summarized in the Table. Image quality in the 22 regions was scored as good in 21, fair in one, and poor in none. In the one case scored as fair, the major iliac arteries were depicted, but $N/2$ artifacts were prominently seen (11). The $N/2$ artifact is a ghost that is shifted in the phase-encode direction by exactly half a field of view or $N/2$ points from the actual image.

Typical flow-spoiled fresh-blood images of the iliac and femoral regions are shown in Figure 7. The iliac artery image (Fig 7, *A*) was obtained with a 0% flow-spoiled gradient, which means no flow-spoiled gradient pulse, and the femoral artery image (Fig 7, *B*) was obtained with a 10% flow-spoiled gradient. Both images were scored as good.

In a patient with peripheral runoff, images were acquired with a 35% flow-spoiled gradient. Stereo-view MR angiograms of the foot are presented in Figure 8. The anterior and posterior tibial arteries, the peroneal artery, the dorsal arch, and even the digital branches are depicted. Therefore, image quality was scored as good.

In another case, an MR angiogram of the hand (not shown) was obtained with 25% flow-spoiled gradient pulses. The radial artery, the ulnar artery, the superficial and deep palmar arterial arches, and even the distal digital arteries were depicted. This MR angiogram was also scored as good.

Results in a female patient with arteriosclerosis obliterans are shown in Figure 9. Both the flow-spoiled fresh-blood image and the contrast-enhanced MR angiogram showed complete obstruction of the right superficial femoral artery and the collateral vessels. In addition, the

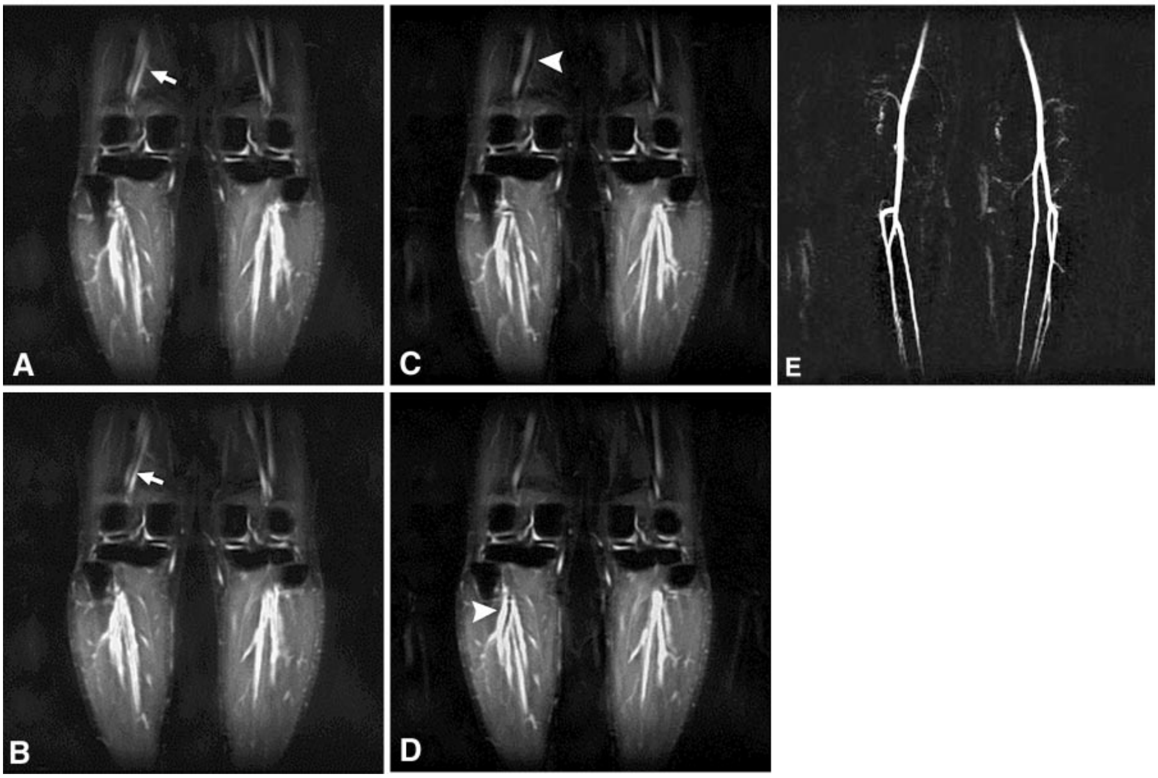

Figure 6. Three-dimensional source images of contiguous sections obtained with a 5% flow-spoiled gradient. *A, B,* Images acquired during diastole. *C, D,* Images acquired during systole. *E,* MIP image processed after diastolic and systolic subtraction. Note that the femoral arteries (arrows in *A* and *B*) are depicted as bright blood during diastole, whereas the femoral (arrowhead in *C*) and popliteal trifurcation arteries (arrowhead in *D*) are depicted as black blood or as flow voids during systole. The femoral and popliteal veins are depicted as bright blood in both diastole and systole. Images were acquired with the following parameters: 3 RR intervals/30 (effective)/190, one signal acquired, field of view of 37 × 37 cm, 3-mm-thick sections, two shots, 20 sections, and diastolic and systolic acquisition times of about 2 minutes each.

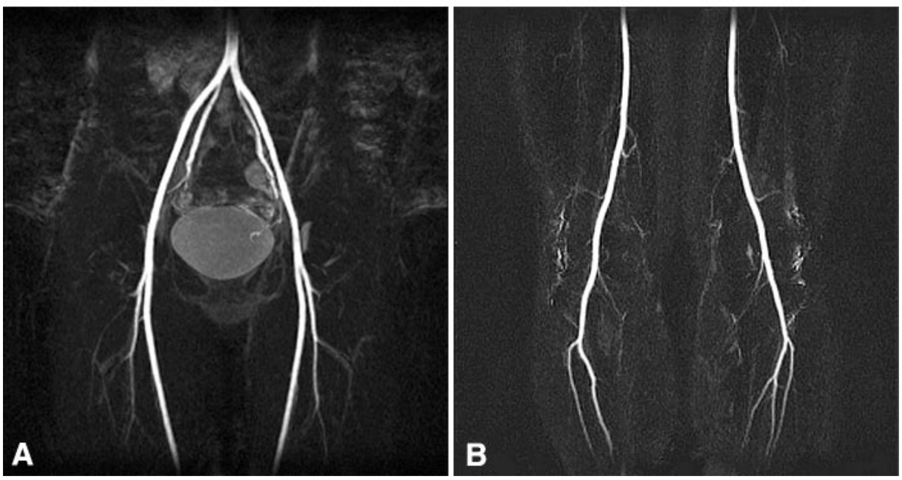

Figure 7. MIP images of the iliac arteries in one subject. *A,* Iliac region image acquired with a 0% flow-spoiled gradient. *B,* Femoral region image acquired with a 10% gradient from the femoral to the popliteal arteries. Depending on the flow velocity, a different flow-spoiled gradient was used. Images were acquired with the following parameters: 3 RR intervals/30 (effective)/190, one signal acquired, field of view of 38 × 38 cm, 5-mm-thick sections, two shots, 14 sections, and diastolic and systolic acquisition times of about 1.5 minutes each.

contrast-enhanced MR angiogram shows venous overlap of the great saphenous vein that was not seen in the flow-spoiled fresh-blood image.

Discussion

Flow-spoiled gradient pulses do not affect the signal intensity of stationary background tissues. In addition, veins are similarly less affected by the flow-spoiled pulses during diastole and systole as a result of their relatively constant slow flow throughout the cardiac cycle (6). Therefore, by applying the flow-spoiled pulses, the signal intensity difference between diastole and systole in arteries is increased. Thus, diastolic and systolic subtraction provides better delineation of the arteries. The strength of the flow-spoiled gradient pulses differs depending on the flow speed in the vessels. Arteries with slower flow necessitate use of stronger flow-spoiled gradient pulses to differentiate their signal intensities during diastole and systole.

Flow preparation imaging is a fast and useful method for determining the appropriate flow-spoiled gradient strength without acquiring the 3D data. For relatively fast flow, such as in the abdominal aorta and the iliac arteries, a 0% flow-spoiled gradient was applied, which resulted in slight $N/2$ artifacts in the phase-encode direction (11). A small negative flow-spoiled readout gradient or a flow-compensation–like pulse may be required. Thus, selection of the appropriate flow-spoiled gradient is an important factor in determining image quality. In addition, even a slightly stronger flow-spoiled gradient affects the visualization of slow-flow branch arteries. Particularly for the extremely slow flow in the foot, stronger flow-spoiled gradient pulses were applied to improve the arterial images.

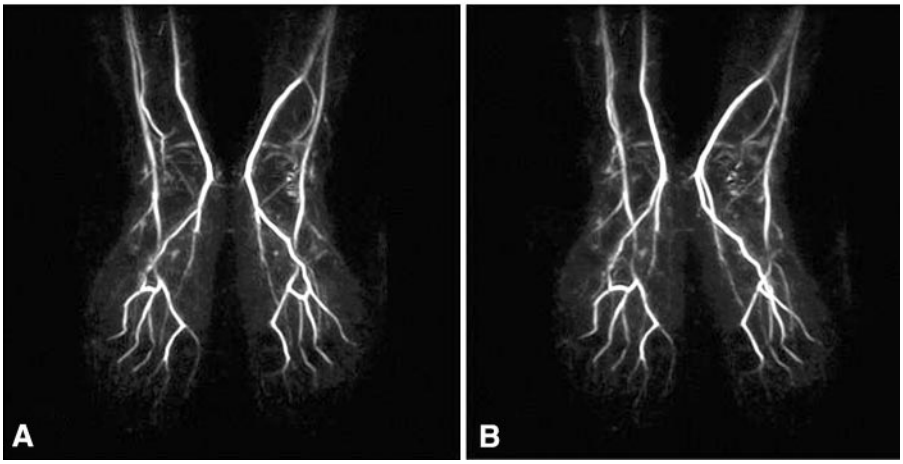

Figure 8. Stereo-view MR angiograms in the foot. *A,* Coronal image. *B,* Coronal-sagittal image rotated 6°. Images were acquired with a 35% gradient with the following parameters: 3 RR intervals/30 (effective)/190, one signal acquired, field of view of 35 × 35 cm, 2-mm-thick sections, two shots, 40 sections, and diastolic and systolic acquisition times of about 4 minutes each. Images were processed with interpolation in all three (section, phase-encode, and readout) directions to improve spatial resolution. Note that a strong flow-spoiled gradient permits delineation of slow-flow vessels, such as the anterior and posterior tibial arteries, the dorsal arch, and even the digital branches.

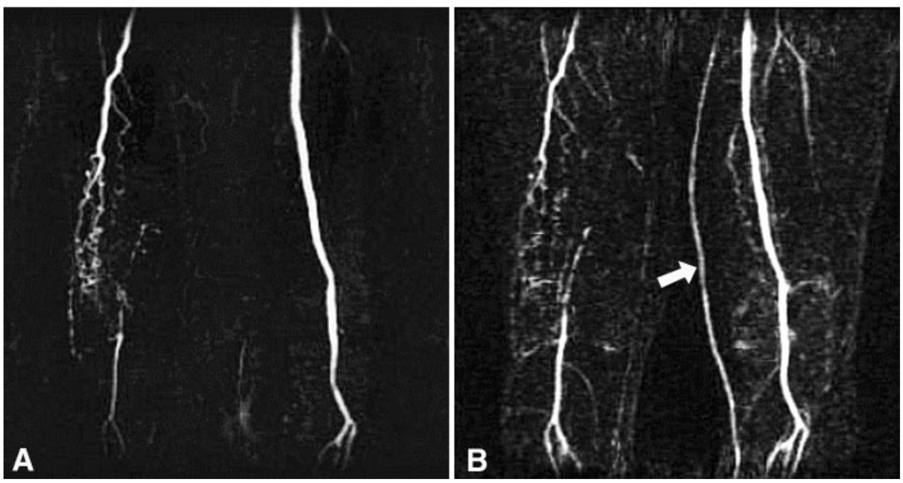

Figure 9. Femoral region MIP images in a female patient with arteriosclerosis obliterans. *A,* Flow-spoiled fresh-blood MR image obtained with a 10% flow-spoiled gradient with the following parameters: 3 RR intervals/30 (effective)/190, one signal acquired, field of view of 30 × 30 cm, 4-mm-thick sections, two shots, 20 sections, 256 × 256 matrix, and diastolic and systolic acquisition times of about 2 minutes each. *B,* Contrast-enhanced MR angiogram obtained after injection of 0.2 mL/kg of gadopentetate dimeglumine, with the following parameters: 3.4/1.2, flip angle of 20°, 4.0-mm-thick sections, 25 sections, 128 × 256 matrix, and field of view of 30 × 30 cm. Both images show collateral vessels, but venous enhancement of the great saphenous vein (arrow in *B*) in the left normal leg is not seen in *A*.

Flow-spoiled fresh-blood imaging provides a spatial resolution of 1.4 × 1.4 mm (in the phase-encode and readout directions) for acquisition with a 256 × 256 matrix, whereas contrast-enhanced MR angiography provides a spatial resolution of 2.8 × 1.4 mm (in the phase-encode and readout directions) for acquisition with a 128 × 256 matrix. With the nonenhanced technique, collateral vessels were clearly depicted with a 10% flow-spoiled gradient. With contrast-enhanced MR angiography, however, images of the left normal leg showed the venous phase, which may be a result of the faster transit time of gadopentetate dimeglumine in the normal leg.

The two-dimensional time-of-flight technique has been used to evaluate peripheral vascular disease in the foot and ankle (12). However, the acquisition time is longer than that with our method. Flow-independent peripheral angiography with T2 preparation shows promising results, but separation of arteries from veins is limited (13). Our technique is based on simple subtraction and MIP processing; these techniques are readily available in the main MR imager console. Therefore, neither additional software nor an offline processing system is required for image processing. In the present study, we acquired a relatively large number of sections to improve the spatial resolution of the section direction. Reducing the number of sections by acquiring thick sections allows a further reduction in acquisition time. Advantages of this technique include a reduction in the acquisition time compared with that in time-of-flight and ECG-triggered spin-echo imaging, the ability to obtain high-spatial-resolution peripheral images, and the ability to visualize both diastolic and systolic MR angiograms. Most important, the method is easy and fast to use, and it permits repeated imaging because no contrast agent is required.

In conclusion, the nonenhanced peripheral MR angiographic technique with flow-spoiled gradient pulses allowed distinction of arteries from veins and provided promising results in healthy volunteers. The total acquisition time was about 15 minutes, including scout, ECG preparation, flow preparation, and 3D acquisitions. This method shows promise for the evaluation of extremely slow-flow runoff. In healthy volunteers, determination of the flow-spoiled gradient strength is important, especially in the iliac region where flow is faster. This may vary in vessels with slower flow. Further clinical studies are required to clarify the clinical usefulness of this diagnostic imaging technique.

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