

Comparison of Auto-moving Table Contrast-enhanced 3-D MRA and Iodinated Contrast-enhanced DSA for Evaluating the Lower-extremity Arteries

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Key Words

arterial occlusive diseases;
digital subtraction angiography;
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Background. This study was conducted to compare diagnostic efficacy of contrast-enhanced 3-dimensional magnetic resonance angiography (3-D MRA) with that of the conventional x-ray iodinated digital subtraction angiography (DSA) in patients with peripheral arterial occlusive diseases (PAOD).

Methods. Twenty patients with a clinical diagnosis of PAOD participated in this study. All patients were evaluated with both contrast-enhanced 3-D MRA and conventional x-ray iodinated DSA for the arteries of their lower extremities. The DSA was performed by a selective catheterization into the bilateral common or superficial femoral arteries, whereas 3-D MRA was performed with an auto-moving table covering the vascular tree from aorta to the arteries of ankle regions with 1 bolus injection of a triple-dose (0.3 mmol/kg) contrast medium. The arteries were divided into 23 anatomic segments and graded by their appearance on a 1-4 scale (1 = normal, 4 = total occlusion or no visible vessel). Evaluators also compared the images of 3-D MRA with those of the conventional x-ray iodinated DSA (as gold standard) with respect to image quality.

Results. There was a high agreement ($k = 0.6 - 1.0$) between 2 observers' interpretations of the images obtained from 3-D MRA and conventional DSA. The agreement within each observer was moderate to fair ($k = 0.32 - 0.57$), and the better agreement was found with the images above knee level than those below knee level. As for the image quality of 3-D MRA, the frequencies of showing a similar image quality were 57.5%, 55%, and 37.5% at the aortofemoral, femoropopliteal, and distal leg levels, respectively.

Conclusions. The main problem of the 3-D contrast enhanced MRA was the returned venous contamination of the image. It was particularly problematic for the areas below knee level. MRA can provide an initial evaluation for patients with PAOD, but cannot substitute for the conventional DSA as a precise diagnostic image modality for peripheral vascular diseases, especially for the distal legs.

Peripheral arterial occlusive disease (PAOD) is a common problem in the aged population. Patients with PAOD may suffer from claudication, rest pain, ulceration, and even gangrene of toes that eventually leads to amputation. To develop an appropriate treatment plan for patients with PAOD, precise imaging of the peripheral vessels is essential. Conventional x-ray iodinated digital subtraction angiography (DSA) has been the gold standard for evaluating peripheral vascular structures for decades. This standard technology, however, has several

disadvantages. First, reports have shown a potential risk of hypersensitivity and contrast-induced nephrotoxicity, especially in patients with a prior history of abnormal renal function and diabetes mellitus.¹ Second, there are procedure-related complications, such as hematoma, vascular dissection, arteriovenous fistula, acute arterial thromboemboli, and infection. Third, it takes time to recover after such an invasive procedure.

Magnetic resonance (MR) imaging has been used as a tool supplementary to DSA. Due to new advances in

MR technology, MR imaging has become more promising in evaluating peripheral vascular structures. For example, the auto-moving table allows radiologists to image longer vascular segment without the limitation of field-of-view (FOV). The faster scanning pulse sequence provides a quicker data acquisition in 1 bolus injection of contrast medium and, consequently, reduces venous contamination. Auto-queuing of pulse sequences provides more freedom to adjust FOV, spatial resolution, and scanning time. Research has shown that sensitivity and specificity for grading hemodynamically significant stenosis ($\geq 50\%$ lumen reduction) on magnetic resonance angiography (MRA) were 94% and 93%, respectively.² One study suggested that MRA was superior to DSA in revealing patent vessel segments of the foot of diabetic patients with severe arterial occlusive disease.³

Because of the increasing use of MR imaging for the assessment of peripheral vascular structures, this study was designed to compare diagnostic efficacy of contrast-enhanced 3-dimensional MRA against the gold standard, i.e. conventional x-ray iodinated DSA, on patients with PAOD. The terms 3-D MRA and DSA will be used hereafter to refer to contrast-enhanced 3-dimensional magnetic resonance angiography and conventional x-ray iodinated digital subtraction angiography, respectively.

METHODS

Patients

From April 2001 to March 2002, 20 patients diagnosed with PAOD were enrolled into this study. Fourteen of them were males. The mean age of the patients was 75 years with a range of 60-82 years. All 20 patients received selective DSA and 3-D MRA. All patients signed written informed consent.

Procedures

MRA

All MR imaging was performed on a 1.5-T system (Signa CVi; GE Medical Systems, Wisconsin, USA) equipped with an auto-table moving system, software of SmartPrep, and the elliptic-centric k-space acquisition technique. The gradient strength was 40 G/cm (mT/m),

and the slew rate was 150 T/m/sec. For the 3-D MRA, 3-D fast spoiled gradient-echo (3-D FSPGR) coronal images with the following parameters were used: TR/TE = 4.6/1; bandwidth = 41.67 kHz; flip angle = 20 degrees; matrix = 256×160 ; ZIP $\times 2$; ZIP = 512; effective section thickness = 4-10 mm; rectangular field of view = 400mm; and the coronal 3-D volume = 80-120 mm in anteroposterior thickness.

Patients were positioned in a supine position with feet first and wrapped over their knees and ankles to eliminate motion. Peripheral vascular phased array coil and an auto-table moving system in 1 single bolus were used to obtain continuous 3-station image data. FOV of 40 cm and an overlap of 4 cm between stations provided anatomical coverage from renal arteries to feet. During the imaging process, we adjusted scanning plans coordinating to each individual patient's vascular trend to minimize the scan time. We were able to reduce the number of contiguous section to a minimum (Fig. 1).

Among the 3 stations, the first 2 stations were scanned with Spectral Inversion at Lipid (SPECIAL) technique, a pulse sequence that offers a rapid and robust method to generate fat-suppressed images. The images of the third station were acquired by the elliptic-centric k-space acquisition technique that fills the center portion of k-space (with the greatest signal to noise) in the first 1 eighth of the total scan time. Non-contrast images were acquired first. For the post-contrast images, we administered triple dosages (0.3 mmol/kg) of gadodiamide injection (Omniscan; Nycomed, Buckinghamshire, UK) via an MR-compatible injector (Spectris; Medrad, Indianola, PA) at a rate of 2 mL/sec for the first 2 doses, following by a rate of 1 mL/sec for the third dose. Then a subsequent flush of 20 mL of normal saline was administered through a 20-21 gauge intravenous cannula in the antecubital vein.

SmartPrep is a tracking pulse sequence that can continuously monitor MR signals that come from a user-prescribed volume of interest in the patient. We placed the localizer above the aortic bifurcation in 2 cm on axial images. When signal amplitude exceeds the contrast dose-dependent threshold, the pulse sequence checks the signal and automatically initiates the preselected protocol. In our study, we used SmartPrep to automatically detect bolus arrival and initiate data acquisition. MR angiographic data sets were postprocessed on the operating consoles. MIP

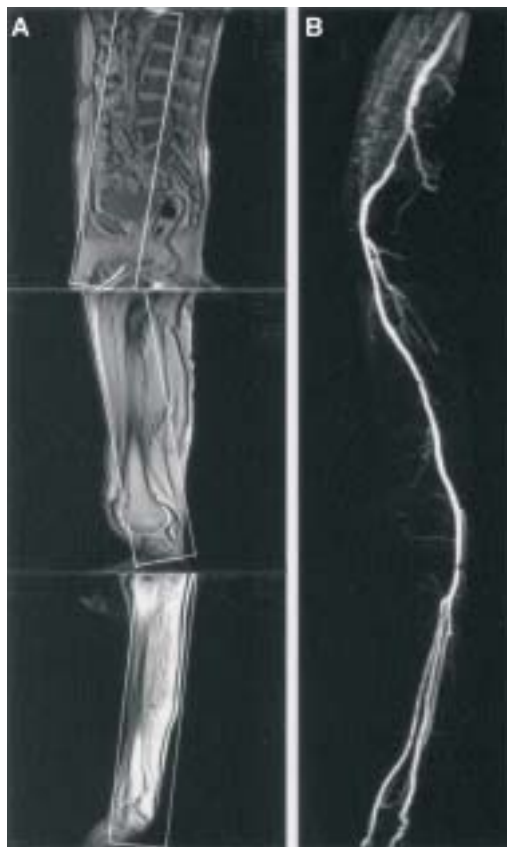


Fig. 1. Image A: Sagittal scout images of lower extremity. We applied oblique scanning plans on scout images (white square lines), which coordinated to the vascular trend. Image B: True lateral images of 3-D MRA. From this image, we can realize that the lower extremity arteries run anteriorly from aortic bifurcation, then posteriorly to popliteal fossa and finally distribute to the distal leg anteriorly and posteriorly.

(Maximum Intensity Projections) of the subtracted images was rendered which contained the area from the lower abdominal aorta to distal runoff vascular territories of the ankle region.

DSA

All the patients received DSA of the pelvic and lower extremity vessels within 72 hours after MRA on 1 standard angiography unit (MultiDiagnost 3 Image Intensified Fluoroscopic X-Ray System; Philips Medical Systems, Best, Netherlands). Since a nonselective injection is inadequate to opacify the diseased vessels, especially in the distal runoff,^{4,5} the optimized diagnostic angiographic procedure suggested by Gates⁶ was adopted as our standard angiographic method. The bilateral lower extremity arteriography was performed by advancing a 4 Fr Cobra catheter (Cook, Bloomington, IN.) or 4 Fr RIM catheter (Cook, Bloomington, IN.) to cross over the aortic bifurcation into common iliac and then common or superficial femoral arteries to study the contralateral limb. After that, the catheter was pulled back for ipsilateral imaging. The contrast volumes and injection rates in each level are shown in Table 1. Approximately 35% of the nonionic contrast medium contrast agent was used (Iopamiro 370 or Ultravist 370 was diluted by normal saline with 1:1 ratio). The biplane angiography of distal calf vessels with frontal imaging perpendicular to the interosseous membrane was taken. Patients' feet assumed the natural po-

Table 1. Parameters of conventional X-ray iodinated DSA

Location & projection	Catheter tip	Iodinated contrast medium	
		rate (mL/sec)	volume (mL)
Pelvic vessels PA projection	Common iliac	10	25
Common & upper femoral PA projection	Common iliac	3-4	6-8
Lower superficial femoral PA projection	External iliac	3	9
Popliteal artery & trifurcation PA projection	External iliac	3	12
Distal leg PA projection	External iliac	3	15
Ankle and foot (Dorsalis pedis & plantar) True lateral	External iliac	3-4	18-24

DSA = digital subtraction angiography.

sition without any external compression. This method was adopted to avoid pseudo-occlusion. No peripheral vasodilator was used during the procedure.

Image analysis

Two radiologists who had experience in MRA and DSA reviewed each patient's images obtained from MRA and DSA. They independently conducted their reviews and were blinded to each other's evaluation. The arterial trees were divided into 23 segments. Each segment was categorized and graded using the following scale: 1 = normal appearance; 2 = less than 50% of stenosis of vessel diameter; 3 = equal or greater than 50% of stenosis of vessel diameter; and 4 = total occlusion or no visible vessels. Using DSA images as the standard, 2 radiologists also rated the diagnostic confidence and quality of MRA as good, fair, or non-diagnostic. Without any knowledge of the prior results, they reviewed all of the MRA and DSA images again 1 month after their first evaluation. A consensus reading on the DSA images was conducted by 2 other radiologists. Cohen's kappa statistics were used to assess the 2 radiologists' agreement and consistency within their observations.

RESULTS

The analysis showed that most of the inter-observer

agreements with DSA and 3-D MRA images had Cohen's kappa from 0.6 to 1.0, which suggested good to excellent agreement between the 2 radiologists. The DSA images taken in the anatomic level of plantar artery had Cohen's kappa $k = 0.50$. Cohen's kappa for the 3-D MRA images in the anatomic level of profunda femoral artery was only $k = 0.46$. With respect to the consistency within the radiologists' observations, the result showed better consistency with images taken above knee level than below knee level. The Cohen's kappa ranged from $k = 0.32$ to $k = 0.57$, which suggested moderate to fair agreements. The worst consistency was with the images of the profunda femoral ($k = 0.15$) and dorsalis pedis arteries ($k = 0.25$). More information is listed in Table 2.

As for the quality of 3-D MRA images (Fig. 2), in the aortofemoral and femoropopliteal levels, the 3-D MRA images had image quality equal to that of DSA, at 57.5% (23/40) and 55% (22/40), respectively. The only MRA image that was superior to the DSA image came from a patient who had Leriche syndrome with a total occlusion at bilateral common iliac arteries. This patient's MRA was able to depict his arteries below the occlusion; yet that was not the case with his DSA image (Fig. 3). Additionally, the distal leg had relatively poor image quality, and 5 of the 20 patients revealed a substantial venous overlay in the calf and foot regions. Only 37.5% (15/40) of the 3-D MRA images showed image quality equal to that of DSA. Malfunction of

Table 2. Interobserver and intraobserver agreement

	Interobserver agreement		Intraobserver agreement	
	DSA	MRA	Reader 1	Reader 2
	Reader 1 vs. Reader 2	Reader 1 vs. Reader 2	DSA & MRA	DSA & MRA
	Kappa	Kappa	Kappa	Kappa
Lower abdominal aorta	0.69	0.79	0.88	0.79
Common iliac	0.84	0.77	0.49	0.61
External iliac	0.86	0.74	0.64	0.69
Internal iliac	0.82	0.80	0.36	0.45
Pro. femoral	0.75	0.46	0.15	0.32
Superficial femoral	0.92	0.85	0.55	0.75
Popliteal	0.60	0.64	0.36	0.57
Anterior tibial	0.77	0.74	0.53	0.53
Peroneal	0.77	0.76	0.44	0.54
Posterior tibial	0.73	0.64	0.39	0.43
Dorsalis pedis	0.85	0.82	0.52	0.25
Plantar	0.50	0.93	0.45	0.47

DSA = digital subtraction angiography; MRA = magnetic resonance angiography.

SmartPrep occurred in 1 case. As a result, the scan time was delayed and that subsequently led to obvious venous contamination in the distal leg region. One case in our study had an unsatisfying subtraction image of 3-D MRA at the third station due to involuntary jerks.

Bowel gas obstacle blurring the pelvic vessels occurred in 3 patients. The quality of their 3-D MRA images was degraded. Further, the results showed that 3-D MRA had a tendency to overestimate stenosis compared to DSA (Fig. 4).

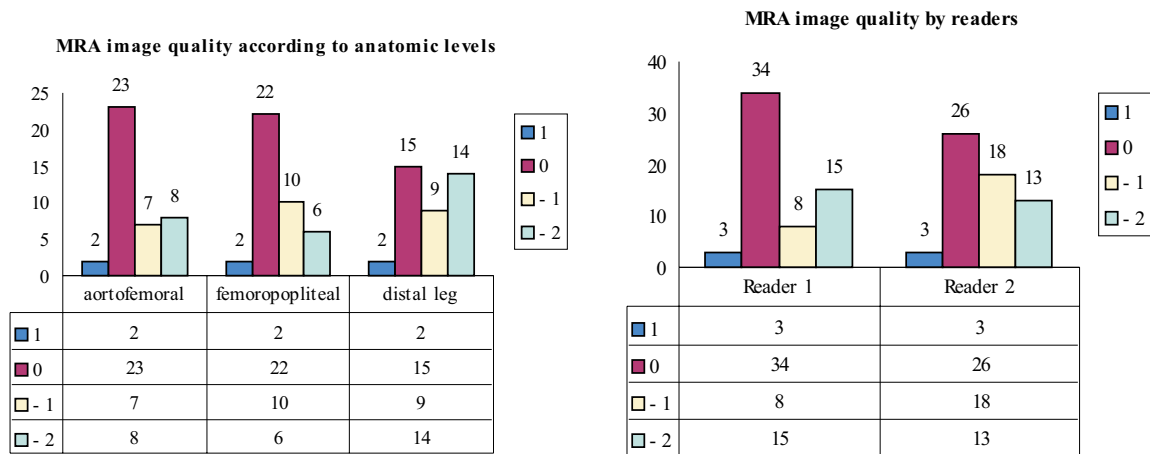


Fig. 2. DSA = digital subtraction angiography; MRA = magnetic resonance angiography; 1 = Image quality of 3-D MRA better than that of conventional DSA; 0 = Image quality of 3-D MRA equal to that of conventional DSA; -1 = Image quality of 3-D MRA worse than that of conventional DSA but could provide diagnostic information; -2 = Image quality of 3-D MRA worse than that of conventional DSA and could not provide diagnostic information.

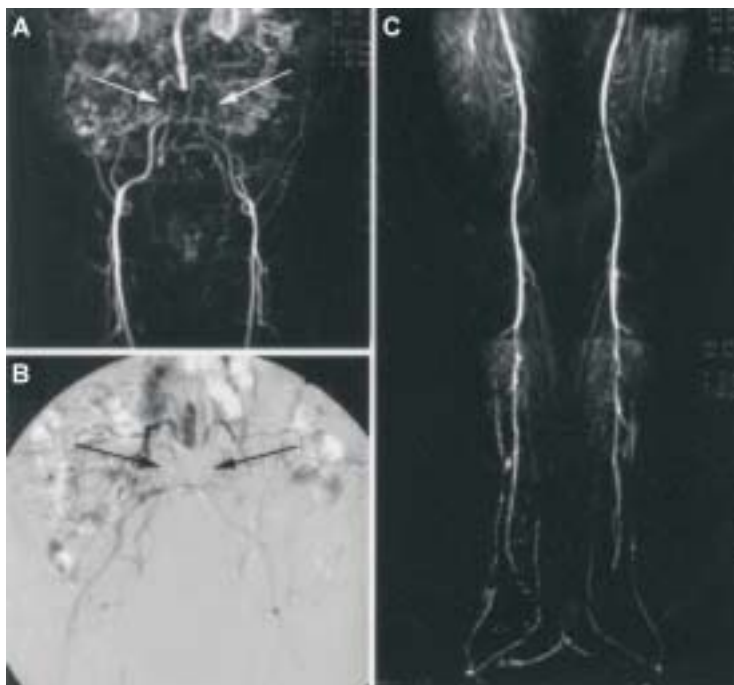


Fig. 3. A 78-year-old man with intermittent claudication and absent bilateral femoral pulses. Iodinated DSA (image B) showed total occlusion of aortic bifurcation (black arrows). 3D-MRA (image A) showed same finding at aortic bifurcation (white arrows), but recanalization of bilateral lower extremity arteries including external iliac, profunda femoral, superficial femoral, and distal run-off were noted, which couldn't be evaluated at iodinated DSA examination.

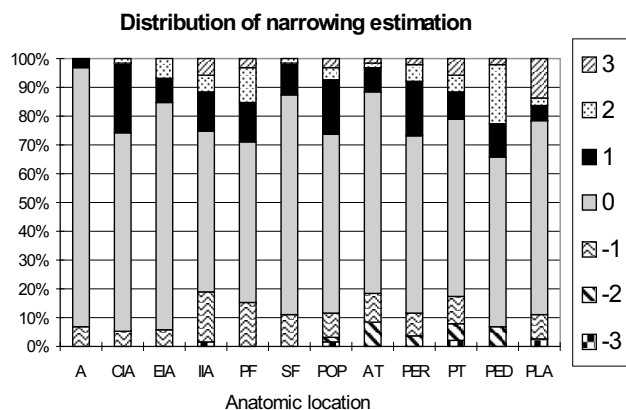


Fig. 4. The digits here represent stenotic grade of MRA subtracting from that of iodinated DSA (stenotic grade: 1 to 4, from normal to total occlusion). Negative values mean underestimation of the stenosis, positive values mean overestimation of the stenosis, and zero value means no estimation difference, using iodinated DSA as a standard. MRA has the tendency to overestimate the stenosis. (A = aorta; CIA = common iliac; EIA = external iliac; IIA = internal iliac; PF = profunda femoral; SF = superficial femoral; POP = popliteal; PER = peroneal; AT = anterior tibial; PT = posterior tibial; PED = dorsalis pedis; PLA = plantar artery).

Among the 20 patients, 1 patient’s most superficial part of the external iliac artery was not included in the scanning volume, which caused a pseudo-occlusion in 3-D MRA. No significant complication or drug allergy occurred when performing 3-D MRA and iodinated DSA. The only issue with 3-D MRA was that 5 patients complained of leg soreness after 1 hour of MR examination.

DISCUSSION

MRA has been used to evaluate PAOD for a long time.⁷⁻¹⁰ However, large anatomic coverage of lower extremities (100~110 cm), spatial resolution for detecting small vessels with atherosclerotic lesions, such as the calf and foot regions, and a long scanning time are major challenges faced by MRA. Nowadays, due to rapid progression in the hardware and software of MR scanners, dedicated evaluation in the whole course of lower extremities, including infrarenal abdominal aorta, can be achieved in 1 single contrast injection by using an auto-moving table 3-D MRA (Fig. 5). The purpose of this study was to use the new 3-D MRA to evaluate the

lower-extremity vascular diseases.

As discussed in other studies, because of the availability of a dedicated phased-array peripheral vascular coil, signal-to-noise consideration is no longer a concern. To have a high-quality image, it is crucial to have the contrast media arrive in the anticipated vascular locations and accurately trigger the scanning process. Radiologists used to use a test bolus with 2-5 mL contrast media to estimate the main bolus arrival time.¹¹ With new software such as SmartPrep used in our study, the automated detection of bolus arrival and initiation of data acquisition has become more efficient.^{12,13} It is possible to inject all of the contrast media at once. When the contrast media reaches the vessels, the machine is activated to scan. One case in our study, however, failed to trigger the scanning process automatically. It may be due to incorrect placement of the trigger volume or inconsistent sampling positions that were caused by respiration motion or electronic noise spikes.

Better signal-to-noise and contrast-to-noise ratios can be achieved by mechanical contrast medium administration with a high injection rate (2 mL/s), followed by a normal saline flushing.^{14,15} Most investigators, including us, used at least double (0.2 mmol/kg)² or more (0.3 mmol/kg)¹⁶⁻¹⁹ dosage of contrast agents to perform peripheral MRA. However, some studies have demonstrated the same good image quality with a low-dose contrast medium administration.²⁰⁻²² There are several advantages to using a reduced dose (0.1-0.2 mmol/kg) instead of a high dose (0.3 mmol/kg) for 3-D MRA. First, the maximum safety dose in human has not been tested. Second, the cost of the procedure will decrease substantially (the cost for 20 mL of contrast medium is approximately NT \$4,000). Third, even if a low dose of contrast medium is given later on, the diagnostic usefulness or overall image quality does not change significantly.²³ As is known, a higher contrast-to-noise ratio can be predicted with a high-dose than a low-dose contrast medium administration. However, given the advantages of reduced dosages, it is worthwhile further comparing the dose effects (high vs. low) on the clinical interpretations of the images.

Subtraction MRA provides higher contrast-to-noise ratios, fewer artifacts, and easier image interpretability than nonsubtracted MRA does.^{24,25} To have the best result

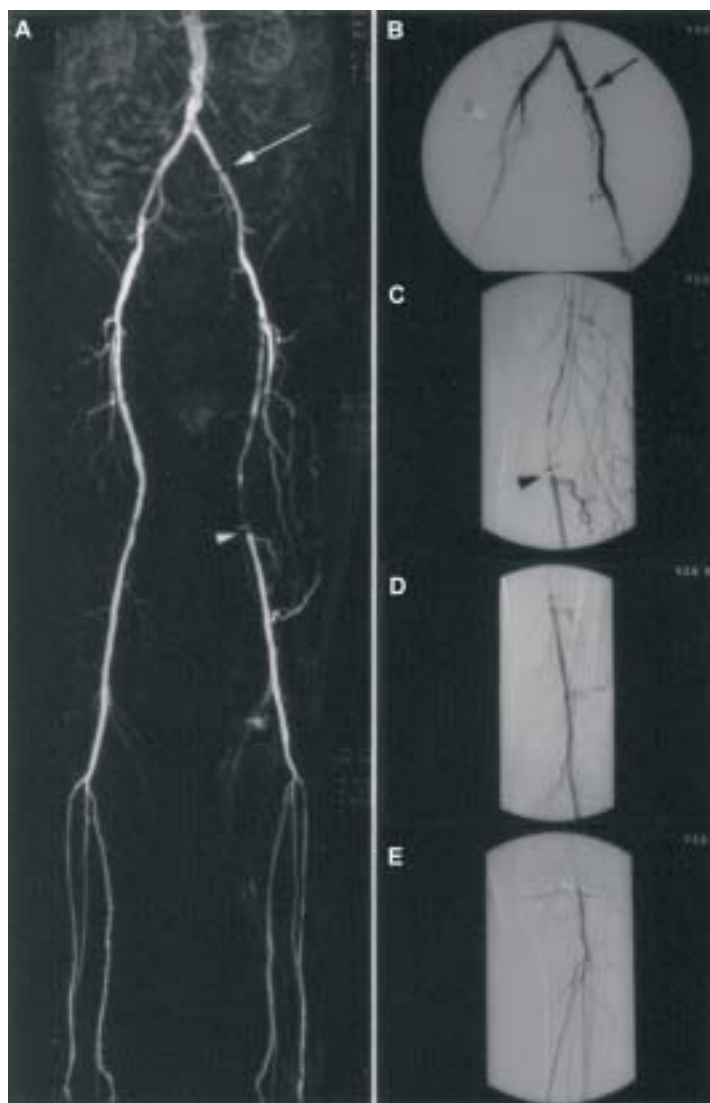


Fig. 5. A 75-year-old man with left leg claudication. 3D-MRA showed severe stenosis at distal common iliac artery (white arrow in image A), long segmental luminal narrowing of proximal superficial femoral artery (white arrow head in image A), recanalization and patency of the distal superficial femoral and popliteal arteries, as well as trifurcation and distal run-off. Iodinated DSA showed corresponding findings at the pelvic region (black arrow in image B), proximal thigh (black arrow head in image C), popliteal region (image D) and trifurcation (image E).

of subtraction, both images ought to show the same location. Thus, precision in reproducing the patient's positions is essential. Because the lower extremities (100-110 cm) are more than twice longer than an MR scanner's scanning range (40 cm), the moving table system was developed to solve the problem of long anatomic coverage. Some manual table-moving devices were also developed for this purpose.²⁵⁻²⁷ In comparison to the mechanically automatic table-moving system, occasionally the manual table-moving system fails to perform a satisfactory subtraction. This is due to the fact that the latter cannot pre-

cisely locate the same position before and after the contrast medium administration. Additionally, extra personnel are needed to perform the procedure.²⁶ Although the automatic table-moving system and fixation of patients' legs can reduce patients' motion to the least possible, 1 case in our study still had an unsatisfactory subtraction image of 3-D MRA at the third station. This patient was diabetic and had involuntary jerks. Pain may be another reason that caused this patient's motion. A liberal use of sedatives and appropriate use of analgesics for pain management to minimize patients' motion can be considered

in the future.²⁶

Fat suppression technique is another choice for increasing signal-to-noise and contrast-to-noise ratios. Because most tissues have fat, when the signals from the fat are suppressed, the background noise can be decreased. The sensitivity and specificity of the fat suppression technique is similar to that of the subtracted images. The only trade-off of this technique is a slight increase in the examination time.²⁴ Now we routinely use the SPECIAL technique at the first 2 stations to offer a rapid and robust method to generate fat suppressed images. Once poor subtracted images result from motion, fat suppressed images provide another choice for clinical evaluation. At the last station, we utilize the Elliptic-Centric K-Space Acquisition technique. This technique fills the center portion of the k-space in the first 1 eighth of the total scanning time and catches the arterial phase with a minimal venous overlay.^{17,28,29}

In our study, venous contamination in the calf and foot regions decrease the image quality and seriously interfered with the interpretation of arterial distal run-off. We assumed that scanning time might have not been brief enough to catch only the arterial flow. We tried to decrease the scanning time at each station in some of our patients afterwards. First, as in Fig. 1, we decreased 2-3 seconds of acquisition time by tailoring the obliquity and dimensions of each 3D volume along the vascular structure instead of orthogonal 3-D volume along the scan table to encompass the desired vascular anatomy with minimal phase-encoding steps.³⁰ However, if the desired anatomic location is not well covered, the desired vascular structures may not be included in the scan. The exclusion of the most superficial region of the common femoral artery occurred for 1 of our patients in the study. Second, we increased the slice thickness from 4 to 8 or even 10 mm. This change dramatically shortened the acquisition time by 5 to 6 seconds at each station. We applied this change to 6 patients afterwards. However, the downside of this approach was decreasing the spatial resolution and having zigzag appearances in the rotary MIP reconstruction. Third, we adjusted the FOV in the phase encoding direction according to the width of the patient on the coronal image. Depending on the patient's volume and anatomic locations, the saved length of time ranged from 2 to 6 seconds. Using the abovementioned meth-

ods, we reduced the scanning time from 70-86 seconds to 40-50 seconds. Although these methods did not work on every patient, particularly those who had severe stenosis and occlusion, we experienced less venous contamination after the changes were made.

In 3 healthy volunteers, we found that the total scanning time was longer (56 to 86 seconds), but there was little venous signal contamination in the distal leg region. In this study, 5 of the 20 patients revealed a substantial venous overlay in the calf and foot regions. Patients with PAOD seemed to have more rapid venous return than healthy people did. The accelerated arteriovenous transit time, which may be associated with arteriovenous malformation, arteriovenous fistula, and abnormal tissues that alter circulation (egg, cellulites, tissue hyperemia, and osteomyelitis), may have caused the venous signal contamination at the 3-D MRA distal station in the PAOD patients. Moreover, a lower cardiac output and vascular pathologies in abdomen and pelvis, such as aortic or iliac artery occlusion, large aortic aneurysms, dissections, and severe occlusive diseases, can substantially alter the arterial enhancement kinetics.³¹ One study also reported that a major potential limitation of bolus-chase 3-D MRA may be the different bolus velocities in the right and left legs.³²

Due to the potential complex hemodynamic condition in arterial enhancement, some acquisition strategies have been recommended. One strategy is multiphase acquisitions of the abdominal and pelvic regions. The purpose is to avoid incomplete enhancement. Following that, the auto-table-moving bolus-chase 3-D MRA should be used to cover longitudinal lower-extremity vessels.¹⁷ Another strategy is combining dynamic 2-D MRA over the distal region (calf and pedal arch) for catching the best arterial phase without a venous overlay, and following by bolus-chase 3-D MRA to acquire the abdominal aorta and vessels in pelvis and thighs.¹⁶ The other strategy is using a dual-rate contrast media injection, beginning with 20 mL at a rate of 0.5 mL/sec and changing the rate to 1.5 mL/sec for the remaining, to increase the arterial signal intensity at the third station and overcome the venous return signal.³³ In theory, the best solution to overcome this complex hemodynamic condition is to complete data acquisitions by matching the scanning time with the contrast media arrival at each station. If the acquisition is too early, it is not possible to reach the enhancement peak; yet, if the

acquisition is too slow, venous contamination is likely to occur. For more accurate and comprehensive acquisitions of a pure arterial anatomy of lower extremities, more studies about the relations between inflow velocity and maximal signal intensity of contrast media, as well as the development of real-time monitoring of the timing of contrast medium movements are needed. Also, designing a method to estimate the lag time of contrast enhancement in different levels of lower-extremity arteries can improve our knowledge about flow dynamics and help develop a scanning protocol to match the best arterial enhancement.

As discussed previously, when we found obvious venous signal contamination in the distal leg, we changed the slice thickness for 6 patients to shorten the acquisition time to catch only the arterial flow. In this study, the scanning protocol was not constant. Additionally, the results of this study cannot be generalized to all patients with PAOD. More cases are needed to answer some of the questions that were discovered in this study.

In conclusion, DSA has been the gold standard for evaluation of peripheral vascular structures for decades. Because of the many advantages 3-D MRA has (e.g., non-invasive, lower risks of nephrotic toxicity and allergy to contrast media, and no post-procedure resting time required), this technology is considered as a substitute for DSA for diagnostic imaging of peripheral vascular diseases. Results of this study show that 3-D MRA had equal image quality to that of DSA in only about half of the cases. Although shorter scanning time (40-50 seconds) can provide better image quality in the distal leg regions, early venous return causing contamination in patients with severe PAOD is still a major problem. 3-D MRA can provide an initial evaluation for patients with PAOD, but this technology cannot substitute for DSA as a precise diagnostic image modality for peripheral vascular diseases, especially for the areas below knee level. More knowledge of contrast flow kinetics in diseased vessels, real-time bolus monitoring, and easier data volume acquisitions are necessary for refining the 3-D MRA examination.

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