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Abbreviations:

MIP = maximum intensity projection
TOF = time of flight

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Peripheral Vascular Tree Stenoses: Evaluation with Moving-Bed Infusion-tracking MR Angiography¹

PURPOSE: To evaluate a magnetic resonance (MR) angiographic technique for imaging of the peripheral arteries with gadolinium enhancement.

MATERIALS AND METHODS: Moving-bed infusion-tracking MR angiograms were obtained in 15 healthy volunteers and in 28 patients with intermittent claudication before and during slow infusion of contrast material. Lower- and upper-leg and pelvic regions were imaged. Unenhanced images were subtracted from gadolinium-enhanced images, and maximum intensity projection images were generated. Image quality was evaluated subjectively and objectively, and maximum intensity projection images were compared with conventional angiograms, which served as the standard of reference.

RESULTS: Moving-bed infusion-tracking MR angiography proved to be a robust technique, and image quality on maximum intensity projection images was comparable with that on conventional angiograms. Sensitivity and specificity for grading hemodynamically significant stenoses were 93% and 98%, respectively, with excellent interobserver agreement.

CONCLUSION: Moving-bed infusion-tracking MR angiography can be used to image all peripheral arteries in 4 minutes by using a small amount of contrast material and a conventional 1.5-T MR imager.

Magnetic resonance (MR) angiography with gadopentetate dimeglumine enhancement has proved to be an important arterial imaging modality (1). Most techniques, however, allow imaging of only one coronal volume that covers 40-50 cm of the vascular tree. Although high image quality can be achieved with gadolinium-enhanced MR angiography, in some cases more than one field of view (40-50 cm) must be imaged. To accomplish imaging of the peripheral vascular tree, time-of-flight (TOF) techniques have been used (2). However, TOF imaging is time-consuming and subject to many artifacts (3).

An alternative to the TOF approach is imaging of multiple gadolinium-enhanced volumes with subsequent multiple doses of gadopentetate dimeglumine. Use of this method, however, increases the cost of the contrast material and can result in unintended effects due to an increase in intra- and extravascular levels of gadolinium. With the technique of moving-bed infusion-tracking MR angiography, only one bolus of gadopentetate dimeglumine (39 mL) is used for imaging of the entire peripheral vascular tree, and the actual acquisition time is only 4 minutes.

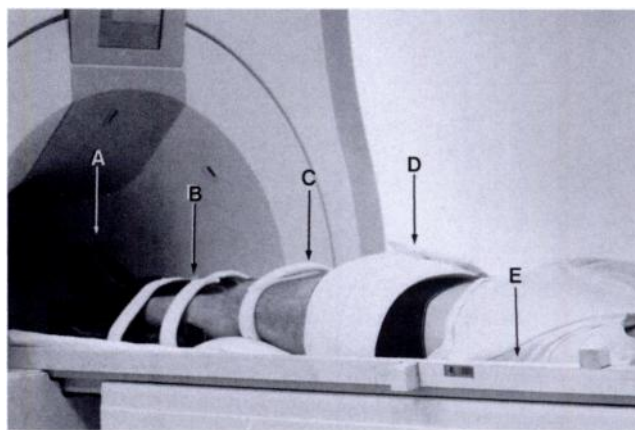
The purpose of this study was to evaluate the feasibility of moving-bed infusion-tracking MR angiography.

MATERIALS AND METHODS

MR Angiography

All MR angiograms were obtained with a conventional 1.5-T MR system (Gyrosan Advanced Clinical System-II; Philips Medical Systems, Best, The Netherlands) with a gradient strength of 10 mT/m and a slew rate of 1 mT/m/msec. The body coil was used for

Figure 1. Photograph of a volunteer on the imaging table. The subject's feet are in the holder (A). Straps (B) are placed around the lower legs, two sandbags are used to stabilize the lower legs, and a strap (C) is placed around the upper legs, to prevent motion of the legs. A tight strap (D) placed around the thighs prevents wraparound artifacts. Premeasured stops on the stop stick (E) are used for exact repositioning of the table after table movement.



signal transmission and reception for all studies. The procedure consisted of four parts: (a) positioning of the subject, (b) determination of arrival time of gadopentetate dimeglumine with the use of a timing sequence, (c) determination of vessel anatomy with the use of four fast TOF sequences, and (d) moving-bed infusion-tracking MR angiography.

Positioning of the Subject

For subject positioning, the feet were placed in a holder, and a sandbag was placed over the feet to stabilize them. Two 30-mm-wide bands were strapped around the lower legs and the two sandbags that had been placed on the sides of the legs, and one 30-mm-wide band was strapped around the upper legs, to prevent patient movement. A fourth 200-mm-wide band was strapped tightly around the thighs to minimize wrap-around artifacts. The knees were elevated so the backs of the knees would be in the same horizontal plane as the heels of the feet. During infusion of the contrast agent, the subjects had to elevate their arms over their head, again to minimize wrap-around artifacts. Figure 1 demonstrates subject positioning.

Determination of Arrival Time

Dynamic gradient-recalled-echo MR imaging was performed with short repetition and echo times (21.7 and 3.4 msec, respectively). Forty-five axial images (matrix, 256×102 ; flip angle, 55° ; field of view, 400 mm; section thickness, 15 mm) of the same location and with the same parameters were obtained consecutively through the abdominal aorta. The acquisition time for each section was 1.4 seconds.

By using dynamic imaging, the preparation phase for the acquisition is performed only once; thus, all sections were identical. A 100-mm-thick caudal presaturation slab was used to suppress signal from inflowing venous blood, and a 80-mm-thick cranial presaturation slab was used to prevent inflow effects from arterial blood. A test bolus of 1 mL of gadopentetate dimeglumine (Magnevist; Schering, Berlin, Germany) and a subsequent

flush of 20 mL of normal saline were administered by using an 18-gauge intravenous cannula (Venflon; Ohmeda, Helsingborg, Sweden) in an antecubital vein to imitate the bolus of gadolinium used with the moving-bed infusion-tracking image. The contrast agent and subsequent normal saline flush were injected by using an MR-compatible injector (Spectris MR; Medrad, Pittsburgh, Pa). The injection of the test bolus and the timing sequence were started simultaneously. The images were then evaluated for an increase in signal intensity in the abdominal aorta, which represents the arrival of the contrast agent. Arrival time of the bolus was calculated by multiplying the number of the section on which the elevated intraortic signal intensity was seen by the acquisition time per section.

Determination of Vessel Anatomy

To plan the volume used in moving-bed infusion-tracking imaging, sagittal maximum intensity projection (MIP) images were generated from images obtained with TOF sequences; these MIP images were used to obtain information about the arterial vessel course in the anterior-posterior direction (Fig 2). The TOF sequences consisted of four non-cardiac-synchronized sequences that covered the peripheral vascular tree from the aorta to the feet.

For the TOF technique, a multiple two-dimensional magnetization-prepared gradient-recalled-echo (turbo "field-echo") sequence was used (50° flip angle preceded by a 180° inversion prepulse [3,4]; repetition time msec/echo time msec, 15.0/6.8; field of view, 250 mm; matrix size, 256×77 ; section thickness, 6 mm with a 2-mm intersection gap; one signal acquired). A 100-mm-thick tracking venous presaturation slab with an

8-mm-thick interslab gap caudal to the imaged section was used to suppress venous signal. The 160 sections (40 for each TOF sequence) were planned so the arterial vascular tree would be covered from the aorta to the feet. Acquisition of the TOF sequences and planning of the volumes for the moving-bed infusion-tracking images took approximately 20 minutes.

Moving-Bed Infusion-tracking MR Angiography

The moving-bed infusion-tracking MR angiographic sequence was a three-dimensional gradient-recalled-echo (fast "field-echo") technique (14.1/6.1; flip angle, 50° ; 32 coronal sections acquired; section thickness, 3 mm [total volume thickness, 96 mm]). The images were acquired overcontiguously (interpolation of the 32 3-mm-thick sections to 64 1.5-mm-thick sections) in 42 seconds with a field of view of 500 mm and a matrix size of 512×171 , which resulted in a voxel volume of 8.4 mm^3 . This sequence was implemented in a dynamic fashion to acquire three identical coronal volumes (ie, identical parameters and location in imager, but the patient was moved for each volume acquisition), each with 64 sections (192 sections for the entire dynamic imaging sequence). These coronal volumes were planned to cover the arteries of pelvic region. Elevation of the knees and ankles of the patient were optimized so the upper and lower leg arteries would run in the same horizontal plane as the pelvic arteries (Fig 2). This alignment of all peripheral arteries made it possible to image the entire peripheral vascular tree by moving the table into or out of the imager.

The dynamic study was acquired twice, once before infusion of contrast material

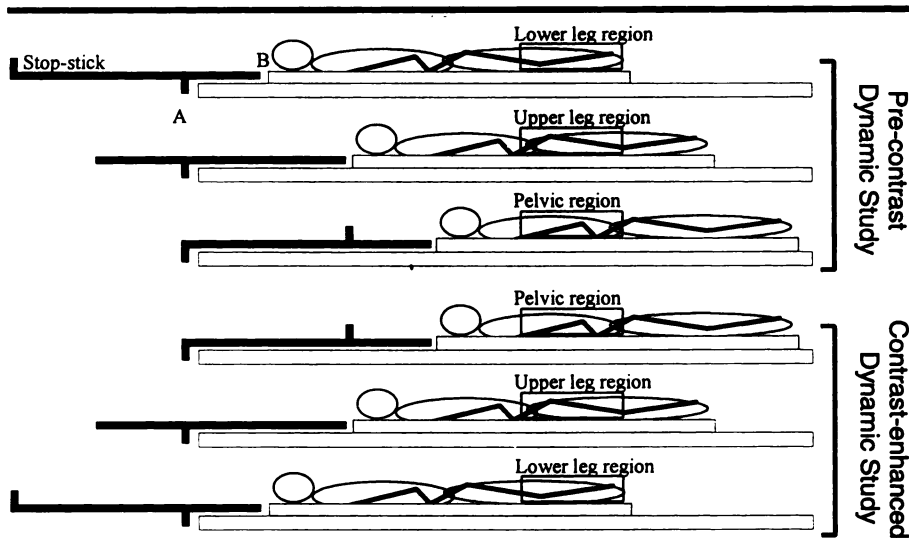


Figure 2. Schematic shows sagittal views of a patient and the planned volumes for lower-leg, upper-leg and pelvic regions. The sequence of table movements is shown for unenhanced (*Pre-contrast*) imaging (top) and gadolinium-enhanced imaging (bottom). During table movement, the premeasured stop (A) of the stop-stick is pushed against the table support structure and the table is pushed against the end of the stop-stick (B).

and once during infusion. To acquire the unenhanced image, the table (with the patient) was pulled out of the imager; therefore, the first volume of the unenhanced study was of the lower legs. The table was then moved into the imager with a fixed table movement. To obtain accurate and reproducible table movements, a wooden stick with three premeasured stops, a so-called stop-stick (Figs 1, 2), was used. A second unenhanced volume was then acquired of the upper legs. Again, the table was moved into the imager by using the stop-stick, and the next volume acquired covered the pelvic region.

After acquisition of the unenhanced study, the preparation phase of the gadolinium-enhanced study was started. The procedure was identical except the imaged regions were acquired in reverse order (pelvic, upper-leg, and lower-leg regions). After the preparation phase, 39 mL of preheated gadopentetate dimeglumine was infused the rate of 0.3 mL/sec by using the MR-compatible injector. The arrival time of the contrast agent, as determined with the timing sequence plus 8 seconds (to ensure an even concentration of contrast material in the imaged volume), was used as an imaging delay between the start of contrast agent infusion and the start of the acquisition of the first volume.

After acquisition of the pelvic volume, the table was pulled out of the imager as fast as possible (approximately 3–4 sec-

onds), and the stop-stick was used to position the table at exactly the same position used for acquisition of the second volume of the unenhanced image. The second volume of the gadolinium-enhanced study was then acquired. After the upper-leg volume was acquired, the table was again pulled out of the imager as fast as possible, and the stop-stick was used to position the table at exactly the same position used to acquire the first volume of the unenhanced image (lower-leg region). The third volume of the gadolinium-enhanced study was then acquired.

The two dynamic studies (a total of six coronal volumes) were reconstructed and sent to a workstation (SPARCstation 5; Sun Microsystems, Mountain View, Calif) for postprocessing (SCIL_IMAGE 1.2; University of Amsterdam Faculty of Mathematics and Computer Science, The Netherlands), which consisted of section-by-section subtraction of unenhanced volumes from corresponding gadolinium-enhanced volumes for all three anatomic regions. The subtracted data were then sent to another workstation (EasyVision; Philips Medical Systems). The left and right sides of the peripheral vascular tree were imaged separately by constructing six target MIP images that were rotated around the craniocaudal axis over a 150° range (0° [coronal MIP image], 30°, 60°, 90° [sagittal MIP image], 120°, and 150°) for each side. The iliac arteries were also imaged by constructing six target MIP images rotated around the horizontal (left-

right) axis (0° [coronal MIP image], 30°, 60°, 90° [axial MIP image], 120°, and 150°).

Subjects

Fifteen healthy volunteers, eight men and seven women aged 19–41 years (mean, 28 years), with no known vascular pathologic conditions underwent MR angiography according to the procedure described earlier in this article.

After we had evaluated the feasibility of this method, 28 consecutive patients, 23 men and five women aged 31–82 years (mean, 62 years), underwent the same MR angiographic procedures as the volunteers. The patients had intermittent claudication, stenotic lesions of the iliac arteries (lumen reduction \geq 50%) demonstrated at Doppler ultrasonography (US), and/or were scheduled for conventional angiography. For the patients, conventional angiographic results served as the standard of reference. Approval was obtained from the medical ethical commission of the hospital, and written informed consent was obtained from all volunteers and patients.

Conventional Angiography

In all patients, conventional angiography was performed within 1 week of MR angiography by using an x-ray system (Diagnostic Arc; Philips Medical Systems) with a programmable stepping C arm, a film-changer (Puck; Elema-Schonander, Solina, Sweden), an add-on digital subtraction angiography system (Technicare DR 960-B; GE Medical Systems, Milwaukee, Wis), and a power injector for infusion of contrast material. All angiographic procedures were supervised by an experienced vascular radiologist (M.W.d.H.).

Conventional angiography was performed in 15 patients by puncturing the common femoral artery and placing a 5-F catheter in the distal aorta just above the bifurcation, if examination of two legs was necessary ($n = 15$), or by using a crossover approach, if examination of only one leg was necessary ($n = 9$). In four patients, conventional angiography was performed with antegrade infusion of contrast material in the common femoral artery. Nonionic contrast medium (iohexol, Omnipaque; Nycomed, Cork, Ireland) was used, with variable volumes and flow rates that depended on both the location of the tip of the catheter and the imaging system (conventional or digital subtraction angiography). Film hard copies were obtained in the posteroanterior

Figure 3. Coronal MR angiographic MIP images of the iliac arteries in (a) a 34-year-old, 202-cm-tall, healthy male volunteer and (b) a 53-year-old, 158-cm-tall, female patient with atherosclerotic disease of the iliac arteries (arrows). These images show the robustness of the technique despite extreme patient variability.

direction; in most patients, additional posteroanterior and oblique views were obtained at digital subtraction angiography.

Image Evaluation

For evaluation purposes, the arterial tree was divided into the following segments: aorta, left and right common iliac arteries, external iliac artery, common femoral artery, superficial femoral artery, deep femoral artery, popliteal artery, anterior tibial artery, posterior tibial artery, and peroneal artery.

Because stenoses were all detected and graded on moving-bed infusion-tracking MIP images, image quality measurements were also performed on moving-bed MIP images. One observer (M.W.d.H.) evaluated the images in the volunteers for vessel visibility, which was classified as good, average, or poor. For the patients, the degree and length of a stenosis were assessed by two observers (P.J.E.H.M.K., J.M.A.v.E.) and were categorized with a five-point scale (1 = no abnormality or stenosis, with a lumen reduction of 0%–19%; 2 = 20%–49% stenosis; 3 = 50%–74% stenosis; 4 = 75%–99% stenosis; 5 = complete occlusion). Only the most severe stenosis per vessel segment was taken into account. Grading of stenoses was performed at a workstation with enlarged MIP images, by using an electronic caliper with 0.1-mm accuracy. The two observers (M.W.d.H., J.M.A.v.E.) were unaware of the results of moving-bed infusion-tracking MR angiography, conventional angiography, Doppler US, or the interpretation of the other observer. Because not all conventional angiograms in patients contained all regions of the peripheral vascular tree, only the vessel segments on moving-bed infusion-tracking MIP images with corresponding vessel segments on conventional angiograms could be compared.

The conventional angiograms were evaluated by the two observers (M.W.d.H., J.M.A.v.E.) with regard to the degree and length of stenoses and were categorized by using the five-point scale. This was performed during separate sessions 4 weeks before the interpretations of moving-bed infusion-tracking MR angiograms. Evaluation of conventional angiograms was achieved with consensus about the results; a third observer (P.J.E.H.M.K.), who was a vas-

cular surgeon, evaluated the images in cases where consensus was not reached.

Finally, moving-bed infusion-tracking MR angiographic and conventional angiographic results were compared directly by two radiologists (M.W.d.H., J.M.A.v.E.), who used a subjective quality score. For this purpose, both the moving-bed MIP images and the conventional angiograms were evaluated simultaneously. Each vessel segment on the MIP images was interpreted in terms of contrast and the presence of artifacts. Contrast was defined as the visualized contrast between vessel and background and was categorized by

using a scoring scale that ranged from –2 to 2 (–2 = much lower contrast compared with that on conventional angiograms, –1 = slightly lower contrast, 0 = equal contrast, 1 = slightly higher contrast, and 2 = much higher contrast). Artifacts were defined as elements in the images that could disturb image interpretation (venous superposition, wraparound artifacts).

Statistical Analysis

The linear, weighted κ statistic (5,6) was used to assess interobserver agree-

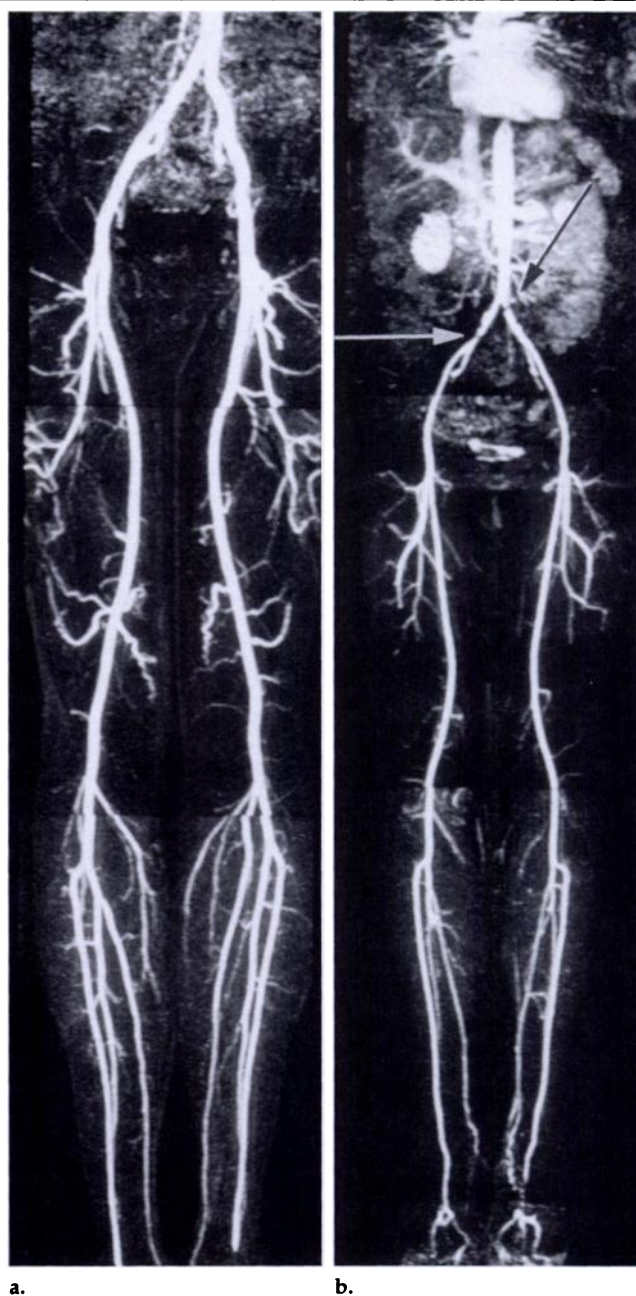


TABLE 1
Stenoses Demonstrated at Conventional Angiography in 28 Patients and 15 Volunteers

Artery	Stenosis Grade				
	1	2	3	4	5
Aorta	14	2	0	0	0
Common iliac	21	4	3	3	3
External iliac	23	2	4	2	3
Common femoral	31	1	4	0	2
Superficial femoral	16	0	0	5	20
Deep femoral	29	0	4	3	1
Popliteal	32	3	0	1	4
Anterior tibial	20	0	2	1	12
Posterior tibial	21	0	0	0	13
Peroneal	28	0	0	0	7

Note.—Data are number of stenotic lesions.

TABLE 2
Sensitivity, Specificity, and Interobserver Variability with Regard to Detection of Stenoses on MIP Images

Artery	Lumen Reduction $\geq 20\%$		Lumen Reduction $\geq 50\%$		κ Value
	Sensitivity (%)	Specificity (%)	Sensitivity (%)	Specificity (%)	
Aorta ($n = 16$)	75	76		100	0.19
Common iliac ($n = 32$)	100	69	95	100	0.81
External iliac ($n = 33$)	96	78	89	96	0.78
Common femoral ($n = 38$)	86	79	67	94	0.85
Superficial femoral ($n = 37$)	100	91	100	100	0.94
Deep femoral ($n = 41$)	94	95	94	100	0.83
Popliteal ($n = 40$)	88	91	100	97	0.84
Anterior tibial ($n = 35$)	100	80	97	100	0.88
Posterior tibial ($n = 34$)	96	88	94	100	0.89
Peroneal ($n = 35$)	79	84	79	100	0.78

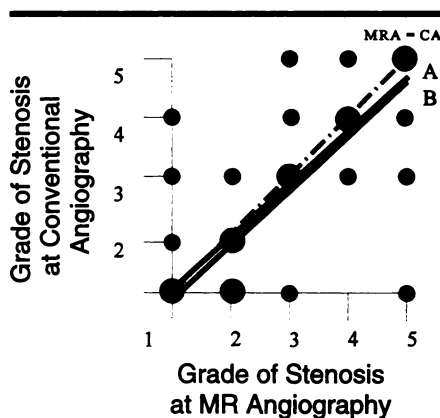


Figure 4. Graph shows results of the linear-regression analysis of findings of stenosis grade at moving-bed infusion-tracking MR angiography (MRA) versus conventional angiography (CA). A = regression line based on findings by observer 1, B = regression line based on findings by observer 2, dashed line = perfect correlation between conventional and MR angiographic findings, large circle = 10 or more results, small circle = fewer than 10 results, 1 = no abnormality (0%–19% stenosis), 2 = 20%–49% stenosis, 3 = 50%–74% stenosis, 4 = 75%–99% stenosis, and 5 = complete occlusion.

ment for stenosis grade. The κ values can range from -1 (no agreement) to 1 (perfect agreement). Interobserver agreement was classified as poor ($\kappa = 0.00$), slight (κ of 0.00 – 0.20), fair (κ of 0.21 – 0.40), moderate (κ of 0.41 – 0.60), substantial (κ of 0.61 – 0.80), or almost perfect (κ of 0.81 – 1.00) (7).

For findings in patients, sensitivity and specificity were calculated for presence of diseased vessel segments (lumen reduction $\geq 20\%$) and for presence of hemodynamically significant stenoses (lumen reduction $\geq 50\%$), with conventional an-

giographic findings as the standard of reference. The relationship between the results of moving-bed infusion-tracking MR angiography and conventional angiography with regard to the length and degree of a stenosis was assessed by using standard linear-regression analysis. To evaluate interobserver agreement for measurements of the length of stenoses, the Pearson correlation coefficient was calculated. This coefficient is a measure of the association between two random variables, given that these variables have a linear relationship (8).

RESULTS

Adequate images were obtained in all volunteers and patients. Representative examples of the results of moving-bed infusion-tracking MR angiography in a volunteer and in a patient are shown in Figure 3. The observer who evaluated vessel visibility in volunteers concluded that all images provided good vessel visibility without disturbing artifacts. The location, number, and degree of stenotic lesions in patients as demonstrated on conventional angiograms are listed in Table 1.

Before we compared moving-bed infusion-tracking MR angiographic results with conventional angiographic results, we excluded data of vessel segments that contained metallic stents.

Interobserver agreement was almost perfect (κ of 0.86 ± 0.02 [1 standard deviation]) with regard to findings of degree of stenosis on moving-bed infusion-tracking MIP images. Interobserver agreement in terms of vessel segments is given in Table 2.

Sensitivity and specificity for detection

and grading of diseased segments in all vessel segments (lumen reduction $\geq 20\%$) were 91% and 92%, respectively, for observer 1 and 99% and 75%, respectively, for observer 2. Sensitivity and specificity for detection and grading of hemodynamically significant stenoses in all vessel segments (lumen reduction $\geq 50\%$) were 91% and 98%, respectively, for observer 1 and 95% and 98%, respectively, for observer 2. These results are listed in Table 2. Figure 4 shows the results of linear-regression analysis of the degree of a stenosis seen on moving-bed infusion-tracking MIP images and on conventional angiograms for all vessel segments.

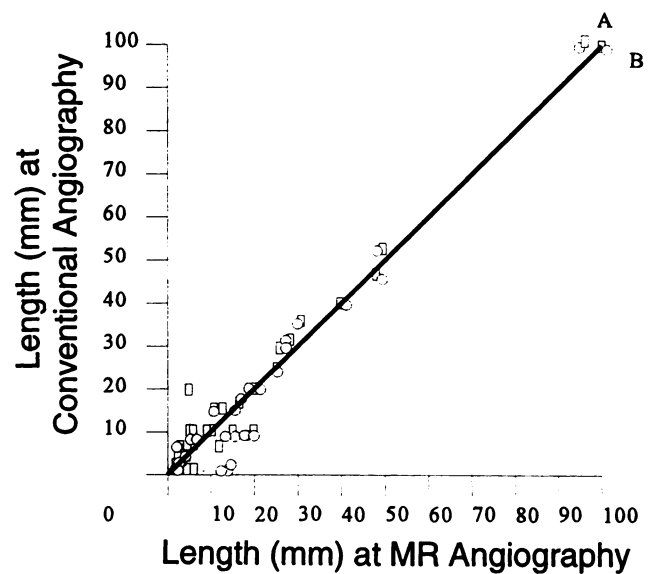
The length of hemodynamically significant stenoses and/or occlusions on conventional angiograms was 1–421 mm. Results of the two observers' assessments of length of such stenoses were highly correlated ($r = .99$). Figure 5 shows the results of the linear-regression analysis of the length of stenoses seen on conventional angiograms and on moving-bed infusion-tracking MIP images.

Table 3 lists the mean subjective contrast score per observer per vessel segment.

DISCUSSION

Several authors have demonstrated the usefulness of gadolinium-enhanced MR angiography for imaging of the aorta (9–14), iliac arteries (15–18), and lower leg arteries (16). To our knowledge, however, no study has yet been published in which the possibility has been demonstrated of imaging all three levels of the peripheral vascular tree in a short time (4 minutes) with only one bolus of contrast material and a conventional MR system.

Figure 5. Graph shows results of the linear-regression analysis of findings of stenosis length at moving-bed infusion-tracking MR angiography versus conventional angiography. The regression lines for observer 1 (A) and observer 2 (B) are almost identical to each other and to a perfect correlation between MR angiographic and conventional angiographic results. ○ = finding by observer 1, □ = finding by observer 2.



Infusion of gadolinium chelates over a longer period can cause two major problems at gadolinium-enhanced MR angiography: Venous enhancement can occur, and uptake of contrast material in surrounding tissue can result in lowered vessel-to-background contrast. In another study (19), we compared gadolinium-enhanced MR angiograms of the pelvic region with conventional angiograms of the pelvic region after injection of 30 mL of gadopentetate dimeglumine within 90 seconds; there were no troublesome artifacts of venous enhancement (20). By using three fast gadolinium-enhanced MR angiographic acquisitions (the three volumes of the dynamic study) right after each other, which extended the total acquisition time to 2 minutes 6 seconds, and by using a slow injection rate (0.3 mL/sec), the technique becomes a "gadolinium optimized tracking" technique, which was our former name for the moving-bed infusion-tracking technique (21).

The slow injection rate also has disadvantages. Because the elevation of arterial signal intensity depends on intraarterial concentration of contrast material (20), the slower injection rate will also diminish vessel-to-background contrast. A subtraction technique with which background signal intensities can be lowered compensates for this effect. Moreover, the subtraction technique also compensates for the elevated background signal intensities (due to uptake of contrast material in tissue) in the upper and, especially, lower leg.

To demonstrate the effectiveness of subtraction in decreasing background signal intensities, Figure 6 shows a nonsubtracted and a subtracted MIP image of the lower legs. An optimal subtraction of an unenhanced image from a gadolinium-enhanced image can be achieved only when the unenhanced image contains no or very little contrast material. With moving-bed infusion-tracking MR angiography, the unenhanced image was acquired before the administration of any gadopentetate dimeglumine (except the 1 mL used for the timing sequence).

Acquisition of all three unenhanced volumes before the gadolinium-enhanced study means that the table must be moved between acquisitions. This might cause artifacts in the subtraction due to mis-

alignment. To obtain exact and reproducible alignment of these images, several precautions must be taken. First, one should ensure that the table be moved to fixed table positions. To achieve this, we used a so-called stop-stick. This simple device, a wooden stick with premeasured stops affixed (Fig 1), is placed on the support structure on which the table lies. A stop is then pushed against the back of the support structure and the table is pushed against the end of the stop-stick (Fig 2). To move from one region to another, the table is pushed into or pulled out of the imager by using the three stops on the stop-stick, as demonstrated in Figure 2. This stop-stick allows exact repositioning of the table, and thus of the patient, for both the unenhanced and the gadolinium-enhanced studies. Second, the patient's legs must be strapped together to prevent patient motion between acquisitions. For this purpose, we used sandbags on both sides of the legs and strapped together with the legs. This effectively prevented any leg motion between acquisitions despite fast table movement. Third, good patient instruction is essential. The patient should be made aware of the fast table movement between acquisitions of the six volumes so that he or she will not be startled when the table is suddenly moved.

To achieve high temporal resolution with a gadolinium-enhanced MR angiographic sequence on a conventional system, the repetition and echo times must be set to the shortest possible, and the rectangular field of view must be de-

TABLE 3
Subjective Contrast Scores on Moving-Bed Infusion-tracking MR Angiograms

Artery	Observer 1	Observer 2
Aorta (n = 16)	0.19	0.00
Common iliac (n = 34)	0.06	0.09
External iliac (n = 34)	0.03	0.06
Common femoral (n = 38)	0.00	0.03
Superficial femoral (n = 41)	0.24	-0.12
Deep femoral (n = 37)	0.03	-0.03
Popliteal (n = 40)	0.38	0.05
Anterior tibial (n = 37)	0.84	0.46
Posterior tibial (n = 37)	0.76	0.49
Peroneal (n = 37)	0.62	0.54

Note.—Subjective contrast (visual contrast between vessel and background) was scored on the basis of the following scale: -2 = much less contrast compared with that on conventional angiogram, -1 = slightly lower contrast than that on conventional angiogram, 0 = contrast equal to that on conventional angiogram, 1 = slightly higher contrast than that on conventional angiogram, 2 = much higher contrast than that on conventional angiogram.

creased to a minimum. By doing so, we were able to achieve an imaging time of 42 seconds per volume (2 minutes 6 seconds per dynamic study). However, this decrease in the field of view means that wraparound artifacts can occur, especially from the thighs. To prevent wraparound artifacts, we used a 200-mm-wide band strapped tightly around the thighs to prevent any artifacts that would disturb image interpretation.

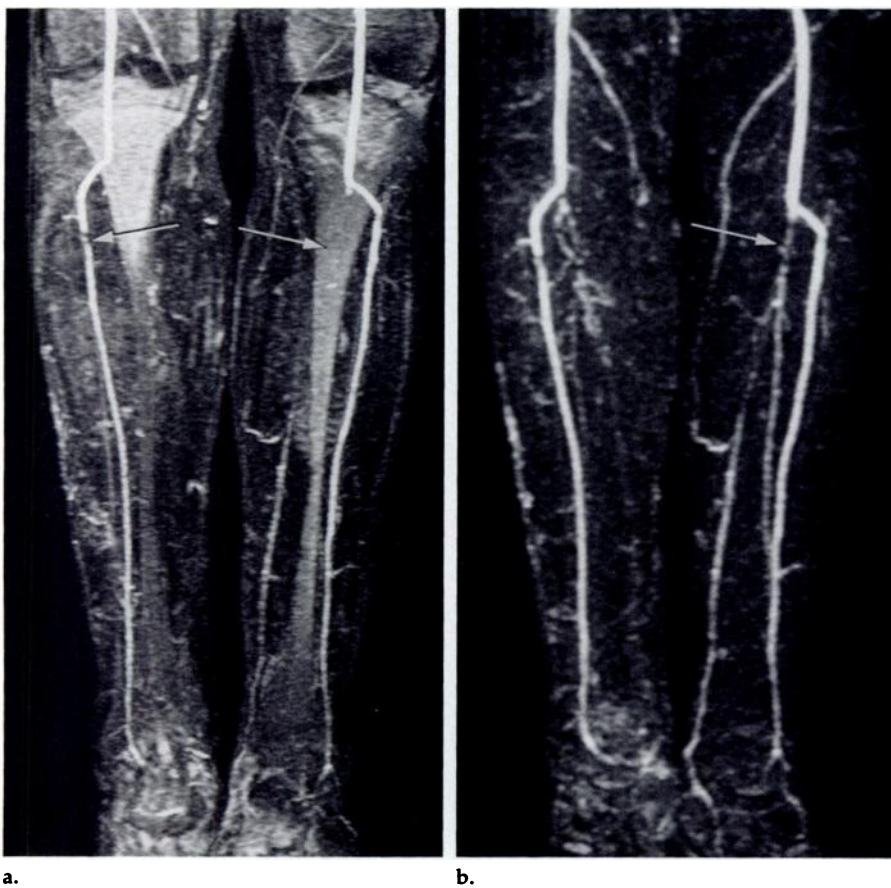


Figure 6. (a) Nonsubtracted MIP image of the lower leg of a 54-year-old male patient with a right-sided single runoff vessel (anterior tibial artery) with a proximal stenosis (left arrow). On the left side, the anterior tibial artery is patent, but the posterior tibial artery (right arrow) seems to have a proximal occlusion, and the peroneal artery cannot be identified. (b) Subtracted MIP image shows the same results on the right side as in a, but owing to the subtraction it can now be seen that the left leg has patent posterior tibial (arrow) and peroneal arteries, with severe stenoses in the tibio-peroneal trunk and proximal posterior tibial artery.

A drawback to the use of a conventional imager is the limited volume thickness one can obtain with an image acquisition time of 42 seconds. This results in a relatively time-consuming procedure (20 minutes) for performance of TOF sequences and generation of their sagittal MIP images and to adjust the patient to the planned dynamic image volumes. The initial volume was planned to cover the arteries of the pelvic region. By elevating the knees and lower legs, upper- and lower-leg arteries were elevated. This meant that all peripheral arteries from the aorta to the feet were in a horizontal plane. By moving the bed and thus the arteries of another region (pelvic or lower- or upper-leg regions) into the imaged volume, we were able to image the entire vascular tree without repositioning of the acquired volume (in the anterior-posterior direction).

Because our imager could only acquire 256 sections per dynamic study, we had to acquire two dynamic studies (unenhanced and gadolinium enhanced). This can result in different amplifier settings, because a different preparation phase was performed for each dynamic study. Obviously, this might have resulted in suboptimal quality of the subtracted volumes. Subtraction of the different volumes could not be performed with the imager but had to be done with a separate workstation. This alternative route for data processing increased our postprocessing time to approximately 3 hours per patient. However, we are now using a more modern system (NT imager with EasyVision workstation; Philips Medical Systems), and postprocessing time has been decreased to approximately 15 minutes per patient.

On MIP images in the volunteers, no artifacts that disturbed interpretation were encountered. On MIP images in the patients, at least one observer interpreted

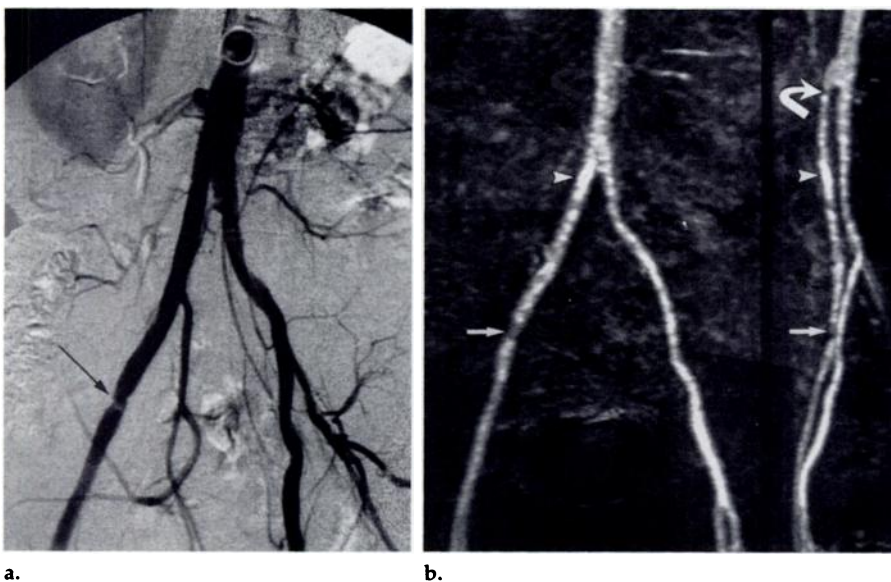


Figure 7. (a) Oblique conventional angiographic view in a 46-year-old male patient depicts a stenosis (arrow) in the right external iliac artery but does not show the true anatomic position of the aortic bifurcation, owing to superposition of the right common iliac artery over the left common iliac artery. (b) Coronal (left) and sagittal (right) moving-bed infusion-tracking MR angiographic MIP images, however, not only provide better views of the stenosis (straight arrows) in the right external iliac artery, but also demonstrate the false position of the bifurcation (arrowheads) and a stenosis (curved arrow) of the right common iliac artery directly below the true anatomic position of the bifurcation.

the images of 33 of 351 vessel segments as having disturbing artifacts.

The observers agreed about findings in only 12 of these segments. Three of these 12 artifacts were caused by metallic stents inserted during a previous vascular intervention. Two of these 12 artifacts were caused by misplanning of the volume for the gadolinium-enhanced images, which resulted in exclusion of part of the common femoral arteries from the imaged volume. Three of these 12 artifacts were wraparound artifacts. The wraparound artifacts occurred in the first two patients, whose thighs were not compressed by the thigh-strap. Also, one of these patients had two vessels in the lower leg that were not distinguishable from surrounding tissue due to a failed subtraction (lower-leg rotation by a patient in whom no sandbags had been placed bilateral to the lower legs). The observers agreed only twice about disturbing artifacts due to venous superposition in a vessel segment, which means that there were unavoidable disturbing artifacts in only two of 351 vessel segments.

Because metallic stents are known to cause artifacts on gadolinium-enhanced MR angiograms (22), we excluded vessel segments that contained stents from our data before we compared the moving-bed infusion-tracking MIP images with conventional angiograms for grading of stenoses.

The moving-bed infusion-tracking MR angiographic technique yielded good results in all vessel segments. Table 2 demonstrates that the results were more or less independent of vessel size or location. We used two cut-off points: diseased vessel segments (lumen reduction $\geq 20\%$) and hemodynamically significant stenoses (lumen reduction $\geq 50\%$).

The comparison of moving-bed infusion-tracking MR angiograms and conventional angiograms in terms of diseased vessel segments can give a better impression of the spectrum of pathologic conditions encountered in peripheral arteries. However, this comparison resulted in lower specificity. This might be explained by the rectangular shape of the voxel used with the moving-bed infusion-tracking MR angiographic sequence, given the possible partial volume effects in the anteroposterior (section-thickness) and left-to-right (low image-percentage) directions. This is also true for high grade stenoses (stenosis of 75%–99%), which sometimes manifested as small complete occlusions. Another explanation for the lower specificity might be the improved measurement accuracy on rotated and

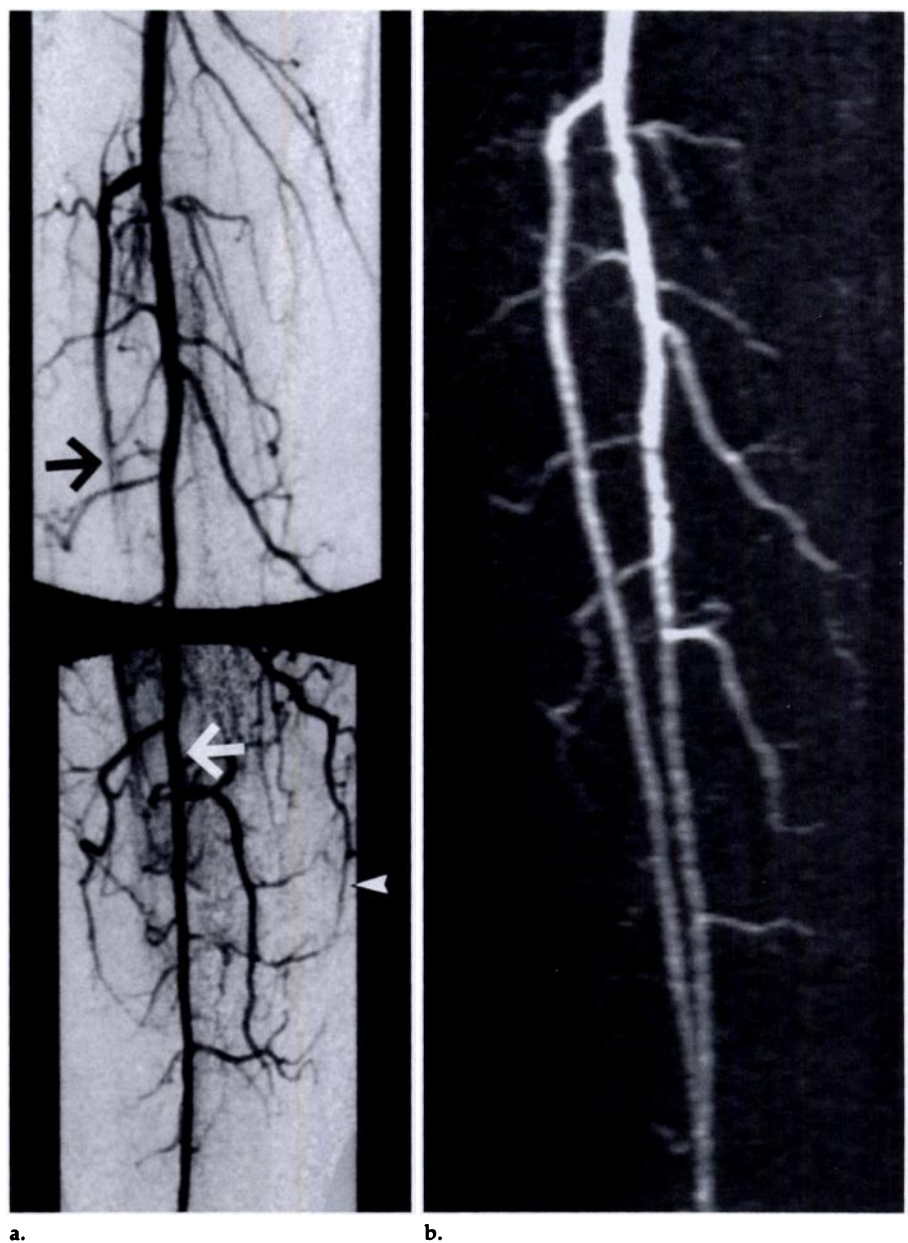


Figure 8. (a) Conventional angiogram obtained with antegrade infusion of contrast material in a 54-year-old male patient. Two consecutive images depict the lower leg from the popliteal artery trifurcation to the ankle. A patent peroneal artery (white arrow), an anterior tibial artery with poor distal runoff (black arrow) and an occluded posterior tibial artery (arrowhead) are seen. (b) The quality of the moving-bed infusion-tracking MR angiographic MIP image is similar to that of the conventional angiogram in a, and similar evaluation results were obtained.

enlarged MIP images when the electronic caliper (with 0.1-mm accuracy) was used, which revealed minor stenoses that were overlooked on conventional coronal or oblique angiographic views.

With regard to the direct comparison between moving-bed infusion-tracking MIP images and conventional angiograms, the observers found the ability to rotate around a vessel segment at MR angiography useful. A typical example of

this advantage can be seen in Figure 7, where a stenosis in the right common iliac artery was overlooked on conventional angiograms on both posteroanterior and oblique views. However, a sagittal MIP image of the gadolinium-enhanced image depicted this “undetectable” stenosis. The subjective contrast scores (Table 3) indicate that the per vessel segment mean scores of the two observers were equal to or better than those obtained

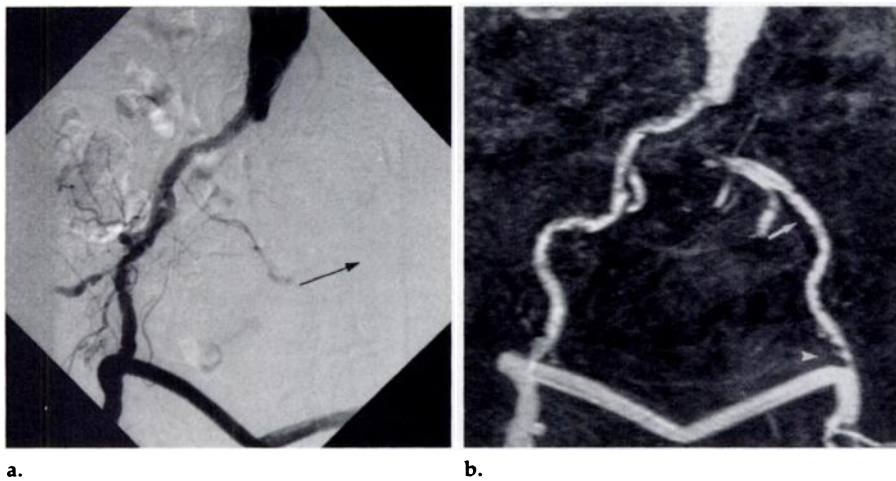


Figure 9. (a) Conventional angiogram in a 79-year-old male patient shows complete occlusion of the left external iliac and common femoral arteries (arrow) due to mistiming. The longer imaging time (42 seconds) for moving-bed infusion-tracking MR angiography prevents problems due to mistimed postobstructive retrograde filling of arteries, as can be seen on the (b) moving-bed infusion-tracking MR angiographic MIP image, which shows patent left external iliac and common femoral arteries (arrow), with two severe stenoses (arrowhead) just proximal to the junction of the bypass and the left common femoral artery.

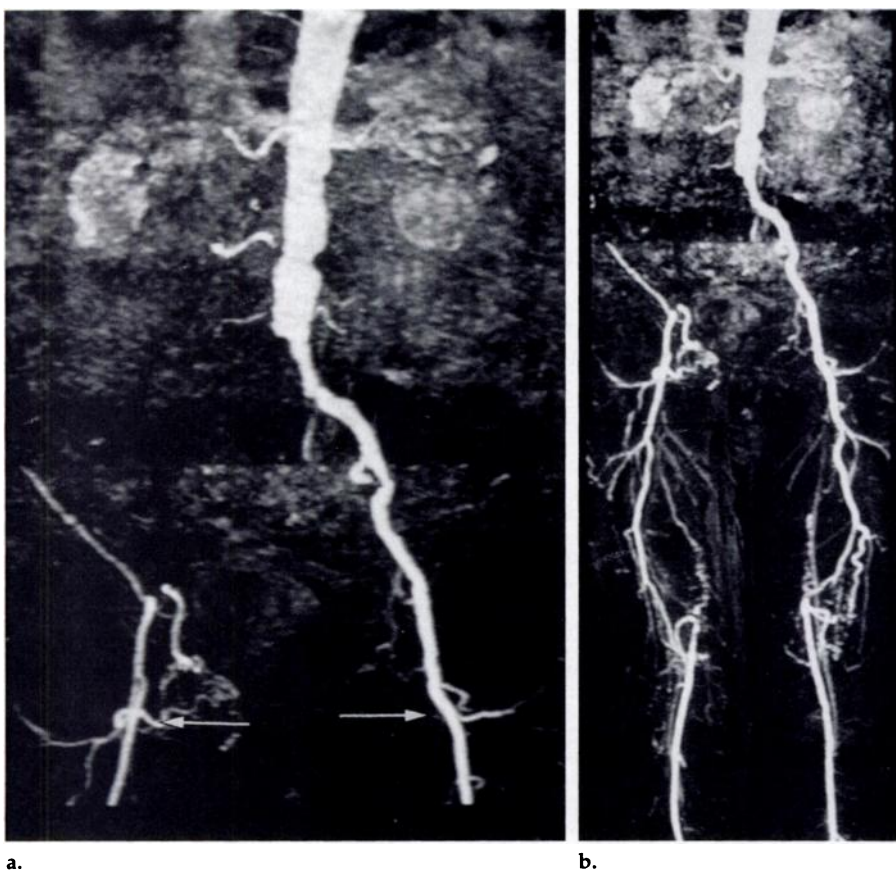


Figure 10. Moving-bed MR angiographic MIP images in a 73-year-old male patient. (a) Image of the pelvic region appears to depict normal superficial femoral arteries (arrows), but the (b) comprehensive image of the pelvic and upper-leg regions clearly demonstrates that both superficial femoral arteries are completely occluded.

with conventional angiography. This was particularly true for the lower legs, which showed consistently higher contrast scores for both observers. A typical example of the lower legs is seen in Figure 8. Most of the lower contrast scores found were due to artifacts (wraparound, mis-

planning of the volume, failed subtraction).

Seven of 65 complete occlusions seen on conventional angiograms were "overlooked" on moving-bed infusion-tracking MIP images. These could be false-negative results. Figure 9a shows a con-

ventional angiogram on which the left external iliac and common femoral arteries were not filled with contrast agent, probably because of mistiming. However, the corresponding moving-bed infusion-tracking MR angiographic MIP image (Fig 9b) depicts the apparently patent vessels. Similar phenomena were seen for the other "overlooked complete obstructions," thought to indicate occlusion on conventional angiograms but not on moving-bed infusion-tracking MIP images. More study is needed, with surgical exploration as the standard of reference, to evaluate whether these findings were overlooked occlusions or false-negative.

In another study (19), we concluded that complete occlusions seen at gadolinium-enhanced MR angiography might best be evaluated by using both nonsubtracted and subtracted images. This was due to the fact that the subtracted images can lack sufficient anatomic information, which sometimes results in misinterpretation of vessel anatomy. Figure 10 demonstrates this effect in the upper femoral region. On the pelvic image alone, one might think that the superficial femoral arteries are unaffected. However, by looking at the comprehensive picture of the pelvic and upper leg region, one can immediately see that both superficial femoral arteries are completely occluded.

With regard to length measurements, the results of linear-regression analysis (Fig 5) show that findings from moving-bed infusion-tracking MR angiography are in excellent accordance with those of conventional angiography. Again, this might be explained by the voxel dimensions, for which the best resolution is achieved in the craniocaudal direction.

All symptomatic patients with arteriosclerotic peripheral vessel disease need an extensive diagnostic work-up, including noninvasive tests, for an accurate diagnosis to be established. Precise definition of vessel anatomy is mandatory for treatment planning and for the decision about

the most appropriate type of intervention. Moving-bed infusion-tracking MR angiography is a promising technique for fulfillment of these needs. However, more patients must be evaluated with this technique to establish its value in imaging of the peripheral vascular tree.

Further improvement of moving-bed infusion-tracking MR angiography is to be expected with the use of newer (eg, faster) imagers. Use of identical amplifier settings between unenhanced and gadolinium-enhanced studies can improve subtracted image quality. For this purpose, it should be possible to obtain more than 256 sections per dynamic study, which is a limitation of our imager that forced us to acquire two dynamic studies (unenhanced dynamic and gadolinium-enhanced dynamic studies). It should also be possible to use three amplifier settings per region (lower-leg, upper-leg, and pelvic region). Better hardware, such as specific extremity coils (instead of the body coil), will improve the signal-to-noise ratio remarkably. Faster imaging times can lead to higher spatial resolution or thicker volume acquisition.

Because sensitivity and specificity for detecting and grading hemodynamically significant stenoses are already approximately 95% (excluding false-negative results), we think that a thicker volume acquisition would be the primary goal for improving moving-bed infusion-tracking MR angiography. Acquisition of a thicker volume may eliminate the need for exact planning of volumes. This would reduce overall patient-handling time considerably, because the time needed for acquisition of TOF images could be eliminated. Because accurate timing of the bolus is important (23), the timing sequence cannot be eliminated unless an automatic bolus detection system such as the one recently described by Foo et al (24) is used. Imaging time can be reduced to include the time of moving-bed infusion-tracking MR angiography alone (4 minutes) with only one bolus of contrast material.

In conclusion, moving-bed infusion-tracking MR angiography is a fast, simple, and robust technique with which the entire peripheral vascular tree can be imaged with a conventional 1.5-T MR imager. Our results in patients are promising. In the iliac and femoral arteries, and

particularly in the lower-leg arteries, results obtained with this technique can even compete with those of conventional angiography. With faster imagers, overall patient-handling time may be reduced to 4 minutes.

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