MR Angiography in the Evaluation of Atherosclerotic Peripheral Vascular Disease[1]

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Index terms:
Angiography, 92.12942, 93.12942
Arteries, extremities, 92.721
Arteries, MR, 92.12942
Grafts, 92.721
Magnetic resonance (MR), maximum intensity projection, 92.12942
Magnetic resonance (MR), three-dimensional, 92.12942

Radiology 2000; 214:325–338

Abbreviations:
MIP = maximum intensity projection
TOF = time of flight
2D = two-dimensional
3D = three-dimensional

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N.M.R. receives research support from Berlex Laboratories and is a member of the Speaker's Bureau for Berlex Laboratories.

Magnetic resonance (MR) angiography of lower extremity occlusive vascular disease has evolved into a feasible diagnostic imaging option. The previous emphasis on time-of-flight techniques was associated with lengthy acquisition times and artifactual signal losses. Those limitations presented an obstacle to widespread clinical implementation. However, the emergence of rapid imaging sequences combined with gadolinium chelate enhancement offers time-efficient alternatives that can yield a truer representation of the vascular anatomic structure. The technology is now poised to serve as a routine screening study, provided that radiologists understand all factors needed to generate clinically relevant MR angiograms. This article is intended to provide a useful resource directed toward achieving that understanding.

Atherosclerotic occlusive disease of the lower extremities is a prevalent disorder. Its treatment accounts for more than 100,000 surgical procedures annually in the United States (1). The disease causes a spectrum of ailments with substantial morbidity, including claudication, rest pain, tissue loss, and gangrene.

When planning a revascularization procedure, information about the number, length, and severity of vascular lesions is essential. Conventional angiography with the use of iodinated contrast media has long served as the standard of reference in this regard; however, magnetic resonance (MR) angiography has recently emerged as a compelling alternative. Its noninvasive nature makes peripheral MR angiography an attractive alternative for all patients who can be studied safely in the MR imager.

Effective MR angiography for the evaluation of peripheral vascular disease hinges on an understanding of what the treating physician wants and needs to know. Up to now, radiologists with a specific interest and training in vascular disorders and conventional angiography have been largely responsible for performing diagnostic evaluations in patients with peripheral vascular disease. The advent of MR angiography has changed the playing field dramatically and is shifting those diagnostic challenges to a broader range of radiologists.

Thus, it becomes essential for the "new" vascular radiologists to be conversant with the clinical issues and treatment options available to vascular surgeons and interventionalists. When this knowledge is combined with an understanding of the technical details that are needed to optimize MR angiographic studies, the informational content available for treatment planning is maximized. This article will illustrate our approach, which allows tailoring of the MR examination to provide the information needed by the treating clinician. The emphasis will be on the evaluation of patients with atherosclerotic occlusive peripheral vascular disease.

OVERVIEW

In planning a lower extremity intervention, it is necessary to characterize the inflow to a lesion, the outflow from a lesion, and the lesion itself. The arterial inflow is defined as the direct-line blood flow proximal to the lesion of interest. If the inflow is flawed (because of proximal occlusive disease), a distal arterial reconstruction may be jeopardized. The outflow from a lesion is defined as the arterial tree distal to the lesion under consideration. If the outflow is limited (eg, with high outflow resistance), the integrity of a vascular reconstruction may be compromised. Ideally, the arterial reconstruction is performed from an area of normal inflow to an area of normal outflow to bypass a lesion or series of lesions.

A general rule in vascular surgery is to augment flow by treating the most proximal lesions first because proximal lesions tend to be those that restrict flow to the greatest extent (2–4). It is not uncommon to achieve an improved clinical status by addressing the most proximal lesion in cases with multiple, segmental atherosclerotic foci.

In planning treatment for patients with atherosclerotic occlusive peripheral vascular disease, the most important distinctions are (*a*) between high-grade stenoses (usually >50% narrowing, including occlusions) and lesser grade stenoses (usually ≤50% narrowing) and (*b*) between short- and long-segment lesions. Those lesions with more than 50% narrowing of a vessel are most often hemodynamically significant. These somewhat broad distinctions represent practical recommendations that are sufficient for the evaluation of atherosclerotic occlusive peripheral vascular disease, unlike the more refined criteria that are employed in the evaluation of carotid artery disease.

Discrimination of the length of the diseased segment stratifies patients who are potentially amenable to a successful angioplasty procedure (≤10 cm in length) from those who are less likely to benefit (>10 cm in length). These broad distinctions, although not absolute, provide a framework for consideration.

The length, type, and site of disease influence the results of angioplasty. In general, the proximal (eg, iliac artery) and shorter-segment (<3 cm in length) lesions yield the best results (5). It should be stressed that an appropriate clinical context is essential in determining whether or not revascularization is necessary. The best treatment plans evolve from an active dialogue between the diagnostic and treating physicians.

Knowledge of the nature of the lesion itself is important to the treating clinician. Atheromatous lesions may be treated with bypass, balloon angioplasty, or stent. Thrombotic lesions are typically managed with thrombolytic therapy, while patients with embolic lesions undergo embolectomy.

The chronicity of the lesion in question will affect the therapeutic options. A chronic and gradual atherosclerotic process usually allows an abundant collateral blood supply to develop. In contradistinction, an acute arterial embolus is a sudden event precluding sufficient time for the development of collateral vessels. In that situation, it is more common for the extremity to be threatened by acute ischemia. Combinations of acute disease superimposed on chronic disease are possible and may complicate the clinical and radiologic assessment (6,7).

Angiography is the diagnostic tool that provides the vascular road map to determine therapeutic options. When considering MR angiography as a feasible alternative to conventional angiography, it is essential to generate MR angiograms that provide uniform intravascular signal intensity and sufficient accuracy in distinguishing high-grade from low-grade lesions. However, certain artifacts inherent in MR angiography pose challenges to these goals. Signal losses from in-plane saturation, turbulent triphasic and pulsatile flow, and susceptibility effects in the region of surgical clips and vascular stents are among the sources of artifacts that may degrade MR angiograms. These artifacts tend to result in an overestimation of disease, particularly when using flow-dependent methods of MR angiography (8–12). An excellent review that demonstrates pertinent artifacts and describes methods for addressing them is available to the interested reader (13).

Although contrast medium–enhanced MR angiography can minimize and sometimes eliminate these shortcomings, careful attention to appropriate timing of the infusion of gadolinium chelates relative to the acquisition strategy is needed for optimization (14–18).

Regardless of the particular MR imaging approach, the maximum intensity projection (MIP) algorithm is most commonly used to display the data. The MIP algorithm functions to project the strong signal intensity of a volumetric data set into a two-dimensional (2D) plane. The MIP images provide a presentation format to which referring physicians are accustomed and one that is similar to conventional angiography.

MR imaging and display strategies must be selected to provide the referring clinician with images that are a true and familiar representation of the vascular anatomic structures so that precise, appropriate, and confident therapeutic decisions can be made.

SCOPE OF THE DISEASE

Functional Division: Intermittent Claudication versus Limb-threatening Ischemia

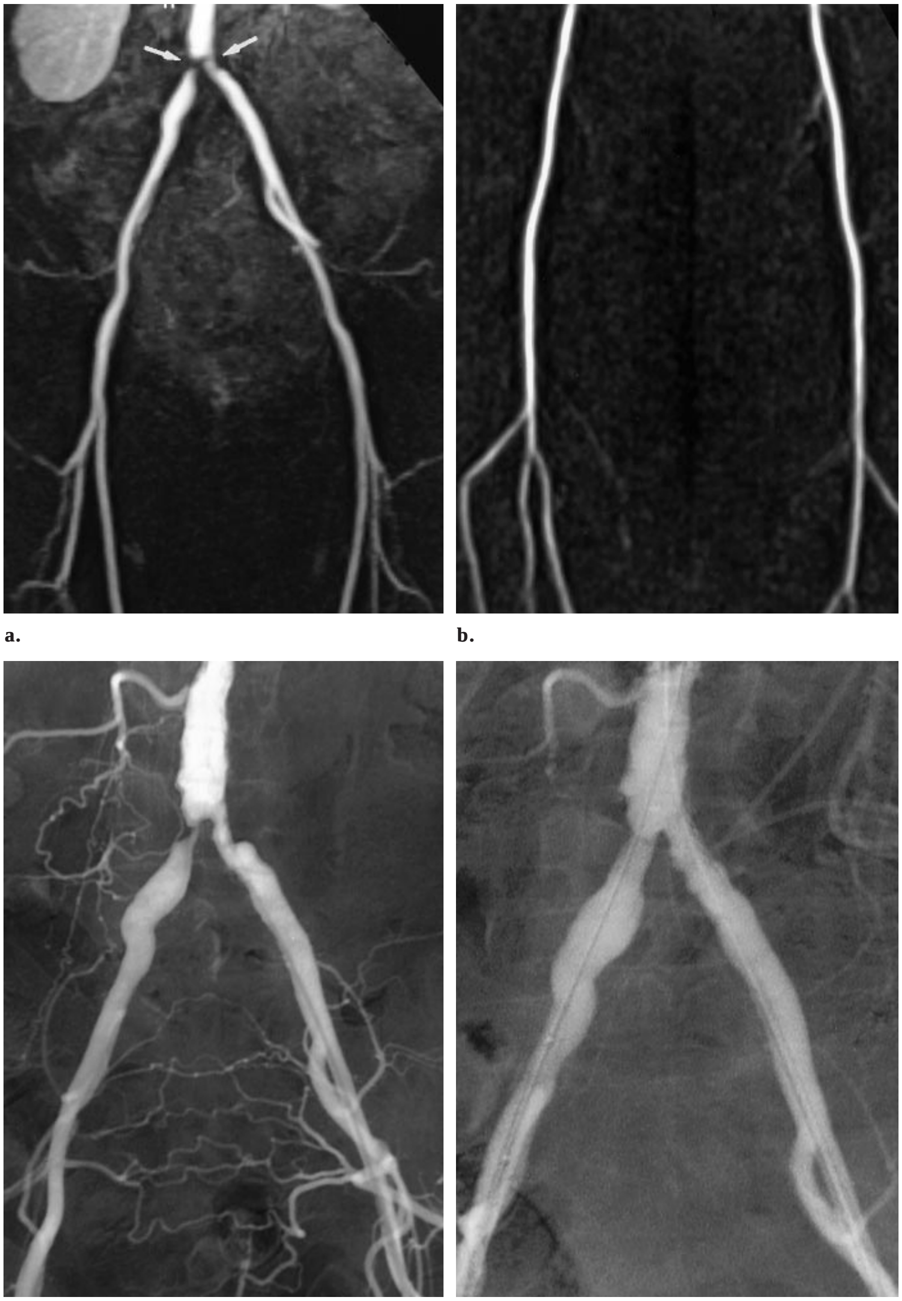
Patients with lower extremity ischemia can be conveniently divided into two groups: those with intermittent claudication and those with limb-threatening ischemia. In general, patients with intermittent claudication are considered to have a good prognosis, a benign course, a low rate of amputation, and a limited need for surgical intervention (19,20). In comparison, patients with limb-threatening ischemia are considered to have a much worse prognosis, with a higher rate of amputation if no intervention is performed, particularly in diabetic patients (21).

In the past, the presence of limb-threatening ischemia was the primary indication for pursuing angiographic evaluation as a means to plan surgical revascularization. However, with the expanded diagnostic and therapeutic armamentarium now available, the approach to patients with peripheral vascular disease is changing. The introduction of less invasive alternatives for the diagnosis and treatment of vascular disease has liberalized the indications for pursuing both. A clear shift in this direction can be found when considering those patients with intermittent claudication.

Intermittent Claudication

Treatment considerations.—The term claudication is derived from the Latin word for limp, *claudicato*. Vasculogenic intermittent claudication is defined as the inability to sufficiently augment blood flow in response to exercise. It consists of three essential features: (*a*) The pain is in a functional muscle group; (*b*) the pain is reproducible with a consistent amount of exercise; and (*c*) the pain is promptly relieved by cessation of exercise.

The level of atherosclerotic occlusive disease will dictate the symptomatic segment. Because blood flow is limited distal to a stenotic vascular lesion, symptoms typically occur one level below the segment of disease. Patients with segmental iliac artery stenosis commonly present with buttock and thigh pain from claudication (22). Patients with superficial femoral artery disease usually have calf claudication (one level below the occlusion). Those with profunda femoris artery disease may have isolated thigh claudication; this branch of the common femoral artery provides the main blood supply to the thigh. To best assess the condition of patients suspected of having vascular disease, the entire femoral bifurcation should be imaged. This is often best depicted by using oblique views or multiplanar reconstructions and is especially relevant



a. b. c. d.

Figure 1. Symptomatic iliac artery occlusive disease, diagnosed with gadolinium-enhanced MR angiography and treated with angiographically guided stent placement. **(a)** Coronal MIP image from a gadolinium-enhanced 3D MR angiographic study (5/2 [repetition time msec/echo time msec], 25° flip angle) performed with administration of gadopentetate dimeglumine at 0.1 mmol/kg demonstrates bilateral severe proximal iliac artery stenoses, with the right greater than the left (arrows). (Reprinted, with permission, from reference 37.) **(b)** The next anatomic station was imaged 10 minutes after the preceding study with a second dose of gadopentetate dimeglumine (0.1 mmol/kg) by using a slightly faster sequence (3.2/1.2, 20° flip angle). There is no occlusive disease. **(c)** Preangioplasty digital subtraction angiogram confirms the bilateral high-grade proximal common iliac artery stenoses. (Reprinted, with permission, from reference 37.) **(d)** Digital subtraction angiogram following angioplasty and stent placement demonstrates markedly improved inflow. This patient remains free of symptoms 2 years after treatment, at the time of this writing. (Reprinted, with permission, from reference 37.)

in the evaluation of the profunda femoris origins.

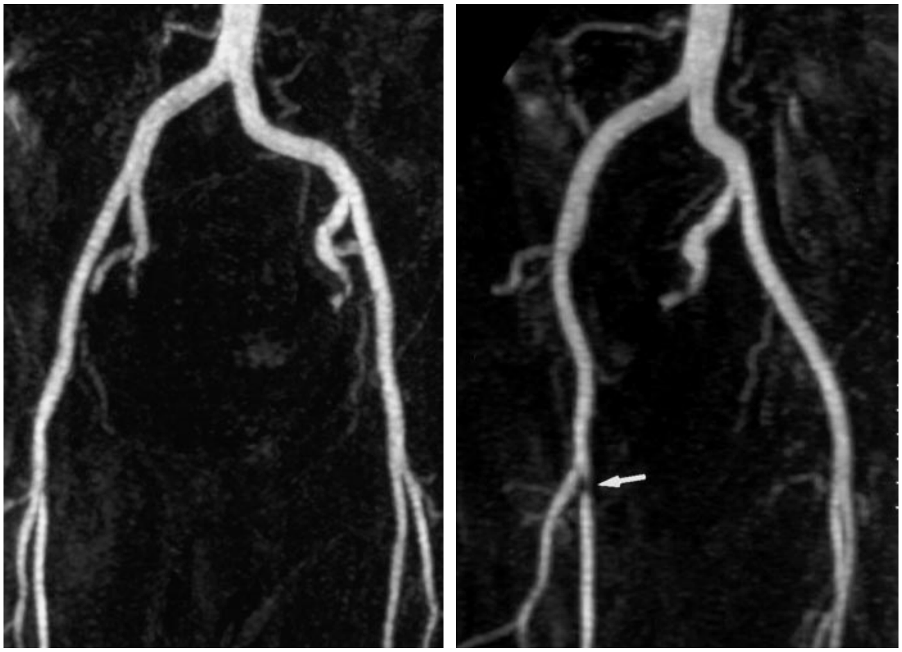
At least 10% of the population over the age of 70 years and 1%–2% of younger patients have claudication (23). From the perspective of the patient, there are two major issues. The first is the fear that such symptoms will progress to a limb-threatening situation. The second is how the patient perceives the limitations posed by a restricted capacity to exercise the affected muscular units. In some cases, this restriction can represent a minor inconvenience, while in other cases, it can interfere with essential functions of daily living.

The results of the most important studies on the natural history of intermittent claudication have been encouraging. The findings from some of these studies show that up to 80% of such patients have improvement during a 2.5–6-year period (20,24). Amputation rates for this cohort are low—in the range of 1%–2% per year (20). Because of this relatively benign course and the definable risks incurred during and after major reconstructive vascular bypass surgery, the vast majority of patients with claudication have been treated conservatively. The risk of surgery is generally not warranted, and surgery is usually confined to the extreme cases.

The advent of balloon angioplasty in the iliofemoral vascular anatomic structures offers an alternative therapeutic option. The safety and efficacy of balloon angioplasty in the iliac arteries have been documented (25,26), and stent placement seems to provide extended patency rates (27–32). Femoral balloon angioplasty procedures have also been shown to be safe but have somewhat lower long-term patency rates (31). Accordingly, imaging the vasculature of the patient with claudication centers on the aortoiliofemoral systems.

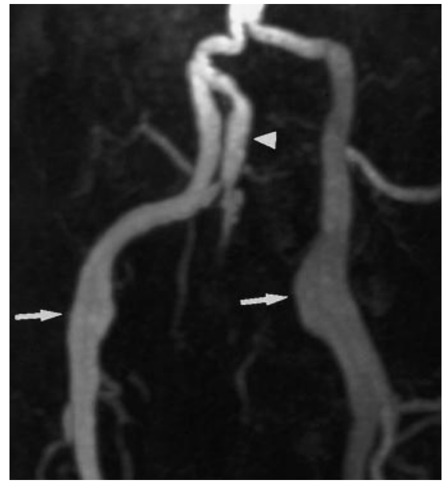
Imaging considerations.—The main goal in imaging patients with intermittent claudication is to distinguish cases that are amenable to angioplasty from those that are not. In our practice, patients with clinically relevant, short-segment (≤5-cm) lesions that are high grade and localized are referred for angioplasty, frequently followed by stent placement in the iliac position. Short, segmental lesions are associated with high success rates following angioplasty, while longer lesions are technically more difficult but possible to treat.

When using MR for diagnosis, the aortoiliac segment is best evaluated with gadolinium-enhanced three-dimensional (3D) MR angiography. Studies specifically comparing 2D time-of-flight (TOF) to gadolinium-enhanced 3D MR angiography uniformly demonstrate greater accuracy with gadolinium-enhanced 3D MR

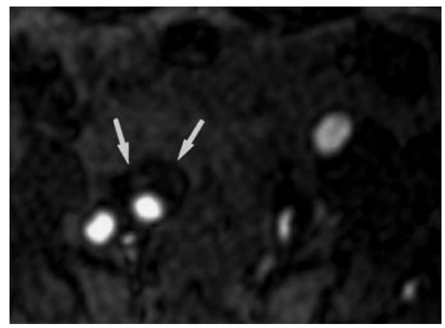


a. **b.**

Figure 2. Improved imaging of disease with an oblique view. **(a)** Frontal MIP image from a gadolinium-enhanced MR angiographic study (3.8/1.3, 30° flip angle) acquired in 23 seconds appears normal. **(b)** Oblique projection offers a different perspective, from which the presence of a high-grade, short-segment stenosis (arrow) in the proximal right superficial femoral artery can be realized. For treatment, it is essential to improve flow at this most proximal lesion.



a.



b.

Figure 3. Use of transverse reformation to diagnosis an occult aneurysm. **(a)** Frontal oblique MIP image from a gadolinium-enhanced MR angiographic study (4.0/1.6, 30° flip angle) acquired in 23 seconds shows aneurysmal disease in the femoral arteries bilaterally (arrows). Note slight prominence of the right hypogastric artery (arrowhead). **(b)** Transverse reformation obtained from the same data set used to generate the MIP image reveals a right hypogastric artery aneurysm with peripherally based thrombus (arrows). The thrombotic material does not enhance and therefore is not depicted with the MIP image. This is a clinically relevant lesion that requires treatment to eliminate the risk of rupture.

angiography (33–35). More recent studies have documented sufficient diagnostic accuracy for planning treatment options (34–36).

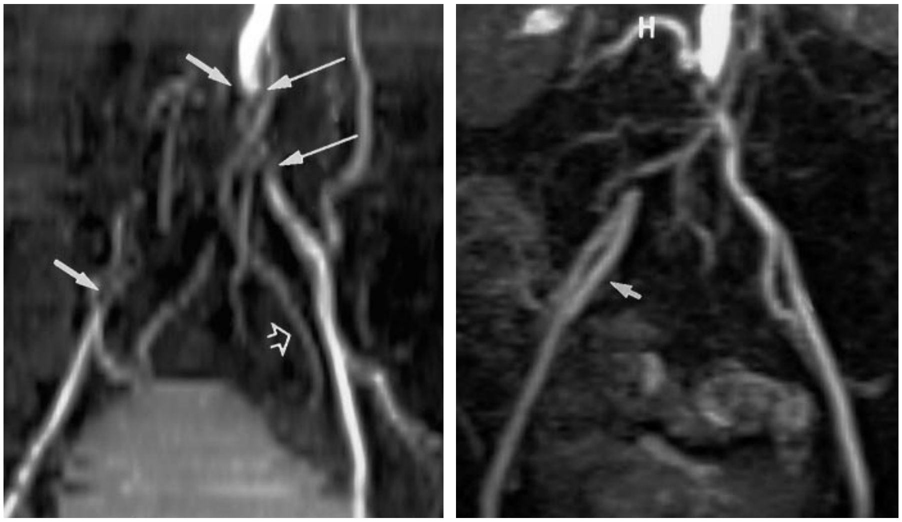
A time-efficient examination is possible by using gadolinium-enhanced 3D MR angiography for the entire claudication study (Fig 1) (37). This can be achieved with separate injections administered for the aortoiliac segment and the femoropopliteal segment (Fig 1) or with one injection by using a bolus chase technique (38,39). Alternatively, TOF (40,41) or phase-contrast MR angiography (42–44) can be used alone or in combination with a gadolinium-enhanced MR angiographic study of the aortoiliac segment.

When gadolinium-enhanced 3D MR angiography is performed with relatively thin (eg, ≤3-mm) partitions, high-quality MIP images, including those that are oblique to the plane of acquisition, can be obtained routinely from a single injection of contrast medium (see ‘‘Data Presentation’’ section for further details). Those oblique planes can be critical for depicting lesions that have a stenotic component in the anteroposterior plane (Fig 2). Recently, thick-section, 2D gadolinium-enhanced MR angiographic techniques have been developed, and these offer the possibility of reducing examination times to an extraordinary degree (45). However, such approaches eliminate the possibility of off-axis and multiplanar analyses and may thus fail to depict lesions that are in the anteroposterior plane or an occult aneurysm (Fig 3).

TOF strategies are limited by a nonspecific suppression of flow. The saturation pulse used to suppress venous flow will also suppress retrograde arterial flow. This suppression may result in an overestimation of the length of an occlusion (8–11,34). Because arterial selectivity with gadolinium-enhanced 3D MR angiography is achieved by appropriately timing the delivery of contrast medium, there is no need for a suppression pulse. Thus, retrograde flow is depicted better with gadolinium-enhanced 3D MR angiography (34). This facilitates a more accurate determination of the length of occlusive disease (Fig 4) (46), and as detailed previously, that capacity may influence the therapeutic options.

Another rationale for pursuing the gadolinium-enhanced 3D MR angiographic approach to aortoiliac vascular evaluations is the substantial reduction in acquisition time that can be achieved. For example, by using coronal gadolinium-enhanced 3D MR angiographic acquisitions, 45 cm can be covered in 20–50 seconds, depending on the resolution of the image and the gradient system of the MR machine; similar anatomic coverage can take 20 minutes with TOF imaging. The decreased acquisition times inherent in gadolinium-enhanced 3D MR angiography favor the likelihood of maintaining a consistent position and thus generating MIP images that are free of motion artifact and more acceptable to referring physicians.

It is important that gadolinium che-



a. b.

Figure 4. Overestimation of segmental occlusions with TOF imaging. **(a)** Coronal MIP image obtained with TOF imaging (repetition time [TR] = triggered; echo time [TE] = 7 msec; 70° flip angle) demonstrates bilateral iliac artery occlusions, with right greater than left. The occlusive segments are depicted between the thick arrows for the right side and between the thin arrows for the left side. Note numerous collateral vessels (open arrow). (Reprinted, with permission, from reference 46.) **(b)** MIP image from a gadolinium-enhanced 3D MR angiogram obtained after administration of gadopentetate dimeglumine. MIP image was obtained just minutes prior to the TOF data and shows a shorter length of each occlusion compared with **a**. Also note the depiction of the right hypogastric artery (arrow), which was not seen with TOF imaging. Suppression of the signal from retrograde flow is a major limitation of TOF strategies designed to eliminate venous signal. *H* = direction of head. (Reprinted, with permission, from reference 46.)

lates can be administered without the nephrotoxic effects and other adverse reactions that may be encountered with iodinated contrast media (47–50). These features are major assets and are important to communicate to referring physicians.

The lack of clinically important nephrotoxicity, even at higher intravenous doses, preserves the gadolinium-enhanced 3D MR angiographic option for patients with underlying renal insufficiency. A case of nephrotoxicity was recently reported after the use of a high dose of gadolinium chelate as a direct intraarterial injection into the renal arteries during conventional angiography (51). That experience suggests that caution should be used with intraarterial administrations but represents a different circumstance compared with the intravenous use of these products in the MR environment.

Limb-threatening Ischemia

Limb-threatening ischemia occurs when the resting blood flow is unable to meet baseline metabolic demands because of arterial occlusive disease. Clinically, this manifests as rest pain (usually affecting the forefoot), ulceration, or gangrene. The pain is typically exacerbated by elevation and alleviated by placing the extremity in a dependent position because gravity increases arterial perfusion. Gangrene occurs when arterial flow is so poor that areas with the least perfusion undergo spontaneous necrosis. However, the assumption that rest pain or tissue loss uniformly results in limb loss is not entirely valid, as shown by several studies evaluating nonsurgical therapy (52,53). Rivers et al (53) reported the healing of ischemic ulcers in 11 of 14 patients with limb-threatening ischemia treated with wound care only and no revascularization. The perception of the risk of limb loss is determined by the findings at clinical examination in conjunction with the results of noninvasive studies. This information is combined with an assessment of the vascular anatomic structures to determine surgical feasibility.

Treatment considerations.—Evaluation of the patient with limb-threatening ischemia is a much more urgent issue compared with the evaluation of the patient with claudication. The patient with critical ischemia has a poor prognosis and a high probability of requiring amputation if there is no intervention. Surgical options such as aortoiliofemoral reconstructions, infrainguinal bypasses, and even tibial reperfusions are more vigorously pursued in ischemic patients because the consideration of surgical risk is tempered by the threat of tissue and limb loss.

These patients typically have multiple areas of occlusive disease and thus require a complete evaluation from the infrarenal abdominal aorta to the foot. High-grade proximal lesions are important to address to improve peripheral perfusion to the lower extremity and to enhance the inflow to a distal bypass. Although ischemia may be lessened with a proximal procedure, it is crucial to restore pulsatile flow to the level of gangrene in patients with tissue loss. Attempts to achieve such restoration are best pursued when there is arterial continuity to the foot, reiterating the necessity for a complete evaluation down to the pedal arch (54).

Imaging considerations.—The considerations for evaluating aortoiliofemoral segments in ischemic patients are similar to those developed in the discussion on imaging patients with claudication. The popliteal artery is a key vessel for evaluation because it is a frequent target for insertion of a surgical bypass graft. It is important to provide osseous landmarks when depicting the popliteal artery so that the site of the surgical incision and the type of graft material are appropriate (55). Surgical procedures on the popliteal artery carry a lower morbidity when confined to the supra- or infrageniculate segments. The portion of artery behind the knee is the most difficult to expose, requiring a division of the medial head of the gastrocnemius muscle. This results in a higher morbidity compared with surgery confined to the supra- or infrageniculate segments. In addition, it is acceptable, if not advisable, to use a prosthetic graft to the suprageniculate popliteal artery, but patency rates decline sharply when a prosthetic graft is sewn to a below-knee segment. Autologous vein is preferred as the graft material when performing a femoropopliteal bypass that inserts below the knee.

When the popliteal artery is being considered as an outflow vessel for a bypass graft, the runoff vessels to the foot must be imaged. It is essential to ascertain whether or not there are tibial vessels in continuity with the popliteal artery and, in turn, with the pedal arch because this information will determine the choice of the outflow vessel in a proposed bypass. For example, consider a superficial femoral artery occlusion with reconstitution of the popliteal artery, as well as occlusive disease in the tibial vessels such that none are in direct continuity with the foot. In this case, a proposed bypass graft would likely be inserted beyond the occluded portion to the reconstituted tibial vessel that demonstrated distal direct-line flow to the gangrenous foot (Fig 5) (37).

On occasion, a bypass may be placed into a "blind" or isolated popliteal segment. The isolated popliteal artery has no direct inflow or outflow (Fig 6) (37,56–58). Bypass to such a vessel may be desirable when the tibial arteries appear inadequate as outflow vessels.

To determine the suitability of a blind popliteal segment for bypass, imaging of the popliteal artery requires a measurement of its length and an assessment of the associated collateral bed. When serving as the insertion site of a bypass, the blind popliteal artery should measure 7–10 cm in length (59) and be associated with multiple geniculate collateral vessels (Fig 6).

When considering the blind popliteal segment, TOF imaging should be used cautiously because it may underestimate the patent length of popliteal artery when retrograde filling occurs, as previously described. Properly timed gadolinium-enhanced images will better define the entire patent segment.

Distal bypasses, including femorotibial artery bypass, are becoming increasingly common when the tibial arteries are the only available outflow vessels (60–62). Such bypasses are useful when restoration of pulsatile flow to a gangrenous pedal segment is needed. For these distal bypasses, osseous landmarks (femoral condyles, tibial tuberosity, and the malleoli) are important components of the images. These landmarks allow the surgeon to make the appropriate incision for the segment of tibial vessel that requires access (Fig 5).

The surgical approaches to the anterior tibial, posterior tibial, and peroneal arteries differ. In addition, surgical exposure of a given tibial vessel can depend on whether the surgical site is in a proximal or distal position. For example, proximal exposure of the peroneal artery requires a medial approach, whereas distally, in the lower third of the calf, a lateral exposure is preferred (63).

Currently, the MR angiographic approach to the tibial vessels is dominated by the use of TOF techniques (41,64–66). This flow-dependent strategy circumvents the challenge of achieving a sufficient concentration of contrast medium to effectively demonstrate the distal arterial vessels.

The use of the extremity coil for the evaluation of the tibial and foot vessels has documented efficacy (66–69) and offers images with high in-plane spatial resolution. However, this strategy requires constant repositioning of the coil, with an attendant time investment. A complete runoff with exclusively TOF imaging and small field-of-view coils can require 2 hours of table time (70).

The tibial vessels have been imaged successfully by using head coils (71,72), dedicated peripheral vascular coils (70,73,74), and the body coil (41,65). The use of larger coils provides an option for improved efficiency in examination times at the expense of the signal-to-noise ratio; despite this trade-off, similar levels of accuracy for surgical planning have been demonstrated compared with the use of the extremity coil. An approach that incorporates larger coils may yield different results across MR imager vendors, exposing differences in the proficiency of their respective coil systems.

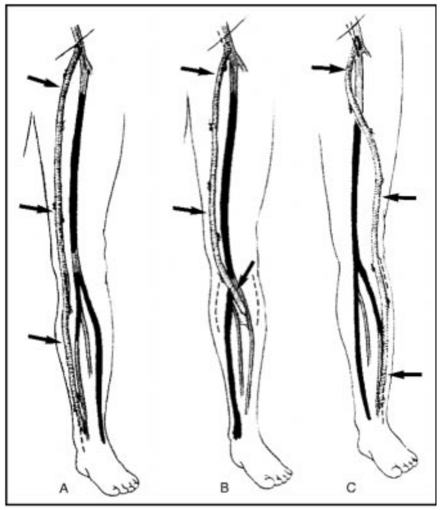
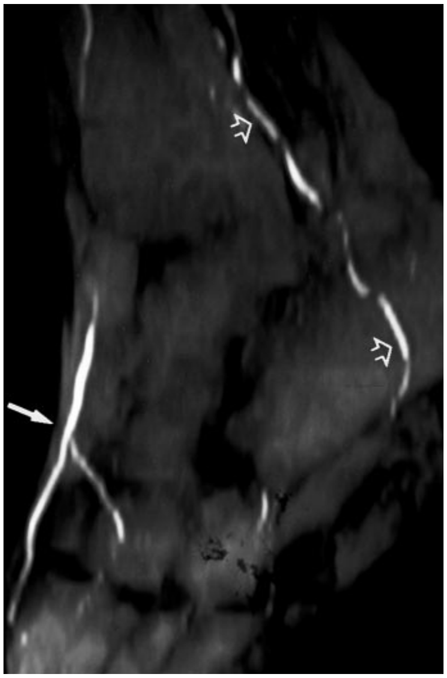


Figure 5. Illustrations of hypothetical distributions of atherosclerotic occlusive peripheral vascular disease, including surgical incisions for routing of bypass grafts. Occluded segments are indicated in black. Graft segments are indicated by arrows. ***A,*** This femoral artery–distal posterior tibial artery bypass graft originates from an area of normal inflow to an area with normal outflow around the levels of occlusive disease. *B*, Femoral–proximal anterior tibial artery bypass graft procedure is best performed with a lateral infrageniculate exposure of the recipient vessel. If the proximal peroneal artery were chosen as a graft insertion site, a medial approach would be preferred. *C,* Femoral–distal anterior tibial artery bypass graft procedure is performed through a distal lateral exposure. That exposure also is sufficient for a distal peroneal artery bypass. The osseous landmarks can be used to help identify the outflow vessel and thus guide the surgical approach. (Reprinted, with permission, from reference 37.)

Figure 6. A "blind" popliteal segment. This frontal MIP image from a 2D TOF MR angiogram (TR = triggered; TE = 7 msec; 70° flip angle) shows a popliteal artery (long arrow) that is isolated from the circulation. Note the relatively long length of that segment, as well as the numerous collateral vessels (short arrows). In this case, a bypass to that popliteal segment would be preferred over a longer bypass to an infrageniculate segment. (Reprinted, with permission, from reference 37.)

Preliminary data suggest that gadolinium-enhanced MR angiography can be used to study the tibial vessels (36,38,45). Gadolinium-enhanced MR angiography offers the possibility of decreased acquisition and examination times. It may also circumvent in-plane saturation effects that at times may limit the demonstration of the proximal anterior tibial artery and portions of the pedal arch. However, it remains to be seen whether gadolinium-enhanced strategies below the knee will provide sufficient accuracy and reproducibility to be implemented on a routine basis.

The selection of a particular tibial artery as a recipient vessel for bypass is favored when that vessel is continuous with the pedal arch (54). Direct flow into the pedal arch has definite benefits. First, it will facilitate pulsatile flow to the level of pedal tissue loss. Second, direct flow into the pedal arch augments the outflow



a.

b.

c.

Figure 7. Evaluations of the pedal arteries with conventional digital subtraction angiography, TOF MR angiography, and intraoperative angiography. **(a)** Sagittal MIP image from a 2D TOF MR angiogram of the foot (TR = triggered; TE = 7 msec; 70° flip angle) demonstrates an isolated segment of dorsalis pedis artery (solid arrow), as well as incomplete posterior tibial artery segments (open arrows). **(b)** Conventional digital subtraction angiogram obtained prior to MR angiography does not depict any outflow vessel in the foot because of multiple-level occlusive disease and a limited delivery of contrast medium to the foot. **(c)** After depicting the occult pedal artery with MR angiography, an anterior tibial–dorsalis pedis bypass procedure was performed. This intraoperative angiogram shows outflow through the dorsalis pedis artery (long arrow), as well as plantar collateral vessels (short arrow).

bed and decreases resistance beyond the bypass graft, thereby favoring improved graft patency rates. Although an isolated (blind) pedal arterial segment is not a direct contraindication to bypass, this poor outflow situation often predicts a shorter period of patency (54,61,62,75). With poor outflow, the surgical procedure may be modified to maximize long-term patency.

The use of TOF imaging can demonstrate pedal vessels that may not be depicted at conventional angiography (41,66,69). When evaluating the comparisons of TOF MR imaging strategies with conventional angiography, it is important to consider the details of the techniques. This is particularly relevant when considering the detection of the ‘‘occult’’ vessel. The use of selective arterial injections and of digital subtraction techniques optimizes conventional angiography (76), and such an approach may decrease the frequency with which an occult vessel is depicted. Nevertheless, when discovered, the occult vessel may provide a surgical bypass option as a replacement for amputation; therefore, MR angiography can serve a vital role for patients with limb-threatening ischemia (77) (Fig 7).

With TOF imaging, there is a limited capacity to image the entire pedal arch. That limitation is caused by in-plane saturation effects. In patients with tissue loss and in those patients under consideration for amputation, the lack of a pedal arch will not deter the surgeon from performing a distal bypass. However, a definitive determination of the status of the pedal arch allows more precise surgical treatment. At present, TOF imaging offers the surgeon sufficient information to make the primary surgical decisions (Fig 7). When the status of the pedal arch is in question, an assessment of outflow may be performed during surgery by using a manual injection of iodinated contrast medium and conventional angiography. A more refined preoperative analysis of the pedal arch may be possible by using gadolinium-enhanced MR angiography, which circumvents in-plane saturation effects. However, the demands for gadolinium-enhanced MR angiography in the more proximal vasculature and the lack of a sufficient number of studies to document efficacy currently limit its use in this capacity. More studies will be required to determine the best overall use of contrast-enhanced MR angiography for atherosclerotic occlusive peripheral vascular disease.

Arterial handling is a concern for the surgeon planning an operation. Manipulations of arteries during bypass include surgical exposure, arterial clamping, arteriotomy, and anastomosis. Although most types of atherosclerosis are readily manageable, arterial calcification may pose a challenge to the vascular surgeon (78). Severe vascular calcification may interfere with both ‘‘clampability’’ and ‘‘sewability.’’ In this regard, diabetic patients and patients undergoing dialysis are more often problematic. MR imaging does not provide a reliable demonstration of vascular calcifications. Although such a capacity would be desirable for surgical planning, the presence of vascular calcifications is not a definitive contraindication to bypass (78). A simple solution is provided by obtaining a radiograph of the extremity at the level of planned anastomotic sites. Inclusion of the osseous landmarks with MR angiography will facilitate a cross-reference between the planned anastomotic sites and any vascular calcifications identified at conventional radiography.

ANATOMIC COVERAGE

In the context of accomplishing a time-efficient evaluation of lower extremity peripheral vascular disease, it is necessary to consider the anatomic coverage that is essential. This is most pertinent in deciding whether inclusion of the renal arteries is required.

The routine evaluation of the renal arteries during conventional arteriography is fairly standard. This approach has evolved from concerns that high-grade renal artery atherosclerotic disease may progress to occlusion or renal insufficiency, or both (79–82).

The inherent risks of conventional angiography provide motivation to study the renal arteries at the time when the catheter is in the abdominal aorta. This is despite the fact that a simultaneous repair of the renal arteries in the setting of peripheral vascular disease is not a consideration unless an aortic procedure is being planned. The routine evaluation of the abdominal aorta should be more feasible as multistation evaluations with bolus chase techniques proliferate (38,39,83,84).

A practical protocol can initiate the peripheral vascular evaluation at the infrarenal abdominal aorta, just above the level of the aortic bifurcation. Anatomic coverage of 40 cm in the craniocaudal plane will usually extend from this level to the proximal superficial femoral artery. A coronal contrast-enhanced acquisition that uses larger fields of view risks some warping of the anatomic findings at the extremes.

Prior to studying the vessels in the pelvis and proximal thigh, one can obtain transverse breath-hold T1-weighted images (8–10-mm section thickness) from the level of the renal arteries to the bifurcation to serve as a screen for disease that might require an aortic procedure. Should aneurysmal disease or substantial plaque be present or if a clinical suspicion of renal artery stenosis exists, a dedicated renal examination could be obtained at another time, later that day or on the following day. Such an examination should also include any portion of the infrarenal abdominal aorta that had not been studied previously.

From a safety perspective, there is no disadvantage to repeating a separate MR angiographic evaluation of the renal arteries at another time. In fact, a gadolinium-enhanced MR angiographic study tailored specifically to the renal arteries will benefit from the use of a smaller field of view to achieve better resolution as compared with a ‘‘comprehensive’’ study that attempts to include the renal arteries along with the pelvic arteries. If TOF techniques are used for the aortoiliac segment, the reduced number of transverse sections will decrease the total examination time considerably when the study excludes the renal arteries and a portion of the infrarenal abdominal aorta.

Imaging Parameters Used in MR Angiography of the Peripheral Vasculature at 1.5 T

Parameter	3D Gadolinium-enhanced: With High-Performance Gradients	3D Gadolinium-enhanced: With Standard Gradients	2D TOF with ECG Triggering	2D TOF
Plane	Coronal	Coronal	Transverse	Transverse
TR (msec)	≤7	≤21	Heart rate	24–45
TE (msec)	≤2	6–7	7	7
Gradient moment refocusing pulse	No	Yes	Yes	Yes
Flip angle	25°–50°	25°–50°	≤70°	≤70°
Section thickness (mm)*	≤3	≤3	Leg, 3; foot, 2	Leg, 3; foot, 2
Field of view (cm)	≥35	≥35	≤35	≤35
In-plane resolution (mm)	≤2.5	≤2.5	≤1.5	≤1.5
Acquisition time	≤40 sec per slab	≤4 min per slab	≥5 sec per section	≥5 sec per section
Gap	NA	NA	≤0	≤0
Gadolinium administration	1–2 mL/sec	Slow infusion	NA	NA

Note.—NA = not applicable. Number of phase-encoding steps = field of view/in-plane resolution.
* Zero fill or interpolation strategies are recommended for the 3D strategies.

PERIPHERAL MR ANGIOGRAPHY ‘‘RUNOFF’’: OUR TECHNIQUE

In our experience, a complete evaluation from the infrarenal abdominal aorta to the feet is best obtained by using a combination of 2D TOF MR angiography and gadolinium-enhanced 3D MR angiography, with the patient positioned feetfirst in the magnet (Table). Depending on the ability of a given patient to cooperate, this strategy takes between 1 and 2 hours of table time. To improve the efficiency of the examination and minimize table time, appropriate patient preparation should occur outside the magnet. This preparation includes establishing intravenous access, application of electrocardiographic leads, effective premedication, breath-hold coaching, consideration of the need for oxygen supplementation, elevation of the lower extremities, and a discussion of the procedures to be performed. We have found that a liberal use of sedatives and the appropriate use of analgesics for pain will minimize patient motion.

In our approach, TOF imaging is performed prior to gadolinium-enhanced 3D MR angiography. If TOF imaging is obtained after gadolinium-enhanced 3D MR angiography, the presence of circulating contrast medium can limit the ability to effectively suppress the signal from veins (85).

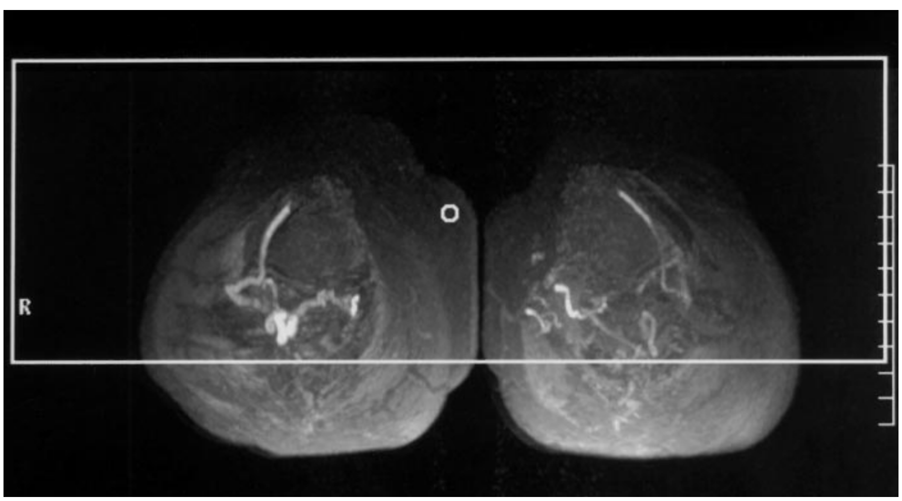
Foot and Tibial Vessels

The anatomic segment from the distal metatarsal bones to just above the ankle joint is acquired with oblique transverse thin sections by using a flow-sensitive 2D gradient-echo sequence with a head coil. The oblique transverse orientation is selected so that the section is perpendicular to the flow in the dorsalis pedis artery and the plantar branches of the posterior tibial artery.

Then true transverse images are obtained by using a spine phased-array coil with a flow-sensitive 2D gradient-echo sequence extending from the ankle joint to the knee joint. Use of the spine phased-array coil eliminates the frequent repositioning required when extremity or head coils are used for this anatomic region and thus decreases the examination time. Our use of the spine phased-array coil combines opportunities for improved anatomic coverage and signal-to-noise ratio but results in less uniform signal intensity, with extremely high signal emanating from tissues closest to the coil. We have found that the use of restricted volumes of interest for the MIP images is an effective means of dealing with that issue (Fig 8).

a.

c.



b.

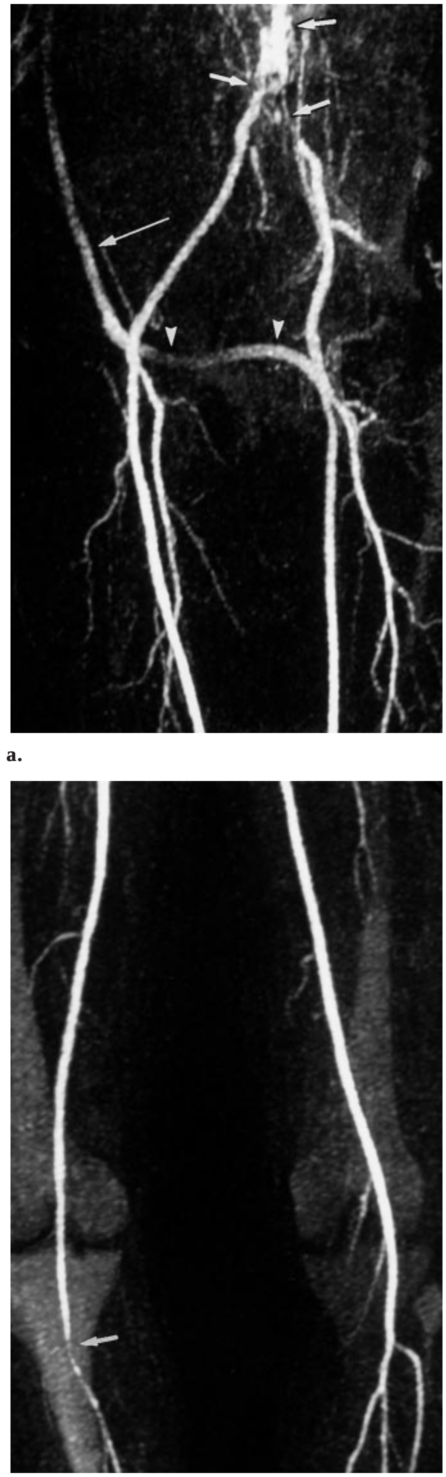
Figure 8. Improved TOF MIP images with use of a restricted volume of interest. **(a)** Vascular anatomy of popliteal and tibial artery segments was obtained with electrocardiographically triggered 2D TOF imaging (TR = triggered; TE = 10 msec; 70° flip angle) by using spine phased-array coil. This coronal MIP image was generated from transverse source images by using the full volume of interest. The MIP algorithm incorporates relatively bright pixels from posterior soft tissues that are close to the coil. **(b)** Collapsed view of transverse source image data depicts the anterior and posterior extent of the vessels. This view allows the operator to exclude bright nonvascular soft tissues by restricting the volume of interest (box). Circle indicates the center about which MIP images would be generated. **(c)** Restricted-volume-of-interest coronal MIP image yields a better demonstration of the vascular anatomic structures. The right posterior tibial artery (long arrow) is now depicted, as are the midtibial vessels on the left (short arrows). Spine phased-array coil allows longer segments of anatomic structure to appear on the MIP image compared with head or conventional extremity coils.

Flow-sensitive imaging below the knee eliminates the challenge of achieving a sufficient concentration of contrast medium to allow for a selective demonstration of the distal arteries. The straight-line flow in the tibial vessels below the knee is ideally suited to TOF imaging.

Aortoiliofemoral Vessels

After the TOF evaluation, the patient is repositioned for an evaluation of the vascular anatomic structures from the infrarenal abdominal aorta to the proximal thigh with the body coil. This segment is studied by using gadolinium-enhanced 3D MR angiography. With this approach, the horizontal and posterior course of the iliac arteries can be assessed free of the in-plane saturation effects that limit a 2D TOF evaluation in this region (33–35). Using a reduced dose in the aortoiliac segment decreases the residual background signal intensity for the subsequent evaluation or evaluations (36).

The next segment encompasses the vas-



a. b.

Figure 9. Bolus chase technique with manual patient movement performed following the insertion of an axillofemoral and femorofemoral graft. **(a)** Oblique coronal MIP image of the first anatomic region obtained during the infusion of gadolinium chelate with a 3D gradient-echo sequence (4.0/1.6, 30° flip angle) acquired in 22 seconds. The distal right axillary graft component (long arrow) is depicted, as is the crossover (femorofemoral) graft (arrowheads), in this patient who had achieved only a partial result following thrombolytic therapy for infrarenal aortoiliac occlusive disease (short arrows). Contrast-enhanced MR angiography is useful for demonstrating both graft segments in a short acquisition time. **(b)** The next anatomic segment was obtained immediately after **a** by manually moving the patient with the use of a plastic board. This coronal MIP image shows a good depiction of the left trifurcation, and a high-grade stenosis (arrow) is noted at the origin of the right tibial–peroneal trunk. There is an occlusion of the right anterior tibial artery.

cular anatomic structures from the proximal thigh to just below the knee and is also studied by using the body coil with gadolinium-enhanced 3D MR angiography. This is best accomplished by first obtaining a baseline series of images to serve as a subtraction mask for a subsequent set of arterial phase images in that segment. More recently, we have been using bolus chase strategies to condense the aortoiliac and femoropopliteal evaluations (see “Bolus Chase Strategies” section).

By ensuring that the anatomic coverage in this region extends below the knee, one can image the trifurcation with a contrast-enhanced study, circumventing the in-plane saturation effects and other artifacts that limit a 2D TOF evaluation in this region. This point is most pertinent to the assessment of the proximal anterior tibial artery. For 2D TOF studies, an evaluation of source images can often be clarifying; however, it may be difficult to convey this information to referring clinicians.

Confidence in the status of the proximal anterior tibial artery is especially important when distal tibial bypass grafts are being considered. If a lesion exists that is falsely attributed to artifact, a bypass graft originating below that level will likely fail. Conversely, a false impression of disease may unnecessarily limit treatment options.

BOLUS CHASE STRATEGIES

Recently, a bolus chase concept has been applied to gadolinium-enhanced MR angiography of the peripheral vasculature (38,39,83,84), and this approach offers potential advantages. The concept relies on imaging sequential anatomic sites during a time when there is preferential concentration of contrast medium in the arteries. This is dependent on moving the patient during the injection of contrast medium.

The bolus chase can be achieved by (*a*) manually moving the patient (eg, by using a plastic board), (*b*) manually moving the table, or (*c*) using automated table movement. The bolus chase approach to peripheral MR angiography extends the anatomic coverage that can be acquired with a given dose of contrast medium and has the capacity to greatly reduce table times. The early data suggest that slower infusion rates (0.3–0.5 mL/sec) are successful. We have had experience with both a manual patient-movement approach to the bolus chase (Fig 9) and, more recently, with a new implementation of an automated table movement.

Our preliminary, unpublished experience with the manual movement approach has yielded good correlation with conventional angiograms for the aortoiliac and femoropopliteal stations. In this approach, the patient is placed feet-first in the magnet and initially is positioned for the aortoiliac evaluation. Before the injection of contrast medium, we obtain a precontrast image of the aortoiliac segment to serve as a mask for subsequent subtraction from the postcontrast image of the segment. We do not obtain a precontrast data set in the femoropopliteal segment because in our early experience we noticed a lack of precision for the patient movement that often resulted in suboptimal subtraction.

A fat-suppressed, fast 3D imaging sequence can be used to minimize background signal intensity, which is especially important for the femoropopliteal segment. To ensure the capture of the arterial phase, a test dose of gadolinium chelate is visualized at the infrarenal abdominal aorta, and the circulation time is determined. The circulation time, in conjunction with the injection and acquisition times, is evaluated to determine the delay time between the initiation of the injection and the initiation of the image acquisition (14).

A 5-second delay is placed between each data set acquisition; during that delay period, two individuals pull the plastic board to move the patient. The infusion of contrast medium at 0.8–1.0 mL/sec with a power injector has proved successful for both the aortoiliac and femoropopliteal segments; we have not been satisfied with the results achieved below the knee. To a large degree, our manual bolus chase technique in that segment has been limited by the inability to perform satisfactory subtraction, coupled with what we believe to be insufficient signal-to-noise ratio.

Automated table movement bestows

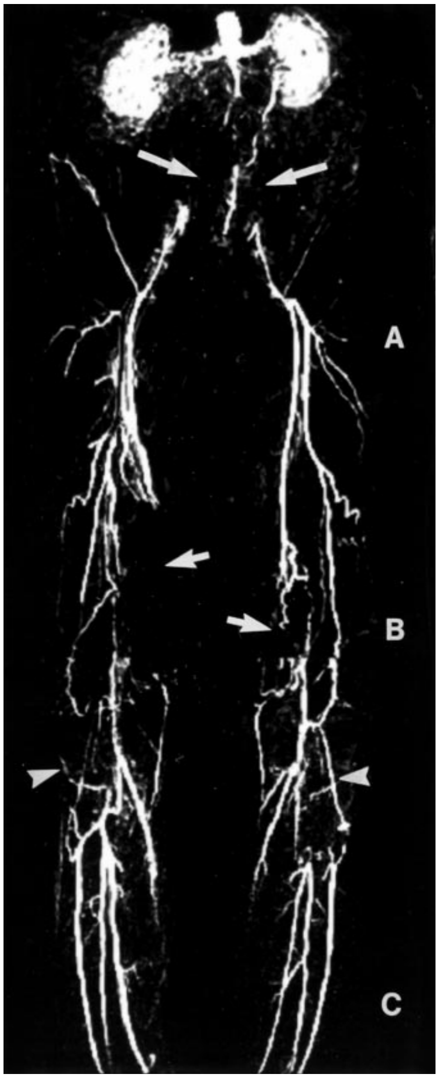


Figure 10. Bolus chase technique with 3D gradient-echo technique (6.0/2.2, 30° flip angle) and automated table movement in a patient with claudication. Three separate coronal MIP images of overlapping regions of vascular anatomic structures are presented in continuous display. *A*, The aortoiliac segment shows occlusion of the infrarenal abdominal aorta and the common iliac arteries (long arrows), with reconstitution of the distal external iliac arteries. *B*, There are bilateral segmental occlusions of the superficial femoral arteries (short arrows) with reconstitution of the popliteal arteries via profunda collateral vessels. *C*, Disease at the popliteal arteries is seen bilaterally with geniculate collateral vessels (arrowheads) reconstituting three-vessel runoff in both legs. The pre- and postcontrast data sets were obtained with only 200 seconds of examination time for both. However, procedural setup and proper positioning require a greater overall table time.

precision in reproducing patient positions. This in turn optimizes image coregistration, and hence subtraction is feasible at all anatomic stations (Fig 10). Because the current bolus chase strategies are limited to the use of the body coil, the tibial vessel component of the evaluation tends to be limited by poor signal-to-noise ratio. Although some data suggest good results in the tibial vessels (38,45), it remains to be seen if such images will be routinely accepted by surgeons as an exclusive means to plan infrageniculate vascular bypass procedures. The use of dedicated peripheral vascular coils in concert with bolus chase strategies is predicted to provide substantial improvements in the signal-to-noise ratio and may yield a more compelling tibial vessel evaluation.

POSTPROCEDURAL EVALUATIONS

Patients who require an anatomic assessment of a treated segment of disease can benefit from MR angiography (86). The study can be used to confirm a suspicion of a failing graft after clinical screening or sonographic screening or both. The extended coverage available in a single acquisition of contrast-enhanced MR angiography is particularly beneficial when long-segment grafts are evaluated, such as axillofemoral, femoropopliteal, or femorotibial grafts. Femorofemoral crossover grafts are commonly used in conjunction with longitudinally oriented grafts (eg, axillobifemoral bypass) (87). In these cases, contrast-enhanced MR angiography is particularly effective at demonstrating both graft components (Fig 9). When a TOF strategy is used to evaluate the condition of patients with axillobifemoral bypasses, one of the two graft components will be vulnerable to in-plane saturation effects. Hence, a single TOF acquisition plane will not be satisfactory, and a complete assessment will be especially time-consuming.

MR angiography after angioplasty is efficacious for the assessment of the pelvic vessels (88,89). However, when patients have been treated with intravascular stents, there is a risk of signal loss from susceptibility effects (90,91). This loss can result in a false impression of disease from artifactual signal losses, even with gadolinium-enhanced approaches (36,70). Measurement of flow velocities proximal and distal to the stent may, in the future, be used to provide indirect data with regard to stent patency. Such an approach requires validation of clinical efficacy and suffers from the inability to image neointimal hyperplasia. However, preliminary data obtained from patients before surgery are encouraging (92).

MR ANGIOGRAPHY: NOT FOR EVERYONE

Some patients with vascular disease are not candidates for MR angiography. There are general contraindications to the MR imaging environment and theoretic concerns with regard to gadolinium chelate administration in certain circumstances (93). Furthermore, the severity of vascular disease may obviate the use of MR imaging.

Acute, severe arterial ischemia requires rapid intervention to minimize the risk of limb loss. This includes patients who present with neuromotor symptoms (eg, paralysis or paresthesias). Patients who require emergency revascularization are often best managed with directed intraoperative angiography (94).

If the working diagnosis mandates a treatment plan of thrombolysis, conventional angiography should be pursued to streamline the transition between diagnosis and treatment. Similarly, a patient who has a thrombosed prosthetic femoropopliteal artery bypass (without neuromotor compromise) is better managed in the interventional radiology suite.

As previously mentioned, the presence of indwelling stents can cause severe artifacts that may render MR angiography inaccurate or nondiagnostic (36,70). The use of MR angiographic techniques with long examination times may be unsuccessful in patients with coexistent morbidities such as severe congestive heart failure and degenerative joint disease. In addition, lengthy acquisition times can render images in these patients vulnerable to motion degradation.

Because the presence of peripheral vascular disease is associated with coronary artery disease (95–97), patients should be screened carefully for the presence of implanted electronic devices such as pacemakers and defibrillators prior to accepting a referral for MR angiography.

IMAGE EVALUATION

Although most of the reported values for sensitivity and specificity of peripheral MR angiography are based on MIP images, it is important to remember that MR angiography has unique informational content in the cross-sectional data set (9,98).

A routine part of our practice includes an interactive phase of the evaluation, during which image manipulation is performed with the commercially available software of our system. The MIP image serves as a reference from which multiplanar reformations are generated in real time. Usually, a reconstruction plane that is perpendicular to the course of a vessel is selected for this purpose. In this manner, cross-sectional data easily can be ascribed to a location in the MR angiogram. This can be particularly useful with diseased tibial vessels, which, when viewed in cross section, can be clarifying.

The MIP technique can provide views from a large number of angles and thus offers a better definition of certain lesions. In particular, that capacity can demonstrate certain details that may be missed in the anteroposterior projection (Fig 2). In addition, some small plaques that are less conspicuous on MIP images may be readily depicted by using the cross-sectional data, either the source images or multiplanar reformations. The cross-sectional content is the truly unique information afforded by MR studies that is unavailable from conventional angiographic evaluations. The radiologist is encouraged to exploit the additional potential of MR angiography by analyzing this information.

Scrutinizing the source data can also expose artifacts that may be helpful for identifying flow. A ghosting artifact, seen as signal intensities visualized along the phase-encoding direction with a size and shape similar to an underlying vessel, indicates the presence of flow. Conversely, jagged details and occlusive appearances may be artifactual, by virtue of signal intensities too weak to be incorporated into the MIP. Those weak signal intensities can on occasion be identified on source images. Discrepancies between the MIP and source data must be clarified for the referring physician. An active dialogue between the diagnostic and treating physicians should facilitate that process; however, a practical reality is that vascular surgeons tend to prefer images that are familiar to them and free of artifacts. Therefore, the radiologist should always be pursuing those imaging strategies that are least prone to artifacts.

DATA PRESENTATION

Image processing and formatting schemes are important considerations. These schemes are directed toward generating a succinct and familiar presentation that provides a ''user-friendly'' data set.

Our routine for generating MIP images is to obtain 13 projections over 180°, beginning from the left lateral projection and proceeding to the right lateral projection. This routine is a semiautomated procedure that uses commercial software available on many MR systems. A projection that is in the identical plane of the original acquisition will demonstrate the best resolution. The off-axis projections introduce the section-select resolution into the image, which is generally inferior to the in-plane resolution.

It is important to limit the presentation to the most relevant images that detail or clarify sites of disease. Most clinicians are not inclined to review the huge number of source images that compose the basis of the MIPs.

The number of images prepared should also be restricted as a practical concern for vascular surgeons. Such an approach appreciates the realities of surgical practice—many operating rooms have a limited number of view boxes, and larger images are more easily viewed from a distance. We like to distill the images down to two films by using a six-on-one format. The first sheet is devoted to presenting the aortofemoral and femoropopliteal segments of vascular anatomic structure, while the second sheet is devoted to presenting the vascular anatomic structure below the knee.

CONCLUSIONS

As diagnostic and treatment options for patients with atherosclerotic occlusive peripheral vascular disease are evolving, a more liberal use of MR angiographic evaluations is emerging. Radiologists must have a thorough knowledge of what the treating physicians want and need to know if peripheral MR angiography is to fulfill its potential as a primary diagnostic strategy. The radiologist who both understands the clinical perspectives and is proficient with MR techniques will be best positioned to serve an integral role in the team approach to the improved care of patients with peripheral vascular disease.

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