Vascular Imaging of the Foot: The First Step toward Endovascular Recanalization

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In the past 5 years, with the introduction of new techniques and dedicated materials, endovascular recanalization of distal tibial and pedal vessels has become a valid alternative to inframalleolar bypass for limb salvage in patients with severe arterial occlusive disease, particularly diabetics. Revascularization of the foot is now often performed by using percutaneous transluminal angioplasty; over a 4-year period, the authors performed more than 2500 antegrade interventional procedures in patients with critical limb ischemia, diabetes, and infrainguinal arterial disease. Intraprocedural angiography of the foot is crucial for successful planning and guidance of percutaneous transluminal angioplasty in tibial and pedal arteries, and its effective use requires both anatomic knowledge and technical skill. To select the best revascularization strategy and obtain optimal clinical results, interventional radiologists, cardiologists, and vascular surgeons performing below-the-knee endovascular procedures also must be familiar with the functional aspects of circulation in the foot. Supplemental material available at http://radiographics.rsna.org/lookup/suppl/doi:10.1148/rg.316115511/-/DC1.

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Introduction
Critical limb ischemia (CLI) is most commonly due to atherosclerotic peripheral arterial disease and develops when the blood flow does not meet the metabolic demands of tissue at rest. This condition, manifested by pain during rest and by nonhealing ulcers and gangrene that are usually located in the toes, forefoot, or heel of the affected limb, is the main nontraumatic indication for lower limb amputation. Diabetes is the most important risk factor for CLI; atherosclerosis not only develops at a younger age in diabetics than in other patients, but also more often affects the more distal vessels (those below the knee and in the foot) (1–5).

Despite the benefits of pharmacologic therapy, arterial revascularization remains a mainstay in the management of CLI because the restoration of adequate blood flow to the foot is crucial to provide pain relief, promote wound healing, and avoid amputation. Although surgical revascularization is an important therapeutic option, recent data support the use of percutaneous transluminal angioplasty, which is both feasible and safe, in this setting (6–9).

In recent years, more aggressive techniques have been developed to improve the results of percutaneous transluminal angioplasty in vessels below the knee. Techniques such as subintimal angioplasty (10), retrograde approach with transpedal access (11), subintimal arterial flossing with antegrade-retrograde intervention (12,13), transcollateral angioplasty (14), and pedal-plantar loop (15,16), which are performed with recently introduced dedicated wires and balloon catheters, are improving the success rates of percutaneous transluminal angioplasty even in the most distal vascular territories. The outcomes of endovascular interventions in isolated below-the-knee vessels have been investigated by Ferraresi et al (8), who reported a limb salvage rate of 93% and a target vessel patency rate of 58% at 1 year after intervention in a series of diabetic patients with CLI (Rutherford category 4 to 6) and infrainguinal arterial disease at our institution (Table). There are no absolute contraindications to endovascular intervention. Relative contraindications such as severe heart failure, impaired renal function, allergy to contrast media, and intolerance to heparin or antiplatelet therapy should be carefully evaluated and compared with the health risks presented by major amputation.

The concept of the angiosome, a three-dimensional vascular territory supplied by a specific source artery, was introduced by Taylor and colleagues (17,18) and further developed by Attinger et al (19) for use in planning clinical treatment of ischemic lesions of the foot and ankle. On the basis of this concept, the foot and ankle can be divided into six distinct angiosomes, each of which is fed by a particular arterial branch. Recent data indicate that restoration of the inflow vascular supply to the angiosome of an ischemic wound leads to improved clinical outcomes of revascularization (20). Because it unites the anatomic and functional aspects of circulation in the foot, the concept of the angiosome can be useful for planning angioplasty in patients with ischemic wounds of the foot and ankle. The concept can be particularly helpful for selecting the target artery that will yield the best local results of revascularization, barring limitations in technique, materials, or degree of vascular disease.

The article describes the technical, anatomic, and functional aspects of angiographic imaging of the foot and discusses the use of this modality for guiding the endovascular recanalization of pedal vessels.

Patient Preparation and Interventional Procedure

From January 2007 to December 2010, a total of 2875 antegrade endovascular procedures were performed in patients with CLI (Rutherford category 4 to 6) and infrainguinal arterial disease at our institution (Table). There are no absolute contraindications to endovascular intervention. Relative contraindications such as severe heart failure, impaired renal function, allergy to contrast media, and intolerance to heparin or antiplatelet therapy should be carefully evaluated and compared with the health risks presented by major amputation.

According to the standard at our laboratory, all patients undergo a noninvasive vascular study to identify any aortic, iliac, or common femoral artery lesions before the endovascular procedure is performed. Dual antiplatelet therapy is routinely administered before the procedure, and a regimen including aspirin and either ticlopidine or clopidogrel is followed for 3 months after discharge. To
Prevent contrast material–induced nephropathy, patients with a calculated creatinine clearance level of less than 60 mL/min/1.73 m² are given normal saline infusion at a dosage of 1 mL per kilogram body weight per hour, beginning 12 hours before the procedure and continuing for 12 hours afterward. They are also given N-acetylcysteine 1200 mg twice daily, starting the day before the procedure, for a total of four doses.

During the procedure, patients require continuous monitoring of vital signs; as a rule, blood pressure, electrocardiographic activity, and oxygen saturation are monitored and recorded at regular intervals. Intravenous access is mandatory. Although many operators use a contralateral crossover technique, when performing complex infrapopliteal procedures, we strongly recommend the ipsilateral antegrade approach, which provides excellent guidewire and catheter support and allows maximal mobility of the image intensifier around the lower limb.

According to our data on fluoroscopy time (mean, 34.5 minutes) and mean dose-area product calculated by the dosimeter integrated in the angiography unit (62.4 Gy·cm²), recanalization of below-the-knee vessels in diabetic patients with CLI is often time consuming, even when performed by an experienced specialist; for this reason, the use of protective shields and lead glasses is recommended. Furthermore, the antegrade approach, by facilitating the correct positioning of the protective lead curtain mounted on the angiographic table and the suspended lead-glass shield, allows better protection of operators from radiation exposure during the procedure.

In our experience, frequent reassurance and warnings to the patient before each angiographic acquisition are generally sufficient to guarantee the patient’s cooperation in maintaining foot and leg immobility and to reduce movement artifacts. Rarely, involuntary movements of the leg and foot may occur because of severe discomfort or pain during the procedure; in such cases, mild sedation and analgesia are necessary to obtain adequate angiograms. In addition, the use of a tight bandage passed around the foot and fixed to the angiography unit table may be useful to achieve immobilization.

The first step in endovascular recanalization is arterial angiography performed with antegrade access via an 11-cm-long 5-F introducer sheath inserted in the femoral artery with ultrasonographic guidance. Immediately after the sheath is inserted, a weight-adjusted dose of unfractionated heparin (initial bolus, 60–70 IU per kilogram of body weight) is administered intravenously to achieve a target activated clotting time of 200–250 seconds.

We routinely perform a preprocedural angiographic study of the lower limb from the femoral tract to the pedal vessels. After baseline angiograms are obtained, the revascularization strategy is planned with the objective of providing a direct, in-line (ie, noncollateral) blood supply to the foot (specifically, to the angiosome of any ischemic wound) by recanalizing the infrapopliteal and, when necessary, femoropopliteal districts in a single endovascular procedure.

**Imaging Technique**

The use of a digital subtraction angiography (DSA) unit equipped with a large matrix with excellent image quality and adequate magnification is crucial for guiding wire navigation through the vessels of the foot.

Many investigators in the 1990s studied various methods for optimizing angiographic visualization of the pedal vessels (21,22). The following angiographic protocol, used at our department
and optimized for our DSA system (Integris Allura 12; Philips Medical Systems, Best, the Netherlands), represents only a basic guide to the technique, since there is substantial divergence among the currently available DSA units.

In general, we have obtained adequate visualization of the pedal vessels by administering 9 mL of a 50% solution of the nonionic isosmolar contrast medium iodixanol (containing 270 milligrams of iodine per milliliter) with a power injector at a rate of 3 mL/sec through the sidearm of the femoral sheath. In a few cases, a total of 15 mL of the contrast medium, administered at the rate of 5 mL/sec, may be needed for optimal vascular enhancement because of poor runoff due to critically diseased vessels.

A frame rate of 1 frame per second is usually used in filming. Prolonged filming is often necessary to record delayed enhancement of pedal vessels by contrast material from collateral or retrograde circulation.

In pedal angiography, digital postprocessing methods are as important as acquisition parameters. For example, remasking and pixel shifting are essential to reduce movement artifacts. Two digital reconstructions are usually obtained. Because differential filling of anterior and posterior pedal vessels is often observed, the summation
function, which allows a series of images acquired during the flow of the contrast medium to be combined into a single image depicting the entire vascular region, is useful and is almost always applied. Partial subtraction, which allows selection of the background anatomy to be included in the image, is preferred over full subtraction because it helps ensure that images contain the anatomic landmarks needed for successful planning and execution of revascularization.

In our experience, and as is reported elsewhere in the literature, a single projection may be inadequate for complete depiction of the pedal vascular anatomy. Standard anteroposterior and lateral oblique projections should be obtained in all cases to allow visualization of the complex vascular anatomy of the foot. To ensure that each projection fully depicts the vascular segments that are crucial to the revascularization procedure (eg, the lateral and medial plantar artery bifurcation and the anastomosis of the dorsalis pedis artery to the plantar arch), we have established two criteria for correct positioning of the image intensifier: First, the base of the fifth metatarsal bone must be seen to project outward from the base of the foot in the lateral oblique view; second, the first proximal metatarsal interspace must be clearly visualized in the anteroposterior view (Figs 1, 2).

Figure 2. Anteroposterior angiographic projection. (a) Photograph shows appropriate positioning of the image intensifier, parallel to the dorsum of the foot, for anteroposterior angiographic projections. (b) Fluoroscopic image shows proper positioning of the foot to satisfy two major projection criteria: visualization of the first proximal metatarsal interspace (square and inset) to obtain the correct inclination, and inclusion of the entire forefoot in the projection area. (c) Angiogram shows the pedal-plantar loop passing from the dorsal portion to the plantar portion of the foot in the first metatarsal interspace (arrowhead). The anteroposterior projection is best for visualizing the pedal-plantar loop and the origins of the tarsal and metatarsal arteries.
Pedal Arterial Anatomy and Angiosomes

The vascular anatomy of the foot is composed of two (anterior and posterior) circulatory pathways that are connected through the pedal arches (22). In the normal anatomy, the anterior tibial artery gives rise to the anterior circulation, and the posterior tibial artery, to the posterior circulation. Both tibial arteries, together with the peroneal artery, supply different regions of the foot and ankle (19). The plantar region of the foot and the medial part of the ankle are supplied by the posterior tibial artery; the anterior part of the ankle and the dorsum of the foot, by the anterior tibial artery; and the lateral border of the ankle and heel, by the peroneal artery.

Anterior Circulation and Angiosomes

The entire dorsal part of the foot is functionally connected in a single angiosome supplied by the anterior circulation (Figs 3, 4). The main vessel in this angiosome is the dorsalis pedis artery. The anterior tibial artery becomes the dorsalis pedis artery at the ankle level; running laterally to medially along the dorsal aspect of the foot to the first metatarsal space, the dorsalis pedis artery gives off the medial malleolar, lateral malleolar, medial tarsal, lateral tarsal, and arcuate arteries. The arcuate artery, which usually arises at the level of the tarsal-metatarsal joint and travels laterally, in turn gives rise to small dorsal digital arteries supplying the second, third, and fourth toes. At the level of the first metatarsal space, just distal to the origin of the first dorsal metatarsal artery (which mainly supplies the first toe), the dorsalis pedis artery curves in the plantar direction; this arterial segment, named the deep perforating artery, communicates with the lateral plantar artery from the posterior circulation.

Posterior Circulation and Angiosomes

The posterior circulation, which is supplied by the posterior tibial artery, consists of three main arteries—the medial plantar, lateral plantar, and medial calcaneal arteries—each of which feeds a separate angiosome (Figs 5, 6).

The medial calcaneal artery is the first vessel of the posterior circulation that originates from the posterior tibial artery; this branch supplies the medial malleolar region and the medial-plantar heel. The use of endovascular recanalization to restore blood supply to a wound located in the angiosome of the medial calcaneal artery is shown in Figure E1 (online).
Figure 5. Posterior pedal circulation. The major posterior pedal arteries are depicted in lateral oblique (left) and anteroposterior (right) angio- graphic projections.

Figure 6. Posterior pedal angiosomes. Photographs with color overlays (a, plantar view; b, medial view) show the first toe (purple), which may be supplied by the medial plantar artery via the deep branch, by the lateral plantar artery via the plantar arch, and by the anterior circulation. Although variants in the supply to the forefoot may be seen, the angiosome of the medial plantar artery (gray) generally includes the medial plantar instep, and the angiosome of the lateral plantar artery (brown) generally includes the lateral plantar surface as well as the forefoot. The angiosome of the medial calcaneal artery (yellow) includes the medial regions of the malleolus and plantar heel.
The distal posterior tibial artery, also known as the common plantar artery, bifurcates into the medial and lateral plantar arteries. The angiosome supplied by the medial plantar artery includes the medial plantar instep. The medial plantar artery has equal importance with the lateral plantar artery, and it should be evaluated with special attention when planning endovascular recanalization. Its superficial branch, which perfuses the dorsum of the foot, often is connected to the anterior circulation through the medial tarsal arteries. Furthermore, its deep branch might be connected to the first plantar metatarsal artery, which supplies the first toe.

The lateral plantar artery travels laterally toward the fifth metatarsal base; turns medially, forming the plantar arch; and proceeds toward the first metatarsal space, where it communicates with the anterior circulation via the deep perforating artery. The plantar metatarsal arteries originate from the plantar arch and feed the digital artery in the forefoot, which in combination with the lateral plantar surface constitutes the lateral angiosome.

**Peroneal Artery Angiosomes**

At the level of the malleolus, the peroneal artery bifurcates into anterior perforating and lateral calcaneal branches, each of which supplies a specific angiosome (Fig 7). The anterior-lateral ankle angiosome is supplied by the anterior branch, and the lateral heel angiosome, by the lateral calcaneal branch of the peroneal artery.

**Pedal-Plantar Anastomosis**

The importance of the anatomic anastomosis between the anterior and posterior pedal circulatory pathways, its influence on runoff, and its effect on surgical revascularization procedures have been known for almost 25 years (23). If endovascular intervention with an antegrade approach via a distal tibial vessel is impossible, then retrograde access may be technically feasible via the pedal-plantar anastomosis (15,16).

The main pedal-plantar connection is the pedal-plantar loop, which consists of the anastomosis of the dorsalis pedis artery in the first metatarsal space to the plantar arch and lateral plantar artery via the deep perforating artery (Fig 8; Movie [online]).
Figure 8. Lateral oblique (left) and anteroposterior (right) angiographic projections show the pedal-plantar loop in the foot of a diabetic patient. The dorsalis pedis artery (arrows) is connected via the deep perforating artery (*) in the first metatarsal space with the plantar arch and lateral plantar artery (arrowheads). Note the enhancing lesion at the head of the fifth metatarsal bone (X).

Figure 9. Lateral oblique angiographic projection shows the deep pedal arch (arrowheads), which connects the superficial branch of the medial plantar artery to the tarsal artery.

The deep pedal arch, the proximal pathway between the superficial branch of the medial plantar artery and the medial tarsal artery, is often narrow, and the navigation of guidewires and balloon catheters along this pathway is difficult. However, in patients with occlusion of the pedal-plantar loop because of severe arteriosclerosis or forefoot amputation, the deep pedal arch often becomes the dominant pedal-plantar connection (Fig 9).

Anatomic Variants of the Pedal Arteries
Anatomic variants of the pedal arteries are well described in the literature (24). We have observed particular variability in the dominant arterial supply to the first toe: It may be fed by the dorsalis pedis artery via the first dorsal metatarsal artery, by the medial plantar artery via the deep branch, or by the lateral plantar artery via the plantar arch and first plantar metatarsal artery (Fig 10). In patients with CLI and an ischemic wound of the first toe, special care must be taken at preprocedural angiography to accurately determine which artery, from the anterior or the posterior circulation, provides the dominant supply to the first toe. This information is crucial for ensuring an optimal supply to the wound when direct inline flow is restored. The medial plantar, lateral plantar, and dorsalis pedis arteries also might jointly supply the first toe (Fig E2 [online]).

The posterior tibial artery is more constant in its presence and course than the dorsalis pedis artery, which is absent in 6%–12% of subjects; in
Figure 10. Anatomic variants in the dominant arterial supply to the first toe. (a) Lateral oblique (left) and anteroposterior (right) angiographic projections show a first toe that is supplied primarily by the medial planar artery (arrowheads) via the deep branch (arrows). (b) Lateral oblique (left) and anteroposterior (right) angiographic projections obtained in another patient after a distal transmetatarsal amputation show that the first toe is primarily supplied by the lateral planar artery via the plantar arch (arrowheads) and the first plantar metatarsal artery (arrow). Note the enhancing lesion in the space between the second and third metatarsal bones (*). (c) Lateral oblique (left) and anteroposterior (right) angiographic projections obtained in a third patient show that the first toe is primarily supplied by the dorsalis pedis artery (arrowheads) via the first dorsal metatarsal artery (arrow). The medial planar, lateral planar, and dorsalis pedis arteries also can supply the first toe simultaneously.
Figure 11. Anatomic variant in anterior pedal circulation in a diabetic patient with an enhancing lesion at the head of the second metatarsal bone (*). Lateral oblique (left) and anteroposterior (right) angiographic projections show the absence of the dorsalis pedis artery; the lateral tarsal artery (arrowheads), the predominant artery of the anterior circulation, supplies the first toe via the first plantar metatarsal artery (arrow). Note also the aberrant connection of the lateral tarsal artery to the plantar circulation.

Figure 12. Lack of connection between anterior and posterior pedal circulation because of absence of the plantar arch and pedal-plantar loop. Lateral oblique (left) and anteroposterior (right) angiographic projections show that the dorsalis pedis and medial plantar arteries provide the predominant supply to the first and second toes, whereas the lateral plantar and arcuate arteries supply the third and fourth toes. The lateral plantar artery alone supplies the fifth toe.

In this group, the tarsal arteries often become dominant and develop anastomoses through the plantar arch to the plantar circulation (Fig 11). The arcuate artery is absent in almost 30% of subjects.

Last, although the pedal-plantar loop anastomosis is complete in almost 90% of subjects, in a minority the anterior circulation and posterior circulation are completely separate (Fig 12).

Conclusions

In patients with ischemic wounds due to CLI, restoration of direct in-line blood flow to the area of the lesion is considered the best treatment, obviating major amputation and preserving ambulation. With the recent introduction of guidewires
and balloon catheters specifically designed for the treatment of below-the-knee vascular disease, recanalization of the pedal arteries has become a technically feasible procedure for restoring tibial vessel outflow and supply to the area of the wound (Fig 13). In this context, familiarity with angiographic technique, normal pedal vascular anatomy, and major anatomic variations of the
Figure 13. (a) Photograph shows multiple ischemic and infected wounds, including an extensive lesion of the forefoot, medial plantar instep, and posterior ankle (in the angiosome of the lateral calcaneal branch of the peroneal artery [inset]), in the foot of a diabetic patient. After revascularization, the patient was scheduled to undergo a Chopart amputation for metatarsal osteomyelitis. (Courtesy of Enrico Brocco, MD, Policlinico Abano Terme, Abano Terme, Italy.)

(b) Baseline angiograms of proximal (left, anteroposterior projection) and distal (right, lateral projection) vessels in the leg show complete occlusion of the anterior and posterior tibial arteries and proximal occlusion of the peroneal artery, the middle and distal segments of which are patent (arrows). A femoropopliteal bypass (arrowhead) also is depicted.

(c) Lateral oblique angiogram of the foot shows occlusion of the medial and lateral plantar arteries.

(d) Intraprocedural fluoroscopic image shows two dedicated 0.014-inch wires (arrows) and a balloon catheter (arrowhead) inserted for retrograde recanalization of the lateral plantar artery via the deep perforating artery by using the pedal-plantar loop technique.

(e) Intraprocedural fluoroscopic image shows the rendezvous of the wires (arrow) from the anterior and posterior circulation to allow recanalization of the posterior tibial artery. Recanalization of the peroneal artery (not shown) also was needed to restore the blood supply to the ankle lesion. (f) Postprocedural angiograms show patency of the anterior tibial, posterior tibial, and peroneal arteries in proximal (left, anteroposterior projection) and distal (right, lateral projection) regions.

(g, h) Lateral oblique (g) and anteroposterior (h) angiographic projections help confirm the patency of the dorsalis pedis artery, lateral plantar artery (arrow in g), and pedal-plantar loop. Enhancement is observed at the sites of the wounds in the posterior ankle (asterisk in g) and head of the first metatarsal bone (asterisk in h).

(i) Photograph shows no sign of dehiscence after the Chopart amputation. Inset shows granulation tissue at the site of the ankle lesion (asterisk) after surgical débridement. (Courtesy of Enrico Brocco, MD, Policlinico Abano Terme, Abano Terme, Italy.)
pedal vessels is essential. In addition, knowledge of the functional aspects of the pedal circulation (angiosomes) is required to obtain optimal clinical outcomes.


References


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