Angiosomes and Wound Care in the Diabetic Foot

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KEYWORDS

• Angiosomes • Wound care • Diabetic foot • Vascular anatomy

Successful limb salvage is dependent on detailed knowledge of the vascular anatomy of the foot and ankle. The foot and ankle are composed of 6 distinct angiosomes; three-dimensional blocks of tissue fed by source arteries with functional vascular interconnections between muscle, fascia and skin. Because the foot and ankle are an end organ, their main arteries have numerous direct arterial-arterial connections that allow alternative routes of blood flow to develop if the direct route is disrupted or compromised. Understanding the boundaries of the angiosome and the vascular connections among its source arteries provides the basis for logically rather than empirically designed incisions for tissue exposure or to plan reconstructions or amputations that ultimately preserve blood flow for a surgical wound to heal.

Ian Taylor[1] first defined the angiosome principle by expanding on the work of previous anatomists[2–9] to further define the vascular anatomy of muscle and skin. He defined an angiosome as a three-dimensional anatomic unit of tissue fed by a source artery. Taylor and Minabe[10] defined at least 40 angiosomes in the body that were interconnected by either reduced caliber choke vessels or by similar caliber anastomotic arteries.[11,12] These choke vessels can be important safety conduits that allow one angiosome to eventually provide blood flow to an adjacent angiosome if the source artery of the latter is damaged. A unified network can be created so that one source artery can provide blood flow to multiple angiosomes beyond its immediate border. Occluding or interrupting one source artery surgically manipulates the system so that blood flows through the neighboring choke vessels. This is an anatomic explanation for the delay phenomenon.[13,14] Although choke vessels provide an indirect connection among angiosomes, there are also direct arterial-arterial connections that allow blood flow to immediately bypass local obstructions in the vascular tree. The 6 angiosomes of the foot and ankle originate from the 3 main source arteries: the posterior tibial artery supplies the medial

Drs Clemens and Attinger have no financial disclosures.

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Foot Ankle Clin N Am 15 (2010) 439–464
doi:10.1016/j.fcl.2010.04.003 **foot.theclinics.com**

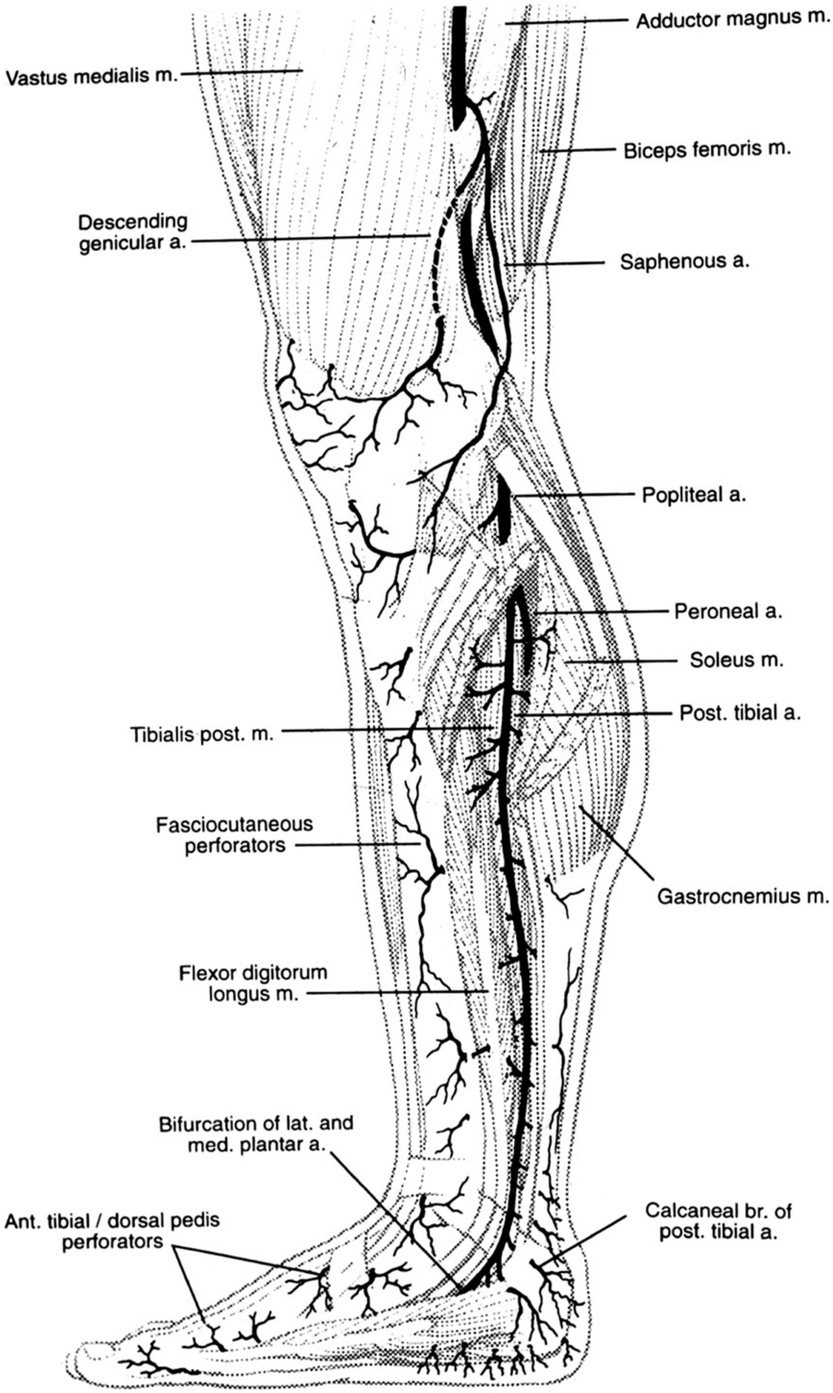


Fig. 1. The posterior tibial artery gives off perforators that arise between the flexor digitorum longus and the soleus muscle. They split into anterior and posterior branches to supply the overlying skin. (*From* Cormack GC, Lamberty BGH. The Arterial Anatomy of Skin Flaps. Edinburgh: Churchill Livingstone, 1986; with permission.)

ankle and the plantar foot, the anterior tibial artery supplies the dorsum of the foot, and the peroneal artery supplies the anterolateral ankle and the lateral rear foot. These large angiosomes of the foot can be further broken into angiosomes of the major branches of the above arteries. The 3 main branches of the posterior tibial artery each supply distinct portions of the plantar foot: the calcaneal branch (heel), the medial plantar artery (instep), and the lateral plantar artery (lateral midfoot and forefoot). The 2 branches of the peroneal artery supply the anterolateral portion of the ankle and rear foot, the anterior perforating branch (lateral anterior upper ankle), and the calcaneal branch (lateral and plantar heel). The anterior tibial artery supplies the anterior ankle and then becomes the dorsalis pedis artery, which supplies the dorsum of the foot. Detailed descriptions of the vascular anatomy[15] and angiosomes of the lower leg, foot, and ankle have been thoroughly illustrated elsewhere.[16–18]

Fig. 2. This injection study shows the angiosome fed by the posterior tibial artery (*salmon*). The island of light blue just above the anterior medial malleolus comes from the peroneal artery via a direct arterial-arterial connection between the posterior tibial artery and the peroneal artery. (*Reprinted from* Attinger C. Vascular anatomy of the foot and ankle. Oper Tech Plast Reconstr Surg 1997;4:183; with permission.)

THE 3 POSTERIOR TIBIAL ARTERY ANGIOSOMES FED BY THE CALCANEAL, MEDIAL PLANTAR, AND LATERAL PLANTAR ARTERIES

In the leg, the posterior tibial artery supplies the medial lower leg, starting from the anterior medial border of the tibia and extending posteriorly to the midline of the calf over the central raphe of the Achilles tendon (**Figs. 1** and **2**). There are smaller perforator arteries along the course of the posterior tibial artery that perforate through the flexor digitorum longus and/or soleus to supply the overlying skin. In addition, there are smaller serial branches to the deep flexor muscles, the medial half of the soleus muscle, and the Achilles tendon.[16,18]

In the foot, this artery gives off the posterior medial malleolar branch at the medial malleolus. The posterior medial malleolar branch joins the anterior medial malleolar branch from the anterior tibial artery, giving rise to an important interconnection between the posterior tibial artery and the anterior tibial artery. This system supplies the medial malleolar area. At the same level, the medial calcaneal artery branches off the posterior tibial artery inferiorly and arborizes into multiple branches that travel in a coronal direction to supply the heel. The angiosome boundary of the medial calcaneal artery includes the medial and plantar heel, with its most distal boundary being the glabrous junction of the lateral posterior and plantar heel (**Figs. 3** and **4**).[19]

The posterior tibial artery then enters the calcaneal canal underneath the flexor retinaculum and bifurcates into the medial and lateral plantar arteries at the level of the transverse septum, between the abductor hallucis longus and the flexor digitorum brevis muscles. The angiosome boundaries of the medial plantar artery encompass the instep (**Fig. 5**). Its boundaries are as follows: posteriorly, the distal-medial edge of

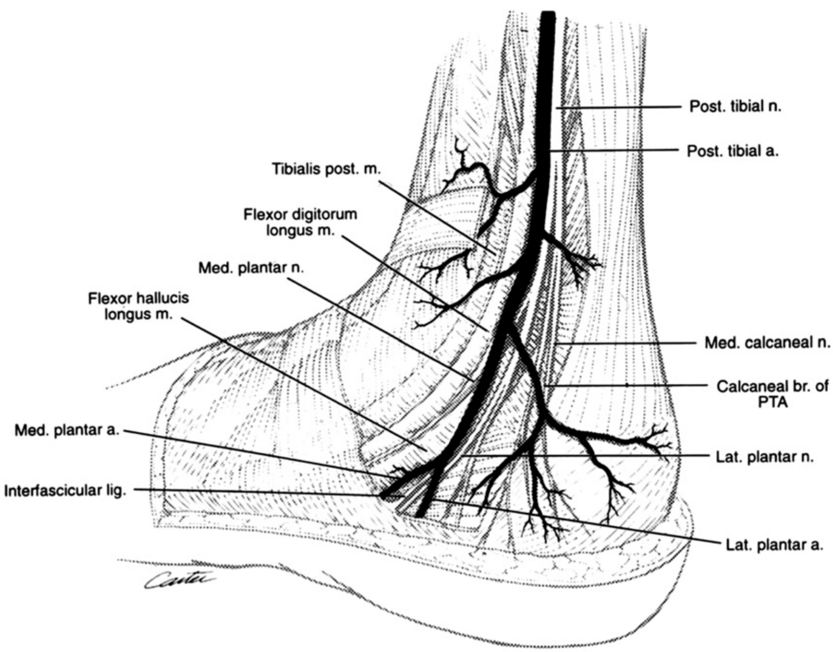


Fig. 3. The medial calcaneal branch is the first main distal branch of the posterior tibial artery. Its angiosome includes the medial heel, the plantar heel, and the lateral plantar heel up to the lateral glabrous junction. (*Reprinted from* Attinger C. Vascular anatomy of the foot and ankle. Oper Tech Plast Reconstr Surg 1997;4:183; with permission.)

Fig. 4. The medial calcaneal branch is the first main distal branch of the posterior tibial artery (*above*). Its angiosome includes the medial heel (*center*), the plantar heel, and the lateral plantar heel up to the lateral glabrous junction (*below*). (*Reprinted from* Attinger C. Vascular anatomy of the foot and ankle. Oper Tech Plast Reconstr Surg 1997;4:183; with permission.)

Fig. 5. The angiosome boundaries of the medial plantar artery encompass the instep and, depending on anatomic variability, can include the hallux. (*Reprinted from* Attinger C. Vascular anatomy of the foot and ankle. Oper Tech Plast Reconstr Surg 1997;4:183; with permission.)

the plantar heel; laterally, the midline of the plantar midfoot; distally, the proximal edge of the plantar forefoot; and medially, an arc 2 to 3 cm above the medial glabrous junction, with its highest point being the anterior border of the navicular-cuneiform joint.

The medial plantar artery gives off 2 main branches: the superficial and deep branches (**Figs. 6** and **7**). The superficial branch of the medial plantar artery travels obliquely up to the navicular-cuneiform joint, then along the superior border of the cuneiform and the first metatarsal bone before descending to the medial plantar aspect of the distal metatarsal. Interconnections with the anterior tibial tree exist, as cutaneous branches connect proximally with medial cutaneous branches from the dorsalis pedis artery and distally with branches of the first dorsal metatarsal artery. The artery then extends plantarly and laterally, where it joins with the deep branch

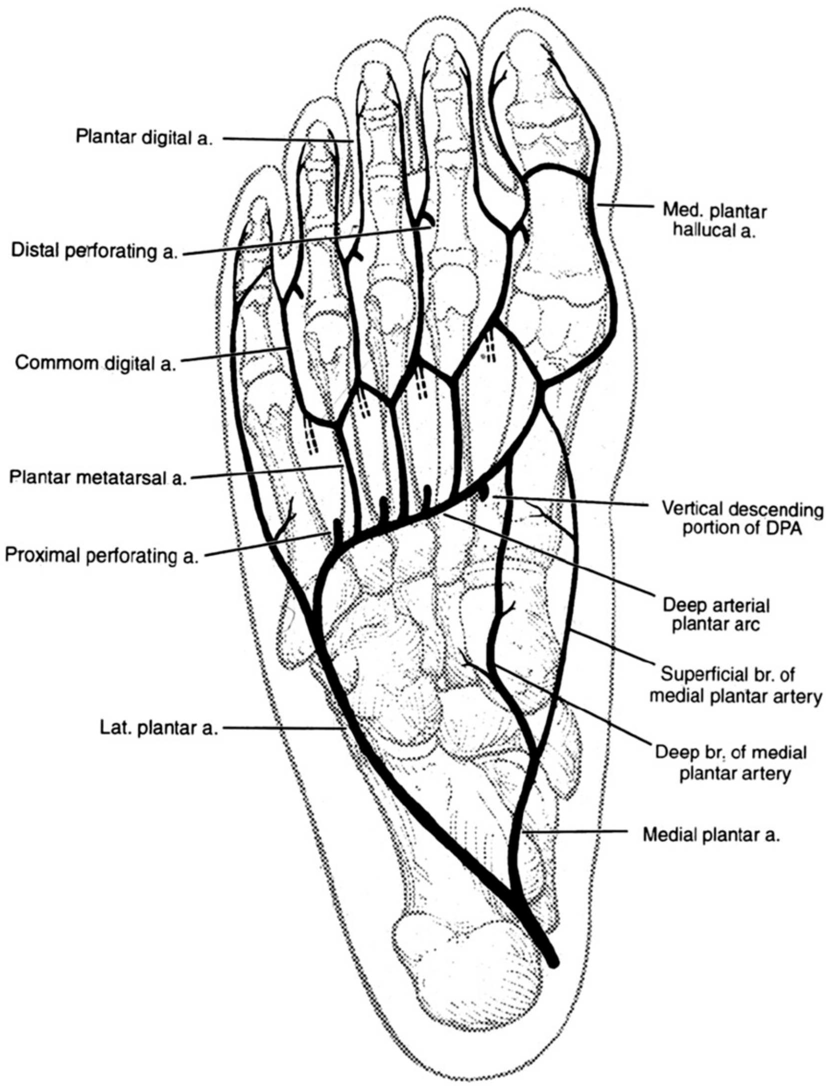


Fig. 6. The medial plantar artery gives off 2 main branches: the superficial branch and the deep branch. (*Reprinted from* Attinger C. Vascular anatomy of the foot and ankle. Oper Tech Plast Reconstr Surg 1997;4:183; with permission.)

of the medial plantar artery and the first plantar metatarsal artery (a branch of the lateral plantar artery).

The second major branch of the medial plantar artery, the deep branch, travels deep and along the medial intramuscular septum between the abductor hallucis muscle and the flexor digitorum brevis. Perforating branches supply the medial sole of the foot. At the neck of the first metatarsal, it passes underneath the flexor tendons and anastomoses with the first plantar metatarsal artery and/or the distal lateral plantar artery.

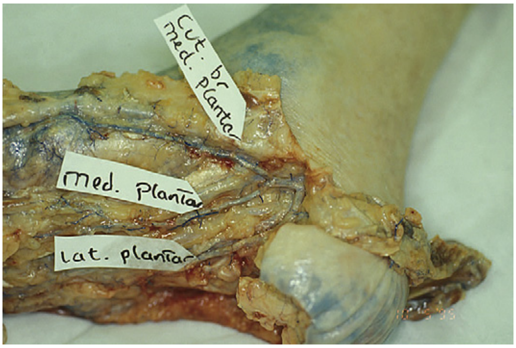


Fig. 7. The 2 main branches of the medial plantar artery are the superficial branch (cutaneous branch medial plantar) and the deep branch (medial plantar). The superficial branch travels obliquely up toward the navicular-cuneiform joint and then travels along the superior border of the cuneiform and first metatarsal bone before descending to the medial plantar aspect of the distal metatarsal. The deep branch travels along the medial intramuscular septum deep and along the fibular side of the abductor hallucis muscle. (*Reprinted from* Attinger C. Vascular anatomy of the foot and ankle. Oper Tech Plast Reconstr Surg 1997;4:183; with permission.)

The angiosome of the lateral plantar artery includes the lateral plantar surface as well as the plantar forefoot (**Fig. 8**). The borders are as follows: posteriorly, the distal lateral edge of the plantar heel; medially, the central raphe of the plantar midfoot; more distally, the glabrous juncture between the medial plantar forefoot and the medial distal dorsal forefoot; and laterally, the glabrous junction between the lateral dorsum of the foot and the plantar surface of the foot (see **Fig. 4**, below). The distal border includes the entire plantar forefoot. Although the hallux is usually part of the lateral plantar angiosome, it can also be part of the medial plantar artery angiosome (see **Fig. 5**) or of the dorsalis pedis angiosome.

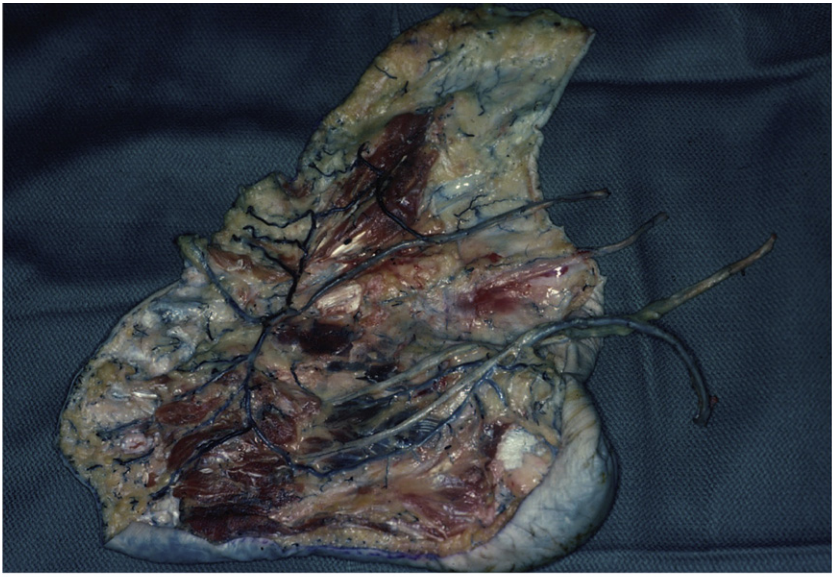
The lateral plantar artery enters the middle compartment of the foot, where it travels obliquely between the flexor digitorum brevis muscle and the quadratus plantar muscle toward the base of the fifth metatarsal. It then travels distal to the proximal fifth metatarsal underneath the flexor digiti minimi muscle, turns medially, forming the deep plantar arch, and crosses the proximal (2, 3, and 4) metatarsals. It finally anastomoses directly with the dorsalis pedis artery in the proximal first interspace (**Fig. 9**). This direct anastomosis between the dorsal and plantar circulation helps ensure that if either the proximal dorsalis pedis or lateral plantar artery becomes occluded, flow is maintained to the entire foot.

The 4 plantar metatarsal arteries emanate from the deep plantar arch to nourish the plantar forefoot. They travel along each metatarsal shaft deep to the interossei and the transverse adductor muscles, but superficial to the deep transverse carpal ligament. According to Murakami,[20] they bifurcate and are joined by the deep plantar arteries and the plantar intermetatarsal arteries to form an arcade of arterial triangles. The common digital arteries arise at the apices of these triangles in the proximal web spaces. The common digital arteries bifurcate into 2 digital arteries for each toe and are joined by distal perforating branches that originate from the dorsal metatarsal arteries. The proper plantar digital arteries are the predominant blood supply to the lesser toes, except for the medial side of the second toe, which is supplied by the first metatarsal artery (see **Fig. 9**).[20]

Fig. 8. The angiosome of the lateral plantar artery supplies the lateral plantar surface as well as the plantar forefoot. Its posterior border is the anterior edge of the plantar heel. Its medial border in the midfoot is the central raphe of the plantar midfoot, and in the forefoot it is the glabrous juncture between the medial dorsum and plantar forefoot. Its lateral border is the glabrous junction between the lateral dorsum of the foot and the plantar surface of the foot. The angiosome usually incorporates the hallux, although this cadaver injection shows that, occasionally, the main vascular flow of the hallux can be from the dorsal circulation. (*Reprinted from* Attinger C. Angiosomes of the foot and ankle and clinical implications for limb salvage: reconstruction, incisions, and revascularization. Plast Reconstr Surg 2006;117;261S; with permission.)

THE ANTERIOR TIBIAL ARTERY AND DORSALIS PEDIS ANGIOSOME

In the leg, the angiosome of the anterior tibial artery includes the area overlying the anterior compartment, with the fibula as the lateral boundary and the anterior tibia as the medial boundary. This artery originates from the popliteal artery and pierces the interosseus membrane to travel deep in the anterior compartment between the tibialis anterior muscle and extensor hallucis longus muscle. Proximally, it gives off muscle branches to supply the proximal third of the peroneus longus and brevis muscles. It then supplies the muscle of the anterior compartment via multiple small pedicles[10–14] to the tibialis anterior muscle, extensor hallucis longus muscle, and extensor digitorum longus muscle. At the ankle, the anterior tibial artery gives off the lateral malleolar artery at the level of the lateral malleolus that joins with the anterior perforating branch of the peroneal artery. At the same level, it also gives off the medial malleolar artery, which anastomoses with the posteromedial artery of the posterior tibial artery. The anterior tibial artery then emerges under the extensor retinaculum of the ankle to become the dorsalis pedis artery. The angiosome of the dorsalis pedis artery encompasses the entire dorsum of the foot (**Fig. 11**). This artery has arterial connections from the superficial medial plantar artery medially, from the calcaneal branch of the peroneal artery proximolaterally, and from the lateral plantar artery



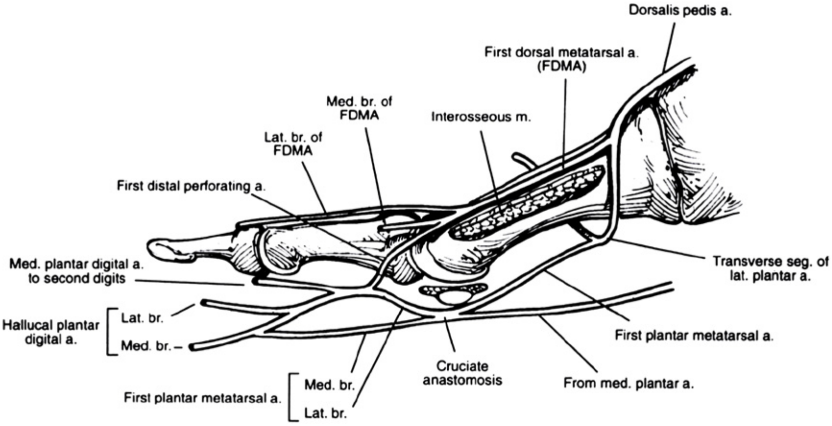


Fig. 9. (*Above*) In this cadaver specimen, all bones except for the calcaneus have been removed. Note the direct connection between the dorsalis pedis artery and the lateral calcaneal artery just distal to where Lisfranc's joint was. The two vessels create a U-shaped conduit that is critical in ensuring continued blood flow to the dorsum and plantar surfaces should the posterior tibial artery or anterior tibial artery become occluded. (*Below*) The skeletal framework shows that the dorsalis pedis artery enters into the proximal first intrametatarsal space at a 90-degree angle and then turns another 90 degrees laterally to join the lateral plantar artery. (*Reprinted from* Attinger C. Angiosomes of the foot and ankle and clinical implications for limb salvage: reconstruction, incisions, and revascularization. Plast Reconstr Surg 2006;117;261S; with permission.)

and its perforators in the proximal metatarsal interspaces. The dorsalis pedis artery travels underneath the extensor hallucis longus and curves between the extensor hallucis longus and extensor digitorum longus along the dorsum of the first interspace. As Huber[21] pointed out, the dorsalis pedis artery is absent or extremely attenuated in 12% of cases, and there are many anatomic variations to its course.

Typically, the dorsalis pedis artery has 3 lateral arterial branches (the proximal and distal tarsal arteries and the arcuate artery) and 2 medial branches (the medial tarsal arteries). The lateral branches are often linked together to form an interconnecting retelike (netlike) pattern.[22] The proximal lateral tarsal artery originates at the lateral talar neck. It travels underneath the extensor digitorum brevis muscle, giving off one or more branches to this muscle. Laterally, it communicates with the calcaneal branch of the peroneal artery. It may also connect superiorly to the lateral malleolar artery and inferiorly to the arcuate artery. The third lateral branch of the dorsalis pedis, the arcuate artery, takes off at the level of the first tarsal-metatarsal joint and travels laterally over the bases of the second, third, and fourth metatarsals. It gives off the second, third, and fourth dorsal metatarsal arteries before it joins the lateral tarsal artery. Medially, the dorsalis pedis artery (usually) gives off 2 medial tarsal arteries. One tarsal artery is located at the middle of the navicular bone, and the other is located at the cuneonavicular joint. Usually, one of these joins with the superficial branch of the medial plantar artery. After giving off the arcuate artery, the dorsalis pedis artery enters into the proximal first intermetatarsal space and in the process gives off the first dorsal metatarsal artery, which courses over the first dorsal interossei muscles. The dorsalis pedis artery enters that space by taking a 90° angle turn plantarly followed by another turn laterally to join directly with the lateral plantar artery (**Fig. 9**). In 22% of cases[23] the first dorsal metatarsal artery originates after the dorsalis pedis has made the initial downward 90° turn. In these instances, it rises toward the dorsum by traveling through the first interosseus muscle until it lies on top of the interosseus muscle at or near the metatarsophalangeal level. Regardless of its course, this artery is important because it supplies the first interosseus muscle, the skin overlying it, and the first web space. In

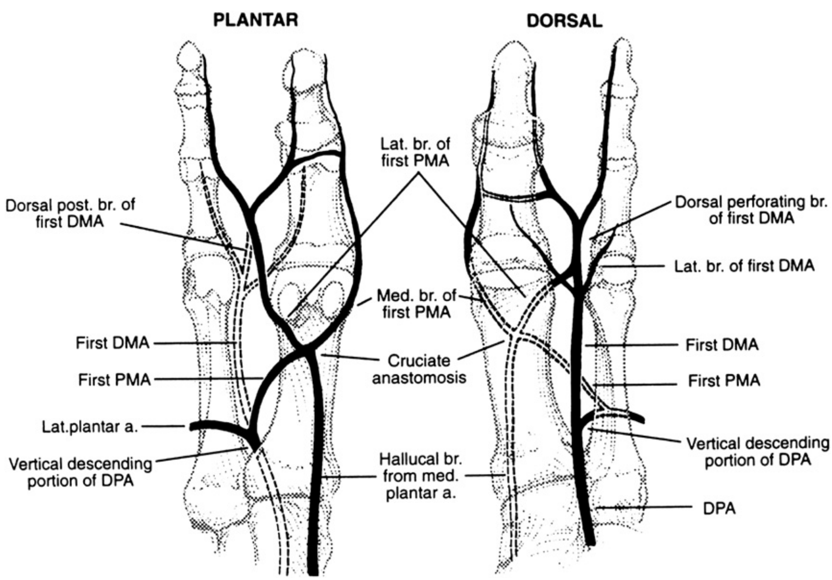


Fig. 10. The most common pattern of the first dorsal metatarsal artery and its connections with the plantar circulation is shown in dorsal and plantar views. Note the arterial-arterial connections proximally and distally in the first metatarsal interspace. (*Reprinted from* Attinger C. Vascular anatomy of the foot and ankle. Oper Tech Plast Reconstr Surg 1997;4:183; with permission.)

addition, the first dorsal metatarsal artery distally gives off medial and lateral branches that supply blood to the hallux and second digit (**Fig. 10**). The dorsal metatarsal arteries, which supply the toes, both originate from the dorsal system (the arcuate artery) and receive additional blood supply from the deep plantar system (the proximal perforating arteries) (see **Fig. 11**, left). At the metatarsal heads, the dorsal metatarsal arteries divide into 2 dorsal digital arteries and then travel to the plantar area via the distal perforating arteries (also called anterior perforating arteries). These perforating arteries join the plantar metatarsal artery to supply the plantar digits. In this way, the web space and the toes on either side of the web space receive dorsal and plantar blood supply from a dual system: the dorsalis pedis artery and the lateral plantar artery.

THE PERONEAL ARTERY FED BY THE CALCANEAL BRANCH AND ANTERIOR PERFORATING BRANCHES

The peroneal artery arises from the tibial peroneal trunk and courses along the medial side of the fibula, supplying the posterolateral lower leg, ankle, and heel.[24,25] Before the peroneal artery emerges at the level of the lateral malleolus, it bifurcates (forming a delta) into the anterior perforating branch and the lateral calcaneal branch (**Fig. 12**). The angiosome of the lateral calcaneal branch includes the plantar and lateral heel

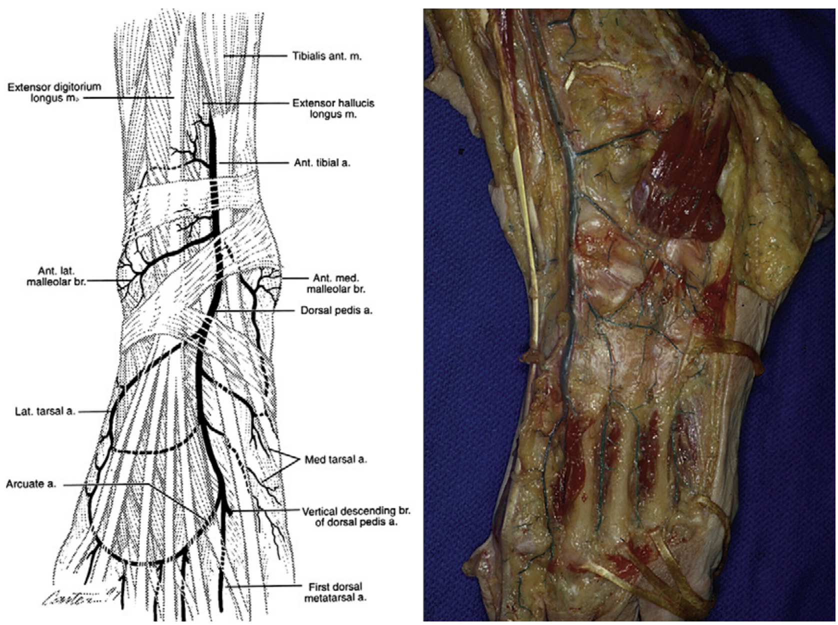


Fig. 11. The dorsalis pedis artery angiosome supplies the entire dorsum of the foot, although it gets contributions medially from the superficial medial plantar artery, anteriorly from the perforators of the lateral plantar artery, and laterally from both the calcaneal and anterior perforating branches of the peroneal artery. (*Right*) In this anatomic dissection, the arcuate artery is vestigial at best and the dorsal metatarsal arteries are getting their main blood supply from the lateral plantar artery via proximal perforators. (*From* Cormack GC, Lamberty BGH. The Arterial Anatomy of Skin Flaps. Edinburgh: Churchill Livingstone, 1986; with permission.)

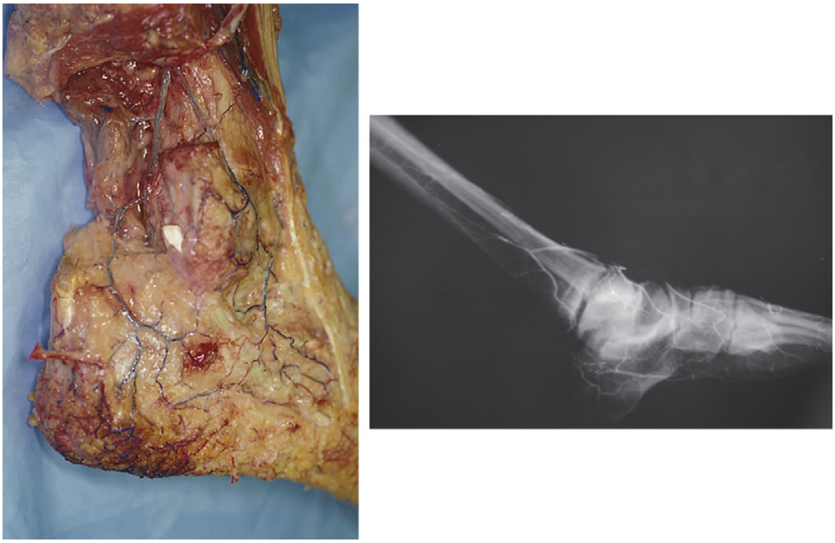


Fig. 12. Before the peroneal artery emerges at the level of the lateral malleolus, it bifurcates into the anterior perforating branch and the lateral calcaneal branch. (*Left*) The cadaver dissection shows the bifurcation after the fibula was removed. (*Right*) Angiogram view of the same bifurcation. (*Reprinted from* Attinger C. Angiosomes of the foot and clinical implications for limb salvage: reconstruction, incisions, and revascularization. Plast Reconstr Surg 2006;117;261S; with permission.)

(**Fig. 13**, left). More specifically, the proximal boundaries extend medially to the medial glabrous junction of the heel, distally to the proximal fifth metatarsal, and superiorly to the lateral malleolus. The course of the lateral calcaneal artery begins at the level of the lateral malleolus as it emerges laterally between the Achilles tendon and the peroneal tendons. It curves with peroneal tendons 2 cm distal to the lateral malleolus and gives rise to 4 or 5 small calcaneal branches.[19] The lateral calcaneal artery terminates at the level of the fifth metatarsal tuberosity, where it connects with the lateral tarsal artery. The heel is privileged in that it has 2 overlapping source arteries: the medial and lateral calcaneal arteries (**Fig. 13**, center and right). This feature ensures duplicate blood supply to an area regularly traumatized during ambulation.[26]

Anatomic and Clinical Evaluation of Arterial-arterial Connections

Arterial-arterial connections allow for uninterrupted blood flow to the entire foot despite the occlusion of one or more arteries. By understanding the location of these arterial connections in the foot and ankle, the surgeon can determine the presence of flow from the source artery and determine which artery is predominately supplying a given angiosome (**Fig. 14**). The use of the handheld Doppler instrument at the specific anatomic locations described earlier (or in any anatomic text) give an accurate description of existing blood flow.[17,27]

After locating the artery with the Doppler, the direction of flow can be evaluated by applying selective occlusion with finger pressure above and below the area being studied. The initial character of the Doppler signal helps to evaluate the quality of flow present in the artery. Triphasic flow indicates normal arterial flow. Biphasic flow indicates mildly compromised flow. Monophasic flow indicates arterial compromise, unless the patient suffers from sympathetic neuropathy (a common complication of

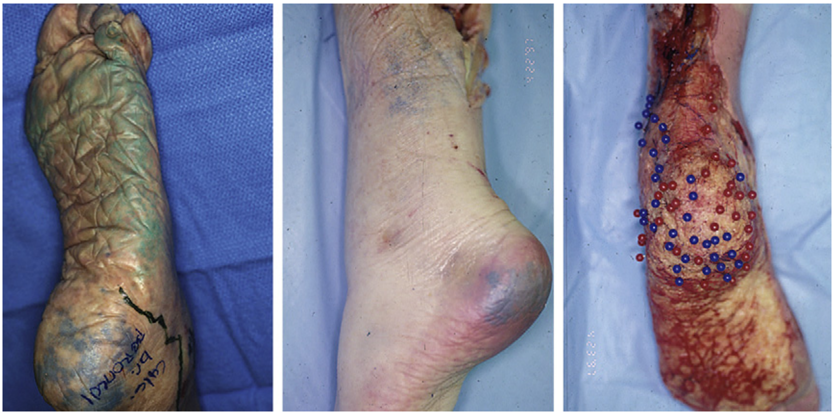


Fig. 13. The calcaneal branch of the peroneal artery supplies the entire plantar heel as well as the lateral ankle (*left*). Note that the heel is privileged in that it has 2 source arteries: the medial (*salmon*) and lateral (*blue*) calcaneal arteries. The overlap is best shown in this cadaver specimen (*center*), where each branch was injected with a different color and they completely overlap. The skin was then removed and the different colored perforators were marked with different colored pins, further emphasizing the overlap (*right*). (*Reprinted from* Attinger C. Angiosomes of the foot and ankle and clinical implications for limb salvage: reconstruction, incisions, and revascularization. Plast Reconstr Surg 2006;117; 261S; with permission.)

diabetes) and the distal vessels have lost their tone. A blunt, short, monophasic spitting sound indicates complete distal occlusion with no runoff. For example, it should be straightforward to determine whether the flow to the dorsum of the foot is derived from the anterior tibial artery, the peroneal artery (via the anterior perforating branch), or the posterior tibial artery (via the lateral plantar artery) by listening and selectively occluding these areas. In addition, one should be able to determine whether the blood flow to the heel is coming directly from the calcaneal branch of the posterior tibial artery, the calcaneal branch of the peroneal artery, or indirectly from the anterior tibial artery via the lateral malleolar branch. In the patient with diabetes mellitus and/or peripheral vascular disease who presents with a foot ulcer or rest pain, this clinical assessment can aid in choosing which incisions to make if the patient requires a debridement, amputation, or closure. In these patients it is crucial that the critically redirected blood flow is not compromised by a poorly planned surgical incision. Moreover, this directional assessment aids the vascular surgeon in ensuring that the bypass reaches the angiosome that is ischemic. It has been reported that 15% of bypasses fail to heal the foot despite remaining patent, because the bypass failed to revascularize the affected angiosome.[28]

ANTERIOR TIBIAL AND PERONEAL CONNECTIONS

The anterior tibial and peroneal arteries are directly connected through the anterior perforating branch of the peroneal artery and the lateral malleolar branch of the anterior tibial artery; thus, the flow of the peroneal artery can be retrograde from the anterior tibial artery via the lateral malleolar artery or antegrade where it supplies the anterior tibial artery (**Fig. 15**). Likewise the flow to the anterior tibial artery and the

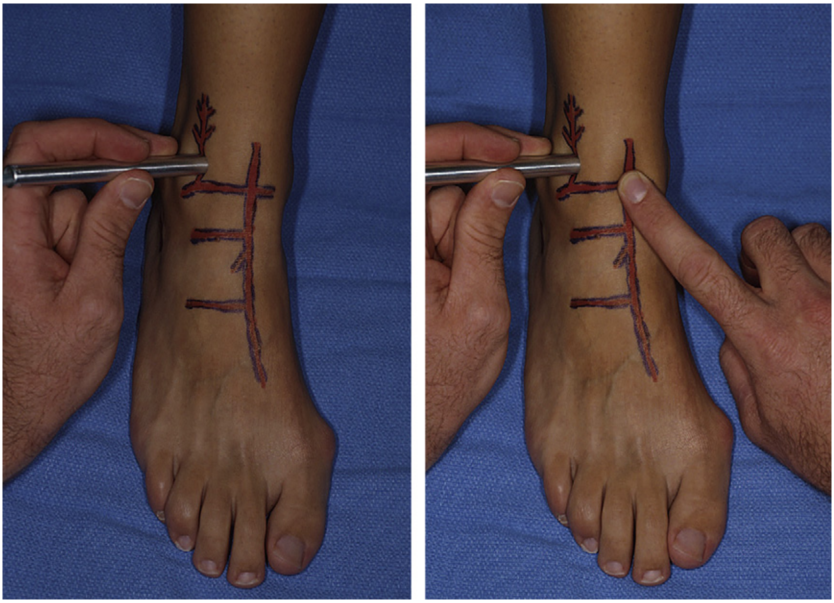


Fig. 14. The anterior perforating branch of the peroneal artery is located in the lateral soft area just above the ankle joint between the tibia and the fibula (*left*). Then, the anterior tibial artery is occluded at the takeoff of the lateral malleolar branch (*right*). If the Doppler sounds continue, then there is antegrade flow along the anterior perforating branch of the peroneal artery. (*Reprinted from* Attinger C. Angiosomes of the foot and ankle and clinical implications for limb salvage: reconstruction, incisions, and revascularization. Plast Reconstr Surg 2006;117:261S; with permission.)

dorsalis pedis can be antegrade from the proximal anterior tibial artery or retrograde from the anterior perforating branch of the peroneal artery via the lateral malleolar artery.

PERONEAL AND POSTERIOR TIBIAL CONNECTIONS

The peroneal artery communicates distally with the posterior tibial artery via 1 to 3 transverse communicating branches that are located within the fat pad deep to the Achilles tendon (**Fig. 15**). These branches are located 5 to 7 cm above the ankle joint, at the ankle joint, and just above the insertion of the Achilles tendon. Because of these connections, it is impossible by Doppler imaging to know whether the flow along the distal posterior tibial artery originates directly from the proximal posterior tibial artery or indirectly from the distal peroneal artery via the above perforators. Likewise, one cannot tell whether the flow along the peroneal artery originates from the peroneal artery or from the posterior tibial artery via those same perforators.[18]

ANTERIOR TIBIAL AND POSTERIOR TIBIAL CONNECTIONS

The anterior tibial artery and posterior tibial artery are also directly connected distal to the Lisfranc joint, where the dorsalis pedis artery enters into the proximal first

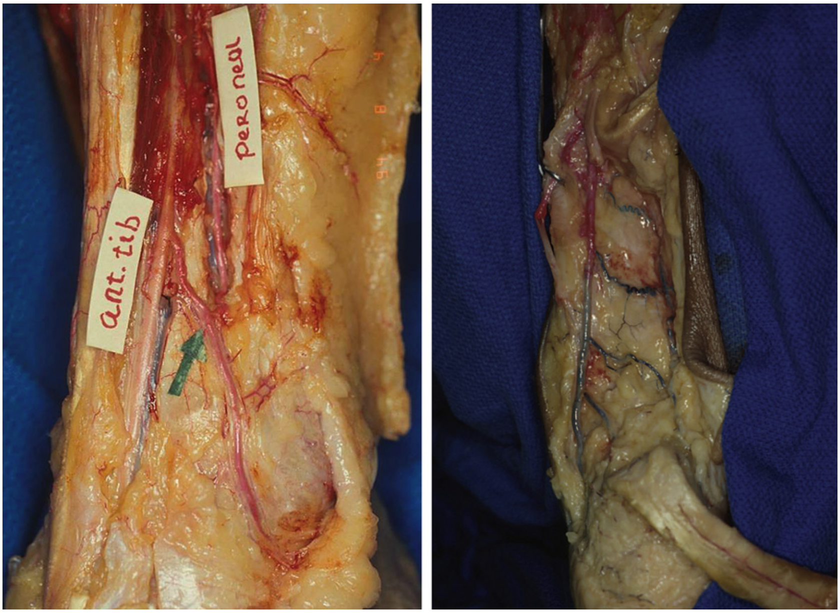


Fig. 15. The peroneal artery communicates distally with the anterior tibial artery via the anterior perforating branch and lateral malleolar artery (*left*). It also communicates distally directly with the posterior tibial artery via 1 to 3 connecting branches under the Achilles tendon (*right*). (*Reprinted from* Attinger C. Angiosomes of the foot and clinical implications for limb salvage: reconstruction, incisions, and revascularization. Plast Reconstr Surg 2006;117;261S; with permission.)

interspace to join directly with the lateral plantar artery (see **Fig. 9**). As we have previously shown,[18] the importance of evaluating the patency of the distal connection between the anterior and posterior tibial arteries cannot be emphasized enough. If that connection is critical to supplying either the dorsal or plantar surface of the foot because of existing obstruction of one of the 2 arteries, damaging that connection while performing an operation or amputation can lead to gangrene on the portion of the foot that was dependent on retrograde flow (**Fig. 16**).

ARTERIAL-ARTERIAL CONNECTIONS AROUND THE HEEL

The heel is unique in that it is the only angiosome that receives inflow from 2 source arteries: the calcaneal branch of the posterior tibial artery and the calcaneal branch of the peroneal artery (see **Fig. 13**, right). The posterior tibial calcaneal branch supplies the medial aspect of the heel, whereas the peroneal calcaneal branch supplies the lateral aspect of the heel. The former runs directly toward the heel pad along the center of the medial heel, whereas the latter curves around the lateral malleolus 2 cm distal to the malleolar tip and travels to the proximal fifth metatarsal head. There are no anatomic arterial-arterial connections between these arteries; therefore, a Doppler signal obtained in this location represents only antegrade flow. However, it is important to assess the flow in the calcaneal branch of the posterior tibial artery and the peroneal artery, to determine whether one artery predominates over the other. This

Fig. 16. (*Above*) This foot's plantar blood supply came from the dorsalis pedis artery via retrograde flow. When the amputation was performed and that connection was cut, the distal plantar surface went on to necrose. (*Below*) This foot's dorsal blood supply came from the lateral plantar artery via retrograde flow. When the amputation was performed and that connection was cut, the distal dorsal surface went on to necrose. (*Reprinted from* Attinger C. Vascular anatomy of the foot and ankle. Oper Tech Plast Reconstr Surg 1997;4:183; with permission.)

issue becomes relevant when one is planning to perform a midline Gaenslen[29] incision to expose the plantar calcaneus.

ARTERIAL-ARTERIAL CONNECTIONS OF THE PLANTAR FOOT

There are multiple levels of arterial-arterial interconnections in the plantar foot. Proximally and medially, there are the connections between the branches of the medial tarsal artery and the superficial medial plantar artery, but the medial tarsal artery is often too small to accurately examine using the Doppler device. At the Lisfranc joint, the dorsal circulation and plantar circulation are linked together via proximal perforators. Medially, the dorsalis pedis links directly with the lateral plantar artery (see **Fig. 9**).

More laterally, the dorsal and plantar metatarsal arteries are linked at their takeoff by the proximal perforating branches. At the web spaces, distal perforating arteries again link the dorsal and plantar metatarsal arteries. The final arterial-arterial interconnection is a fine subdermal arteriolar plexus linking the dorsalis pedis with the lateral plantar artery in a circumferential wraparound pattern about the plantar foot.

DORSALIS PEDIS, LATERAL PLANTAR ARTERIES, AND CRUCIATE ANASTOMOSIS

In the plantar foot, the principle connection to evaluate is that between the dorsalis pedis and lateral plantar arteries. First, use the Doppler device to examine the lateral plantar artery proximal to the base of the proximal first interspace. Then, occlude the dorsalis pedis at the tarsal-metatarsal joint. If the signal disappears, then flow in the lateral plantar artery depends on the dorsalis pedis arterial flow. However, if the sound remains, it means that there is antegrade flow from the posterior tibialis artery to the lateral plantar artery.

A second source of arterial-arterial anastomosis occurs proximal to the first metatarsal head at the cruciate anastomosis, where the superficial and deep medial plantar arteries join (see **Fig. 10**). The distal lateral plantar artery also joins the cruciate anastomosis, linking the medial plantar artery with the lateral plantar artery. The blood supply to the first toe depends on which arteries anastomose and which provide the major blood supply to the cruciate anastomosis: the medial plantar artery, lateral plantar artery, or first dorsal metatarsal artery.

The final arterial-arterial interconnection was first described by Hidalgo and Shaw,[30] who showed a fine subdermal arteriolar plexus linking the dorsalis pedis with the lateral plantar artery in a circumferential wraparound pattern about the plantar foot. They span the angiosome boundaries of the dorsalis pedis artery, medial plantar artery, and lateral plantar artery.

CONNECTIONS ON THE DORSUM OF THE FOOT

As discussed earlier, the dorsal and plantar arterial systems are closely linked at multiple levels. The most proximal is located in the medial foot, where the medial tarsal artery communicates with the superficial (medial branch) of the medial plantar artery. It is usually too difficult to use Doppler imaging on this small connection. Laterally, there is the rete that connects the proximal lateral tarsal artery, the distal tarsal and arcuate arteries, and the lateral malleolar artery and the anterior perforating branch of the peroneal superiorly. In addition, the calcaneal branch of the peroneal artery connects with the lateral tarsal artery. Because of this complex network of connections, it is difficult to determine the source of retrograde flow over the major tarsal artery when it is occluded proximally. If there is retrograde flow along the proximal lateral tarsal artery, it signifies an intact network of connections that can include the anterior perforating branch of the lateral plantar artery, the lateral malleolar artery, the calcaneal branch of the peroneal artery, the distal tarsal artery arcuate artery, and the arcuate artery. The arterial connection described in detail earlier occurs just distal to the Lisfranc joint, where the dorsalis pedis artery joins the lateral plantar artery in the proximal first interspace (see **Fig. 9**). At the proximal metatarsal interspaces and at distal web spaces, the proximal and distal perforating arteries, respectively, link the dorsal and plantar metatarsal arteries (see **Fig. 11**, left). The direction(s) of flow along the dorsal metatarsals can be easily determined. This close linkage ensures that collateral flow compensates for occlusions to either the dorsalis pedis or posterior tibial artery.

Using the Principles of Angiosomes to Make Safe Incisions in Normal and Vascularly Compromised Patients

As we have previously reported in more detail,[18] there are 4 important factors to be considered and balanced when choosing where to place an incision. The incision must provide adequate exposure for the planned procedure. In addition, there must be adequate blood supply on either side of the incision to optimize healing. Third, the incision should spare the sensory and motor nerves. Fourth, the incision should not be placed perpendicular to a joint, because of the risk of causing scar contracture and resultant joint immobility. Although adequate exposure, nerve location, and scar contracture are important factors, we focus primarily on the vascular ramifications of typical incisions in the foot and ankle.

We have described earlier in detail the importance of assessing the blood flow to each angiosome. As we stated, the presence of a palpable pulse or a Doppler-detectable triphasic sound over the source artery to a given angiosome indicates adequate blood flow to that angiosome. If there is good blood flow from the source artery feeding each angiosome, the safest incisions to make are along the border between 2 adjacent angiosomes, because each side of the incision has maximal blood flow. Therefore, incisions along the central raphe over the Achilles tendon, along the glabrous junction separating the sole of the foot from the dorsum of the foot, or along the midline of the sole of the foot are safe incisions.

One cannot reach all areas of the foot through these incisions, and blood flow to each angiosome is not always satisfactory; thus, well-deliberated compromises need to be made. When the signal of a source artery to one of 2 adjacent angiosomes is absent, the affected ischemic angiosome depends on the surrounding angiosomes for blood flow via the choke vessels. Because the choke vessels can require 4 to 10 days to become patent after a given angiosome becomes ischemic, incisions placed too soon after an arterial occlusion for collateral circulation to develop run the risk of poor healing, necrosis, or gangrene.[13,14] However, in patients with chronic arteriosclerosis, the occlusion is gradual and the choke vessels are usually patent by the time the source vessel closes.

In the vascularly compromised patient, collateral flow may keep the ischemic angiosome vascularized, and incisions must be planned so that this collateral flow is not disturbed. In the more extreme ischemic cases, in which there are no palpable pulses and the Doppler sounds are monophasic, then possible surgical revascularization should be entertained before proceeding. When one of the pulses is not present, it is best to place the incision away from the patent source artery, as we have previously reported.[18] This is the safest location, because there is minimal risk of damaging the patent source artery or the crucial choke vessels. We briefly discuss the most frequently used incisions and refer the reader to the article by Attinger and colleagues[18] for a more detailed discussion.

INCISIONS AT THE ACHILLES TENDON

Incisions over the Achilles tendon are the safest if they are made along the midline that divides the peroneal angiosome from the posterior tibial angiosome. Incisions on either side of the Achilles tendon to expose the distal tibia or fibula are also safe, provided that the posterior tibial artery and the peroneal artery are patent. The rich interconnecting vascular plexus around the Achilles tendon keeps the skin above the Achilles tendon viable. A medial to lateral S-shaped incision minimizes injury to the sural nerve and lesser saphenous vein. If an incision is made along the glabrous junction of the posterior heel, the medial portion of the incision should not extend to the medial edge of the Achilles tendon, to avoid damaging the medial calcaneal neurovascular structures. It is safer to make the incision laterally along the glabrous junction, which represents the distal angiosome boundary of the calcaneal branch of the posterior tibial artery.

INCISIONS AT THE LATERAL CALCANEUS

To expose the lateral calcaneus to treat calcaneal fractures, an L-shaped incision should be used, as advocated by Benirschke and Sangeorzan.[31] It is the safest incision if the lower portion of the incision is made along the glabrous junction between the plantar heel and the lateral heel (see **Fig. 17**, above).[19] Because the lateral heel glabrous juncture is the lateral border of the angiosome fed below by the calcaneal branch of the posterior tibial artery and above by the calcaneal branch of the peroneal artery, an incision above that glabrous juncture leaves the intervening tissue between the glabrous junction and the incision in jeopardy (see **Fig. 17**, below). In the usual trauma patient with a calcaneal fracture, the choke vessels between the posterior tibial

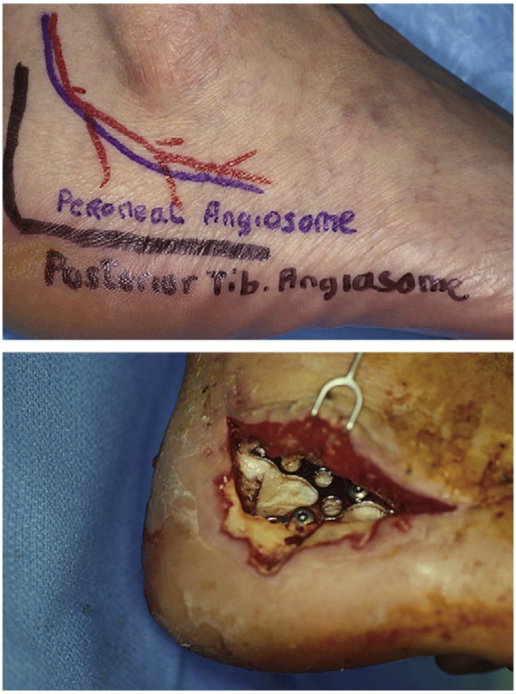


Fig. 17. The L-shaped incision, advocated by Benirschke and Sangeorzan, to expose the lateral calcaneus in calcaneus fractures should be designed with the lower portion of the incision along the glabrous junction between the plantar heel and the lateral heel (*above*). The lateral heel glabrous juncture is the boundary that represents the lateral extent of the angiosome fed by the calcaneal branch of the posterior tibial artery. An incision above the glabrous juncture into the lateral heel proper leaves the tissue between the glabrous junction and the incision in jeopardy, because that tissue lies in the just-divided angiosome of the calcaneal branch of the peroneal artery (*below*). (*Reprinted from* Attinger C. Angiosomes of the foot and ankle and clinical implications for limb salvage: reconstruction, incisions, and revascularization. Plast Reconstr Surg 2006;117:261S; with permission.)

calcaneal and peroneal calcaneal angiosomes have not had the time to open up and allow the calcaneal branch of the posterior tibial artery to feed the tissue beyond its boundary. As we stated earlier, it usually takes 4 to 10 days for the choke vessels to become patent, and it may take even longer in the setting of overlying soft-tissue damage and inflammation.[13]

INCISIONS OVER THE PLANTAR HEEL

In general, incisions over the plantar heel are reserved for hindfoot limb salvage in the presence of osteomyelitis. Safe incisions over the plantar heel from a vascular perspective can be coronal or sagittal in orientation, if the posterior tibial and peroneal arteries are patent. Whether the resultant scar is acceptable is another question.[31] Recall that the blood flow to the heel lies primarily in a coronal direction from the calcaneal branch of the posterior tibial artery (medial) and the peroneal artery (lateral). The coronal incision does not disturb the coronal flow or the sensory nerves that travel in the same direction.

If the incision is in the sagittal direction, then the flow comes to each side of the incision from the respective calcaneal arteries. However, the sensory nerves will be damaged, which is less problematic if the patient is neuropathic. In that instance, a Gaenslen[29] incision down the central heel pad is the ideal choice to expose the calcaneus for calcanectomy. Taking care to adequately evert the edges when closing the incision avoids an inverted and chronically calloused scar.

INCISIONS AT THE PLANTAR MEDIAL MIDFOOT

The plantar tissue is fed by perforators principally on either side of the plantar fascia (**Fig. 18**). If both plantar arteries open, the safest incision is along the plantar midline separating the medial plantar angiosome from the lateral plantar angiosome (**Fig. 19**, left). One can also use a curved or Z-shaped incision with the top 2 limbs following more or less along the boundary of the medial plantar artery (see **Fig. 19**, center). If a curved incision is chosen, it should have its apex laterally based to better follow the angiosome boundary between the medial and lateral plantar arteries (see **Fig. 19**, right). Care has to be taken to preserve the perforators along either side of the plantar fascia. Coronal incisions are also equally secure if the proximal and distal perforators or the underlying neurovascular bundles are not damaged.

INCISIONS ALONG THE MEDIAL AND LATERAL FOOT

For approaches to the medial midfoot, the incision is made along the border between the medial plantar artery angiosome and the dorsalis pedis angiosome (see **Fig. 5**). Two to 3 cm above the medial glabrous junction is safe, provided that the superficial and deep medial plantar arteries are open. To accurately map out the border, one should use the Doppler device to determine the course of the superficial medial plantar artery and design the incision dorsal to its course. The plantar side of the incision is then carefully lifted off the underlying bone, with care taken not to damage the superficial medial plantar artery. Alternatively, the incision can be made at the glabrous junction in the center of the medial plantar angiosome. Because 2 medial plantar arteries provide blood supply to the medial plantar angiosome, it is safe to make an incision in between them, provided they are both patent. Laterally, the safest incision is along the glabrous junction at the border between the dorsal and plantar tissue (see **Fig. 4**, below). The incision lies at the border between the dorsal foot angiosome (dorsalis pedis artery) and the plantar angiosome (lateral plantar artery).

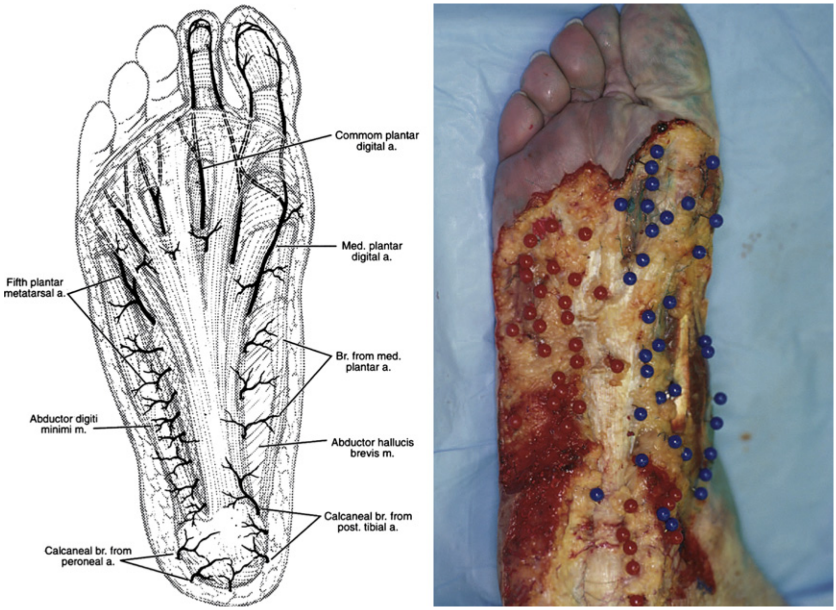


Fig. 18. Most of the perforators that feed the plantar midfoot arise along each side of the plantar fascia from the lateral plantar artery and deep medial plantar artery (*left*). The different colored pins show the location of the perforators on either side of the plantar fascia (*right*). (*Reprinted from* Attinger C. Vascular anatomy of the foot and ankle. Oper Tech Plast Reconstr Surg 1997;4:183; with permission.)

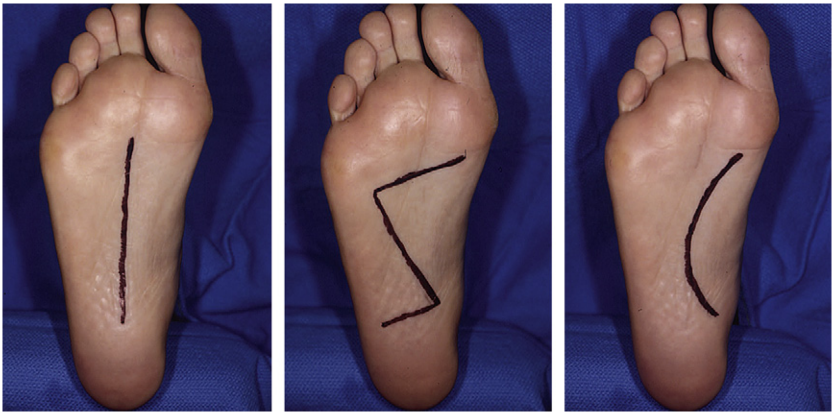


Fig. 19. (*Left*) A straight incision down the midline of the sole of the foot is the safest from a vascular perspective. (*Center*) One can also use a curved or Z-shaped incision with the top 2 limbs following more or less along the boundary of the medial plantar artery. (*Right*) If a curved incision is chosen, it should have its apex laterally based, so as to better follow the angiosome boundary between the medial and lateral plantar arteries. (*Reprinted from* Attinger C. Angiosomes of the foot and ankle and clinical implications for limb salvage: reconstruction, incisions, and revascularization. Plast Reconstr Surg 2006;117; 261S; with permission.)

INCISIONS ON THE DORSUM OF THE FOOT

When considering dorsal foot incisions, recall that the dorsal circulation proximal to the Lisfranc joint travels in a coronal direction, and distal to the Lisfranc joint it travels in a sagittal direction (see **Fig. 11**, left). The lateral proximal dorsum of the foot is composed of a rete of coronally interconnected arteries of the lateral malleolar, tarsal (proximal and distal), and arcuate arteries. This rete is linked superiorly to the anterior perforating branch and laterally to the calcaneal branch of the peroneal arteries. Medial to the dorsalis pedis artery is the medial tarsal artery, which may be directly linked to the superficial medial plantar artery. We placing the incision parallel to the direction of the arterial supply. Coronal incisions in the lateral proximal dorsal foot are parallel to the coronally directed arteries (proximal tarsal, distal tarsal, arcuate arteries, and their perforators). In addition, the dorsalis pedis artery should be identified and spared, unless it is clear that the antegrade and retrograde flow is strong. For approaches to the medial proximal dorsal foot, the safest incision is along the border between the medial plantar artery angiosome and the dorsalis pedis angiosome. For incisions of the distal forefoot, it is important not to place an incision through the metatarsal arteries, unless they both have antegrade flow (from the arcuate artery and proximal perforators) and retrograde flow (from the distal perforators). Recall that the metatarsal arteries arise from the arcuate artery, travel along the interosseus space, and are connected to plantar circulation proximally and distally by perforators. If the metatarsal artery flow is bidirectional, then coronally directed incisions are safe. However, if the flow is unidirectional, the incisions should be in the sagittal direction, over the metatarsal bones themselves, in order not to disturb the dorsal metatarsal arteries. Multiple parallel sagittal incisions over the distal dorsal forefoot can be performed as long as the dorsal metatarsal arteries are preserved. Only 3 incisions are necessary to gain access to all metatarsals, and the incisions should be short, with little undermining of the skin overlying the interosseus muscles.

INCISIONS FOR AMPUTATIONS

In general, performing forefoot and midfoot amputations in patients who have intact circulation with the dorsal and plantar antegrade blood flow has minimal risk. All incisions should be designed at the angiosome boundaries to maximize blood flow at the edges of the amputation. Medial and lateral incisions should be at the glabrous juncture between the dorsal and plantar circulation, whereas dorsal and plantar incisions should be to bone, without undermining to preserve the metatarsal arteries in the flaps. When there is compromised flow and a forefoot or midfoot amputation is planned, it is important that the remaining blood flow and arterial-arterial connections are mapped completely. If the dorsal circulation depends on the plantar circulation or vice versa, then connections between the 2 regions cannot be disturbed (see **Fig. 17**). That is, the connection between the dorsalis pedis and lateral plantar arteries at the proximal first interspace must be maintained. To preserve that connection when performing a short transmetatarsal or Lisfranc amputation, the lateral 4 metatarsals are removed laterally whereas the first metatarsal is removed medially.

Using the Angiosome Principle in Planning the Optimal Revascularization

Despite the current advances in revascularization techniques, vascular bypass surgery fails to heal approximately 15% of ischemic lower extremity wounds with a patent bypass.[28–43] Gooden and colleagues[44] found that up to 25% of patients with heel ulcers ultimately succumbed to a proximal leg amputation despite a palpable pedal pulse. The failures may be due in part to inadequate postoperative wound care,[45] but the major part of the problem is caused by the inadequate revascularization of the local ischemic area, because the vascular connections between the revascularized vessel and the source vessel nourishing the ischemic area are absent or occluded.

Thus, successful revascularization for ischemic wounds is more complex than simply restoring circulation to a specific artery. The failure of limb salvage in a percentage of successful bypasses suggests that more effective revascularization may occur if the bypassed vessel directly feeds the source artery of the angiosome containing the ulceration. That is, revascularization of the major artery directly supplying the ischemic and ulcerated angiosome should be more successful than revascularizing one of the other 2 major arteries and hoping that existing arterial-arterial connections for the blood flow reach the ischemic ulcerated angiosome.[46]

We retrospectively examined the results of direct versus indirect consecutive revascularization of 52 limbs. There was a 9.1% failure rate when wounds were directly revascularized versus a 38.1% failure rate in the wounds indirectly bypassed (P = .03). Those who failed to heal went on to a major leg amputation. The amputation rate, therefore, in the indirectly bypassed group was 4 times that of the directly bypassed group. This study supports the suggestion that direct revascularization of the affected angiosome leads to higher limb salvage rates.

If the vascular surgeon has more than one vessel to bypass to, or has the choice of endovascularly opening more than one vessel, they should preferentially open the vessel that directly feeds the affected angiosome. For heel wounds, the peroneal or posterior tibial artery should be preferentially revascularized. For plantar foot wounds, the posterior tibial artery should be preferentially revascularized. For lateral ankle wounds, the peroneal artery should be preferentially revascularized. For dorsal foot wounds, the anterior tibial artery should be preferentially revascularized. If the vascular surgeon cannot revascularize the source artery to the affected angiosome, they can then predict a failure rate of the revascularization to be 15% or higher unless the surgeon can show that the arterial-arterial connections between the artery to be revascularized and the source artery of the affected angiosome are open.

SUMMARY

Three major arteries supply the foot and ankle and create vascular redundancy through multiple arterial-arterial connections. A Doppler device may be used to map out the patient's vascular tree, including the direction of flow. Knowledge of the 6 angiosomes of the foot and ankle combined with an adequate Doppler examination can optimize the success of any planned treatment or procedure. This information is essential for successful limb salvage in diabetic patients and patients with peripheral vascular disease and ultimately helps a surgeon to decide whether a reconstruction is possible or an amputation is indicated.

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