Venous outflow of the leg: Anatomy and physiologic mechanism of the plantar venous plexus

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Purpose: Mechanisms of venous outflow from the leg and foot have not been clearly defined. The purpose of this study was to evaluate the anatomy and physiologic mechanism of the plantar venous plexus and its impact on venous drainage from the tibial veins.
Methods: Fifty phlebograms that contained complete foot and calf films were reviewed. On lateral films, the number of veins in the plantar venous plexus and its tibial outflow tract were counted. The length and diameter of the longest vein in the plantar venous system and the length of the foot arch were measured. The ratio of the length of the plantar venous plexus to the arch length was calculated. The presence or absence of valves within the plexus was recorded. Plantar venous plexus outflow was evaluated by an duplex ultrasonographic scan of the posterior tibial, anterior tibial, and peroneal veins during intermittent external pneumatic compression of the plantar surface of the foot.
Results: The plantar venous plexus was composed of one to four large veins (mean, 2.7 veins) within the plantar aspect of the foot. The diameter of these veins was 4.0 ± 1.2 mm. The veins coursed diagonally from a lateral position in the forefoot to a medial position at the level of the ankle, spanning 75% of the foot arch. Prominent valves were recognized within the plantar veins in 22 of 50 patients. The plexus coalesced into an outflow tract of one to four veins (mean, 2.5 veins) that flowed exclusively into the posterior tibial venous system. Small accessory veins that drained the plantar surface of the forefoot flowed into either the posterior tibial or peroneal veins. This pattern of selective drainage of the plantar venous plexus was confirmed by duplex imaging. Mechanical compression of the plantar venous plexus produced a mean peak velocity in the posterior tibial veins of 123 ± 71 cm/sec, in the anterior tibial veins of 24 ± 14 cm/sec, and in the peroneal veins of 29 ± 26 cm/sec.
Conclusions: The plantar venous plexus is composed of multiple large-diameter veins that span the arch of the foot. Compression of the plantar venous plexus, such as that which occurs during ambulation, is capable of significantly increasing flow through the posterior tibial venous system into the popliteal vein. Its function may be integral to venous outflow from the calf and priming of the more proximal calf muscle pump. (J Vasc Surg 1996;24:819-24.)

Although the venous anatomy of the leg has been well described for centuries, the mechanisms of venous outflow from the leg and foot have not been clearly defined. In a series of landmark contributions more than 30 years ago, Ludbrook[1-3] demonstrated that muscular contractions of the gastrocnemius and soleus were sufficiently forceful to rapidly empty intramuscular venous tributaries. This action appeared to reduce calf volume. Over time, the hypothetical concept of the calf muscle pump evolved in which the muscular actions of the calf promoted, augmented, or assisted venous outflow from the deep various system of the lower leg.[4] Attempts to prove the hypothesis have been frustrating for many investigators. The force required to overcome the pressure of the column of blood within the venous system of the lower leg exceeds that generated within the muscular compartments of the calf during motion.[5] The discrepancy between the pressures required and those generated has compelled investigators to seek

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Fig. 1. Appearance of plantar venous plexus after injection of contrast medium into a distal superficial vein. In all patients, plexus was composed of a number of large and small veins within deep space of foot. To assess the relationship between length of major veins of plantar venous plexus and arch of foot, the arch was measured from inner surface of calcaneus to inner surface of first metatarsal head.

alternative mechanisms for the driving force of venous outflow from the deep veins of the calf.

More recently, attention has been drawn to the plantar venous plexus.[6,7] The location of this plexus of veins within the plantar surface of the foot subjects it to high-pressure compression during ambulation, which raises the possibility that these veins may constitute a mechanism for driving the venous outflow from the leg. Neither the relationship between this venous plexus and the deep venous system of the calf nor the physiologic mechanism of plantar venous compression has been completely described. The purpose of this study was to evaluate the anatomy and physiologic mechanism of the plantar venous plexus and its impact on deep venous drainage from the calf.

METHODS

Anatomy of the plantar venous plexus. Phlebograms containing complete foot and calf films that had been obtained as part of a deep venous thrombosis study were reviewed. There were 25 men and 25 women. Twenty-eight of the studies had been previously reported by the radiology department as being normal, whereas the remaining 22 demonstrated thrombosis within the deep veins. Of these, 11 had clot above the level of the knee and 11 had clot confined below the knee. Patients who had above-knee clot had obstructing thrombus within the superficial femoral vein. None of these patients had iliofemoral venous thrombosis. Those patients who had clot below the knee had thrombus within the posterior tibial (PT) vein, the peroneal vein, or both. No patient had clot within the anterior tibial (AT) veins. Phlebograms were evaluated for the number of major veins that comprised the plantar venous plexus. The length of the longest vein within the plantar venous system and the length of the foot arch were directly measured on the phlebogram (Fig. 1). The ratio of the length of the major plantar veins to the foot arch length was calculated. The diameters of the largest vein within the plantar venous plexus and the largest deep calf outflow vein were measured. The ratio of plantar vein diameter to outflow vein diameter was calculated to permit size comparison of veins independent of x-ray magnification. The mean plantar vein diameters of normal veins, those with above-knee clot, and those with below-knee clot were compared. The presence or absence of valves within the plexus veins was recorded. The location and number of outflow vessels within the deep venous system of the calf ware noted.

The plantar venous plexus was surgically exposed in the foot of three patients who underwent amputation for ischemia. The entire foot was intact and without tissue loss proximal to the metatarsophalangeal joints. The course of the major veins of the plantar venous plexus was noted.

Plantar venous plexus compression. To assess the impact of plantar venous compression on flow within the deep venous system of the calf, an intermittent pneumatic compression foot pump system was used (AV Impulse System, Kendall Co., Mansfield, Mass.). The system consists of a boot containing an air bladder that, when appropriately applied, spans the area of the plantar venous reservoir on the sole of the foot. As used in this study, the air bladder is inflated within 0.4 seconds to a pressure of 130 mm Hg by an air impulse generated by a controller and transmitted by a flexible hose. The rigid sole of the boot beneath the inflation pad contains and directs the air impulse toward the sole of the foot. The plantar surface of the foot is contacted with a pressure of approximately 130 mm Hg. Although the actual contact pressure may vary slightly, there is not a significant variation in the velocities detected by ultrasound. The rapid inflation of the air bladder flattens and stretches the plantar arch, which mimics the natural effects of weight bearing and ambulation. A 3-second impulse is applied to the sole of the foot approximately every 20 seconds, allowing time for the plantar venous plexus to refill.

Venous imaging of the deep veins of the calf. Ten volunteers (20 limbs) were placed in the supine position with the bed in a 15 degree reverse Trendelenburg position. This stable leg position was chosen to permit refilling of the planar venous plexus during intermittent pneumatic compression of the foot while performing technically precise venous imaging. After a minimum of 10 minutes of intermittent compression of the plantar venous plexus, imaging of the deep veins of the calf was undertaken. A 7-4 MHz linear array transducer was used with a standard color Doppler imaging system (Ultramark 9 HDI, ATL, Bothell, Wash.). The PT, AT, and peroneal veins were initially identified in the transverse plane. Doppler information was obtained using a 60 degree angle from a longitudinal view. Resting venous velocities and changes in the venous spectral waveforms were recorded for three cycles of the pneumatic foot pump compression device for each deep calf vein. The peak venous velocity was measured and averaged for the three compression cycles for each of the three major deep calf veins.

Statistical analysis. The ratio of plexus vein to outflow vein diameter for normal veins, those with above-knee clot, and those with below-knee clot, and the mean peak velocities of the deep calf veins were compared with Student's unpaired t test. A value of $p < 0.05$ was used to indicate statistical significance.

RESULTS

Anatomy of the plantar venous plexus. Of the 50 patient phlebograms that were reviewed, all of the foot films demonstrated the presence of a plantar venous plexus after injection of a contrast medium into a dorsal vein of the distal foot (Fig. 1). The plantar venous plexus was composed of one to four large veins (mean, 2.7 veins) within the plantar aspect of the foot. The veins coursed diagonally from a lateral position in the forefoot to a medial position at the level of the ankle and remained in the deep space of the foot throughout. The ratio of the mean length of the major plantar veins to the mean length of the foot arch was 0.75. The plantar venous plexus was not present under the calcaneous or the first metatarsophalangeal joint.

Fig. 2. Valves within major veins of plantar venous plexus.

Prominent valves were recognized within the plantar veins in 22 of 50 patients (44%; Fig. 2). The plexus coalesced proximally into one to four veins (mean, 2.5 veins), which flowed in all cases into the PT venous system (Fig. 3). The ratio of the mean

Fig. 3. Outflow tract of plantar venous plexus. Note direct flow of contrast medium from plexus into PT veins. Accessory outflow veins from plantar venous plexus *(arrow)*, when present, emptied into PT veins in most patients, although there appeared to be communication with peroneal veins in a few patients.

plexus vein diameter to the mean PT vein diameter was 1.91:1. The mean diameter of the major plantar plexus veins was unaffected by the presence of clot within the deep venous system of the leg regardless of location ($p > 0.05$ for negative vs below-knee clot and negative vs above-knee clot). Small accessory veins that drained the plantar surface of the forefoot were occasionally seen that flowed into either the PT or peroneal veins (Fig. 3). The diameter of the accessory draining veins was smaller than the major veins of the plantar venous plexus.

Physiologic mechanism of compression of plantar venous plexus. Mechanical compression of the plantar venous plexus produced a mean peak velocity of 123 ± 71 cm/sec in the PT veins, 29 ± 26 cm/sec in the peroneal veins, and 24 ± 14 cm/sec in the AT veins (Fig. 4). The acceleration of flow within the PT veins was significantly greater than in either the AT veins ($p < 0.001$, PT vs AT) or the peroneal veins ($p < 0.001$, PT vs peroneal). There was no difference between the mean peak velocities generated within the AT and peroneal veins ($p = 0.593$, AT vs peroneal).

DISCUSSION

Since the publications of Barcroft,[8,9] Ludbrook,[1-3] and others, the calf muscle pump has been frequently discussed but incompletely defined. Functionally, it represents the mechanism by which blood in the deep calf veins is propelled cephalad. Physiologically, compartment pressures do not rise sufficiently during ambulation to adequately compress the deep calf veins and displace the blood they contain. Ludbrook[3] attempted to measure intrinsic muscle pressures and correlate them with calf volume changes during muscle contraction. A percutaneously placed indwelling catheter was used to record resting and forceful contraction pressures within the gastrocnemius and soleus muscles. Air plethysmography was used for the assessment of calf volume changes during muscle contraction. Ludbrook determined that calf muscles contract with a pressure that exceeds 200 mm Hg and that the contraction is associated with an 80% reduction in calf volume. From these data, he concluded that the pressure of muscle contraction was of sufficient magnitude to expel blood from the intramuscular veins into the deep system. These studies did not address the mechanisms by which blood is propelled from the deep veins of the calf.

Recently, Alimi and colleagues[10] attempted to correlate changes in compartment pressures with popliteal venous pressures to better define the mechanisms of calf deep-vein emptying. These investigators used methods similar to those used by Ludbrook, placing indwelling cannulae into the three major calf compartments and the popliteal vein. The intramuscular cannulae were placed just under the aponeurotic structures parallel to the muscle fibers so that compartmental rather than intramuscular pressures could be recorded. In the standing position at rest, popliteal pressure exceeded the intramuscular pressures in all calf compartments. During ambulation with the foot forward, only the deep posterior compartment pressure (61.9 ± 14.4 mm Hg) exceeded that of the popliteal vein (56.9 ± 5.8 mm Hg), and with the foot behind, only the AT compartment pressure

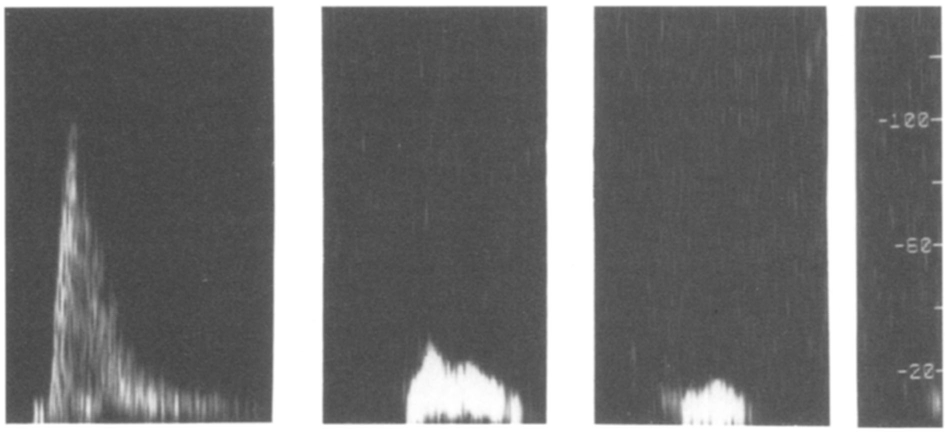

Fig. 4. Velocity changes within deep veins of calf during compression of plantar venous plexus. Note significant increase in mean peak velocity of PT veins with minimal acceleration within peroneal or AT veins.

(43.3 ± 7.8 mm Hg) surpassed popliteal venous pressure (35.0 ± 10.6 mm Hg). The functional relationship between these compartment pressures and venous pressure is unclear because of the large standard of error of these measurements and the diminutive nature of the pressure gradient. In addition, venous pressures measured more distally are higher. These data, therefore, do not support the hypothesis that changes in calf compartment pressures provide a compressive pumping mechanism for the deep veins of the calf and suggest that alternative mechanisms be sought.

Although the presence of major deep veins within the foot has been recognized for centuries, the impact of these veins on flow within the deep venous system of the calf was not questioned until recently. Gardner and Fox[6,7,11] extended the body of knowledge of the plantar venous plexus using video phlebography. These investigators demonstrated that the plantar venous plexus fills rapidly with the foot in the dependent position and empties immediately when weight is placed on the arch of the foot. Outflow from the plexus is independent of calf muscle contraction.[12] The current study was undertaken to extend these seminal observations.

The anatomy of the plantar venous plexus underscores its physiologic function. There are most often several large veins within the plexus (mean, 2.7; range, 1 to 4) traversing the deep layer of the plantar surface of the foot. These veins reside largely under the arch of the foot and are therefore somewhat protected from repeated trauma during weight bearing and ambulation. As noted by the reporting radiologist, the injection of a contrast medium into a superficial dorsal vein of the distal forefoot and its flow through the tissues resulted in visualization of the plantar veins of the foot, which suggests that the plexus veins collect blood not only from the deep spaces of the foot but also from superficial veins. Outflow of the plantar venous plexus is always through the PT deep veins and so provides unidirectional movement of blood from the foot into the deep system.

This directed flow of blood is assisted by the presence of valves within the plantar venous plexus. Although the retrospective review of phlebograms demonstrated valves in only 22 of 50 patients, a more detailed study performed with the intent of defining valves within the plantar system might better assess the incidence and function of these structures. There was no increase in plantar vein diameter in the presence of clot within the deep venous system above or below the knee that suggested preserved patterns of outflow.

The major veins of the plantar plexus are larger in diameter than the PT veins within the calf. The ratio of plantar vein diameter to that of the posterior tibial veins is 1.91:1, which creates a bellows-type effect, rapidly increasing the velocity of flow within the PT veins during compression of the plantar veins and displacement of the blood they contain. The impact of plantar venous plexus compression on the hemodynamics of the deep veins of the calf was confirmed in our study by duplex imaging. The reverse Trendelenburg positioning of the volunteers was sufficient to permit venous refilling during intermittent pneumatic compression of the plantar plexus. More rapid filling of these veins would be expected with the patient in the upright, non–weight-bearing position, but flow patterns are unchanged. There was a significant increase in mean peak velocity within the PT veins but not in the peroneal or the AT veins during relatively gentle pneumatic compression of the plantar surface of the foot.

These data suggest that the plantar venous plexus is an important venous pump of the leg. Because it is compressed with a significant force during ambulation, the plantar plexus is able to overcome the pressure of the column of blood within the deep venous system of the calf.[13,14] Additional mechanisms of compression may also cause ejection of blood from this plexus and from the deep veins of the calf. Gardner and Fox[6,7] demonstrated that because of tethering of the plantar venous plexus across the foot arch, stretching of the arch without weight-bearing may be sufficient to forcefully empty the veins. The length-to-diameter relationship of blood vessels predicts that the diameter of a blood vessel decreases as it is stretched beyond its resting length. Venous diameter changes have more recently been addressed by Raju and colleagues,[15] who surmised that venous wall collapse may play a role in regulating and reducing calf deep venous pressures.

Whether through direct compression or stretch, the plantar venous plexus represents the most distal of the musculovenous pumps of the leg. Because it is predicated on the coordinated muscle activity of the calf, the plantar venous plexus works in concert with the forceful drainage of the intramuscular veins of the upper calf. Its function may be integral to venous outflow from the calf and priming of the more proximal calf muscle pump. Further study is required to clarify its effects on the superficial and more proximal portions of the venous system of the leg.

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