Measurement of ambulatory venous pressure and column interruption duration in normal volunteers

Seshadri Raju, MD, FACS, William Walker, BS, MS, *and* Corbin May, BS, MS, *Jackson, Miss*

ABSTRACT

Background: Ambulatory venous pressure (AMVP) measurement is considered the gold standard in evaluating calf pump function in chronic venous disease. The AMVP protocol was standardized in the 1970s with pressure monitoring through the dorsal foot vein. This technique was based on the belief that it represents calf venous pressure dynamics owing to rapid equilibration in the superficial and deep systems. This notion is subject to some doubt not only on theoretical grounds, but also owing to a lack of clinical correlation in a segment of the population with chronic venous disease. Our aims were to (1) examine if AMVP measured simultaneously through the dorsal foot vein (DFV) and the great saphenous vein (GSV) would be similar and (2) attempt to devise a noninvasive substitute via duplex measurement for the AMVP test.

Methods: The study was conducted in 76 limbs in 38 normal volunteers. Simultaneous AMVP measurements in DFV and GSV were made in 28 of these normal limbs. Column interruption duration (CID) after calf pump ejection was measured by monitoring duplex resumption of flow in the tibial veins and GSV after calf ejection. The return of AMVP back to baseline implies column restoration. The venous refill time therefore represents the CID via the pressure method. The pressure and duplex methods of CID were compared in the GSV.

Results: Key AMVP parameters (percent drop and venous refill time) significantly differed in DFV and GSV, showing a lack of pressure equilibration. CID measured by duplex in GSV was not significantly different from pressure-derived CID in the same vein.

Conclusions: AMVP measured through the DFV does not reflect calf pump generated pressure events in GSV. A duplex method of measuring CID in GSV and posterior tibial vein is described. Duplex-derived CID is not significantly different from pressure-derived CID in the GSV. (J Vasc Surg: Venous and Lym Dis 2020;8:127-36.)

Keywords: Calf pump; Ambulatory venous pressure; Venous column interruption; Venous reflux

It has been known for over a century that ambulatory venous hypertension is a pathophysiologic factor in chronic venous disease (CVD). Seminal works by Ludbrook, Pollack and Wood, Hojensgard and Sturup, and, later, Arnoldi lay the framework of our current concept of calf venous pump.[1-6] This work can be termed: the unicameral model.

Unicameral calf pump model. The various pressure changes that occur with calf exercise have been traditionally explained on the basis of postsystolic popliteal valve closure, interruption of the venous column, and its restoration at the end of calf diastole with reopening of the popliteal valve.[7] This model is thought to function in normal limbs as follows: The venous pressure in the deep and superficial systems in the erect position at rest is roughly equal, corresponding with the height of the hydrostatic column of blood extending from the foot to the heart. The resting pressure in the deep system is slightly higher, keeping the perforator valves closed in the motionless erect individual. When the calf muscles contract (systole), the pressure in the deep veins in the calf increase owing to the sudden discharge of blood from the numerous muscular tributaries propelling blood through the popliteal vein. Blood also egresses through the great saphenous vein (GSV) through avalvular connectors with the deep system, notably the soleal sinusoids. After calf pump ejection (systole), the popliteal valve closes, as well as valves in the GSV at the knee level. After a transient systolic increase of 10 to 25 mm Hg, pressures in the superficial and deep systems above the knee return to the normal resting level of about 50 mm Hg. Veins below the knee collapse with saphenous and tibial pressures reaching as low as 20 to 30 mm Hg. This signifies interruption of the hydrostatic column with calf pump action.

A period of calf diastole lasting 20 seconds or more begins. During this period, calf pump refills from arterial inflow draining through the muscular veins. A small amount of blood in the superficial venous network consisting of the GSV and branches in the leg may empty into the tibial veins through perforators, whose valves

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Correspondence: Seshadri Raju, MD, FACS, The RANE Center, St. Dominic's Memorial Hospital, 971 Lakeland Dr, Ste 401, Jackson, MS 39216 (e-mail: rajumd@earthlink.net).

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now allow drainage into the emptied calf pump reservoir (diastolic drainage). When calf refilling is complete, the popliteal valve opens with column restoration in the erect volunteer. The duration from pressure nadir to recovery of baseline pressure in the ambulatory venous pressure (AMVP) test is thought to represent the duration of popliteal valve closure. In this unicameral model, the superficial and deep veins of the calf are treated as a single coordinated unit.

AMVP test. Early attempts to measure calf pump pressure dynamics were hampered by primitive equipment by today's standards, imprecise zero calibration, and varying calf exercise protocols. The AMVP test has become standardized since then, using the dorsal foot vein (DFV) with a standard calf exercise protocol of 10 tip-toe stands. Modern digital transducers and recorders have vastly enhanced metric accuracy. A decrease of at least 50% in dorsal foot venous pressures (%drop) with calf exercise and a minimum of 20 seconds for recovery (venous refill time [VFT]; also called VRT in some publications) to baseline are considered normal. Some authors also have used the highest pressure point reached during the oscillations of calf pump action (usually the first wave) as an indicator of outflow obstruction. A value of greater than 40 mm Hg above baseline (approximately 80-100 mm Hg) has been suggested as indicating outflow obstruction.[8]

Interpretation of the AMVP test is based on the unicameral model as described. The core concept that superficial and deep venous pressures are similar is assumptive based on Pascal's law. Rapid equilibration of pressures in the interconnected system is assumed.[9,10] However, Arnoldi[1,2] compared simultaneous pressure profiles in the GSV and the posterior tibial vein in 9 normal individuals and additionally in 22 limbs with CVD. The pressure nadir in the GSV was found to be significantly higher in the GSV compared with the posterior tibial vein in the normal limbs; that seemed to be the case in CVD limbs as well, although no statistics were provided. Ludbrook[4,11] had also noted that the pressure in the GSV noticeably differed from posterior tibial vein during different phases of calf pump action. These findings contradicting the unicameral model had not received much attention. Much of the current concepts in calf functional anatomy is derived from observations in patients with CVD. Except for the few small series noted, there have been no other comparative pressure measurements in the superficial and deep systems in normal limbs.[1]

The use of the dorsal pedal vein in the AMVP test was first described by Arnoldi[12] in two limbs with perforator incompetence. The use of DFV in AMVP test as a proxy for posterior tibial venous pressure nevertheless has gained wide acceptance without further validation because of the relatively easy access to it compared with the deep vein.

ARTICLE HIGHLIGHTS

- **Type of Research:** Single-center, prospective, nonrandomized cohort study
- **Key Findings:** Ambulatory venous pressure via the dorsal foot vein was significantly different ($P < .005$) from simultaneously recorded great saphenous vein pressures in 28 normal limbs. Duplex-derived column interruption duration (CID) was not different from pressure-derived CID in the great saphenous vein.
- **Take Home Message:** Traditional ambulatory venous pressure measurement through the dorsal foot vein does not reflect calf pump pressure dynamics in the superficial and deep axial veins. CID may be an easier noninvasive surrogate of direct pressure measurement.

We had previously reported on direct pressure measurements (transducer tipped catheter) in the posterior tibial vein in 45 limbs with advanced CVD features.[13] The standard AMVP test via DFV was normal in many of the limbs and did not reflect their severe CVD clinical presentation. The mean %drop and VFT measured through the DFV in the group were normal at 75% and 44 seconds, respectively. The mean %drop and VFT directly measured in the posterior tibial vein was significantly worse at 21% and 16 seconds, respectively, more reflective of the clinical features. In a similar group of eight CVD limbs with discordant clinical and AMVP findings simultaneous pressure measurements were made in the posterior tibial vein, the GSV, and the DFV.[14] The pressure profiles were widely different in the three veins. The %drop and VFT were normal in the DFV, but were abnormal in the saphenous and posterior tibial veins.

The aim of the current study is to show that (1) AMVP measured in the DFV is different from the GSV near the ankle in normal volunteers, (2) the duration of saphenous and tibial venous collapse with calf pump ejection can be measured noninvasively with duplex, as well as pressure, (3) these collapse durations are different between the saphenous vein, tibial vein, and DFVs consistent with a polycameral model of calf venous pump function.

METHODS

Normal volunteers

Thirty-eight healthy volunteers (76 limbs) without venous complaints and a normal clinical and duplex Vexamination were recruited for the study under an informed consent, and experimental protocol approved by the institutional review board. Permission to publish this report was also granted.

Procedures

Duplex. A color duplex instrument (Logiq 9, GE Medical Systems, Waukesha, Wisc) was used. B-mode/B-flow/color flow images were used in combination to identify and monitor the valve of interest in standing position. A hockey stick probe (GE Logiq S8, 8-18 MHz) and linear probe (GE Logiq S8, 8.5-10 MHz) were preferred for the GSV and the deep axial veins respectively. Machine settings: color flow, scale at 5 cm/second; B-flow, speckle reduction at 5; and low flow setting, line density at 1 and auto optimization.

B-flow and color flow yielded nearly identical valve action related time measurements during calf diastole. In 56 parallel comparisons (5 minutes apart) of the two methods examining GSV or tibial veins in 14 limbs, the mean variation in seconds was 4%. B-flow was preferred for the GSV and the linear probe for the deep veins for best image quality.

Calf ejection.

Active calf ejection. A standard tip-toe heel exercise (10×) was used.

Passive calf ejection with pneumatic cuff. Patients were examined in the erect position with full weight bearing on both limbs (Fig 1). Patients were instructed to remain motionless while holding on to a rigid support. Rapid inflation/deflation cuffs (Hokanson, Bellevue, Wash) were used to produce calf ejection. The cuff was applied to the upper calf; inflation pressure was 110 mm Hg.

Diastolic valve closure time. The diastolic valve closure time (DVCT) of the femoral and popliteal valves were measured as follows: A timer was turned on as soon as the monitored valve was seen to close after calf ejection with toe stands or pneumatic cuff. The time duration when the valve reopened establishing upward flow again (average of three separate measurements) was recorded. This is referred to as the DVCT. Note: this measure is different from the more commonly measured reflux duration, also known as valve closure time (VCT), which is an end-systolic reflux measurement.[15] Examined valves were: the uppermost femoral valve located approximately 1 cm below the deep femoral vein confluence and the popliteal valve located behind the joint crease.

Column interruption duration by duplex. There are multiple tibial valves spaced 1 to 2 cm apart in the lower calf below the pressure cuff. The DVCT of tibial valves cannot be determined individually because they are small and difficult to image. One of the paired tibial vein segments immediately below the pneumatic cuff is monitored. Tibial flow ceases after calf ejection is complete. Tibial flow restoration occurs in series of pulse waves from below of increasing frequency. The very first pulse is the one that is timed. The interval from calf ejection with pneumatic cuff to reappearance of flow represents column interruption duration (CID) in the tibial veins.

Fig 1. Measurement of column interruption duration (CID). The volunteer is examined in full weight-bearing erect position, remaining motionless while holding on to a rigid support. An automated quick inflation/deflation cuff is applied to the upper calf. Calf ejection is produced by cuff inflation to 110 mm Hg followed by deflation. One of the posterior tibial veins below the cuff is monitored after cuff deflation. The duration of reappearance of flow (B flow or color flow) represents CID for the tibial vein. The CID for the great saphenous vein (GSV) is similarly determined via duplex probe focused on the vein immediately below the cuff. See text.

CID by pressure measurement

Restoration of pressure to resting levels after calf ejection with standard tip-toe exercise implies column restoration. The VFTs in the saphenous and DFVs that were measured with AMVP test represent respective CID for these veins.

AMVP

AMVPs were measured simultaneously via two needles, one in the DFV and the other in the GSV anterior to the medial malleolus. Pressures were recorded with 10 tip-toe movements.[16] The pressure nadir immediately after cessation of calf exercise represented postexercise pressure also referred to as the AMVP. Ambulatory pressure drop (%drop) was calculated as (base−pressure drop/base) × 100. The time in seconds (VFT) for pressure recovery back to base line was recorded. The respective percent drop and VFT obtained through the great

Table I. Demographics

No. of limbs (patients)	76 (38)
Median age, years (range)	34 (15-42)
Male:female	1:1
Right:left	1:1

saphenous and DFVs are indicated by the letters GSV and DFV appended in subscript to those measurements (VFT_{GSV} and VFT_{DFV}).

Statistics

Analyses were performed using commercial software (Prism Corporation, Irvine, Calif). Paired or unpaired two tailed *t*-tests were used as applicable, using significance at a *P* value of less than .05. Pearson's correlation was used for continuous data. Individual n values varied among experiments, which is indicated in context. When techniques such as color flow versus B-flow or CID via duplex were compared, the same limb was used.

RESULTS

The demographics of the volunteers are shown in Table I. The male to female ratio was 1:1. The left to right ratio was also 1:1.

Supine pressures and AMVP parameters along with normal reference values culled from the literature are shown in Table II. Supine pressures in GSV and DFV were in the normal range in all categories. Erect base pressure was significantly less in both GSV and DFV in women compared with men. All other parameters were in the normal range.

DVCT data for the same limb with toe stands (×10) and pneumatic cuff inflation are shown in Table III. Calf ejection with pneumatic cuff produces similar or better DVCT data than toe stands, signifying similar or better calf ejection. The shorter DVCT with tip-toe calf exercise was in part owing to motion-related delay in valve monitoring. The VFT of AMVP test via DFV was several times longer than DVCT of either the femoral or the popliteal valve. The femoral valve stays closed after calf ejection for a short duration, a median DVCT of 8 seconds (range, 2-33 seconds). Popliteal valve remains closed a few seconds longer; even so, it is still roughly one-tenth of the VFT_{DFV}.

Parameters of simultaneous recording of saphenous and DFV pressures are shown in Table IV. There is no significant difference in supine or erect base pressures. Key AMVP parameters, percent drop, and VFT are significantly different; the percent drop is greater and the VFT is longer in the DFV compared with the GSV.

CID values derived either through pressure or duplex for the various veins are shown in Table V. Duplex-derived CID of the tibial vein was significantly longer than the DVCT of the femoral and/or popliteal valve (DVCT data in Table III) in 100% of limbs ($P < .0001$).

Duplex-derived CID trended longer than pressure-derived CID in the same GSV, but the difference was not statistically significant ($P = .08$; Pearson's $r = -0.07$). Duplex-measured tibial CID is not significantly different from duplex-derived CID of the GSV in the same limb, but with poor correlation ($P = .6$; $r = 0.26$). Duplex-derived CID of the tibial veins was longer than duplex CID of GSV of the same limb in 91%.

As a group (unpaired data), tibial CID (duplex) was significantly longer than CID (pressure) of DFV, that is, the VFT_{DFV} ($P = .005$). The tibial vein had a shorter CID than the DFV (paired data) in about two-thirds of limbs.

Table II. Male vs female and right versus left

Vessel	Parameter (normal value)	Male (n = 32)	Female (n = 25)	Right (n = 30)	Left (n = 28)
GSV	Supine pressure (<11 mm Hg)	10 (4-18)	10 (5-18)	10 (3-20)	9 (3-15)
	Erect base pressure (<100 mm Hg)	101 (91-109)	91 (83-100)[a]	95 (85-107)	94 (75-106)
	First peak (<140 mm Hg)	113 (100-122)	100 (58-110)	104 (91-127)	109 (12-119)
	Postxercise pressure (<50 mm Hg)	48 (22-70)	43 (34-55)	42 (23-76)	43 (20-67)
	Percent drop (>50%)	54 (35-78)	53 (38-60)	52 (29-76)	54 (23-80)
	VFT (>20 seconds)	25 (5-80)	45 (9-102)	22 (4-117)	27 (6-107)
DFV	Supine pressure (<11 mm Hg)	9 (4-17)	10 (4-20)	10 (2-21)	10 (3-17)
	Erect base pressure (<100 mm Hg)	99 (86-112)	87 (69-104)[b]	99 (76-112)	98 (78-112)
	First peak (<140 mm Hg)	113 (100-130)	102 (85-116)	110 (86-133)	109 (89-127)
	Postexercise pressure (<50 mm Hg)	24 (9-54)	25 (11-58)	28 (7-71)	25 (7-76)
	Percent drop (>50%)	76 (42-90)	72 (38-100)	72 (17-92)	75 (16-91)
	VFT (>20 seconds)	77 (28-200)	72 (29-111)	73 (26-200)	74 (20-200)

DFV, Dorsal foot vein; *GSV,* great saphenous vein; *VFT,* venous refill time.
Values are presented as median (range).
[a] $P < .001$.
[b] $P < .0001$.

Table III. Diastolic valve closure time (*DVCT*) versus venous refill time (*VFT*) dorsal foot vein (*DFV*)

	DVCT, seconds—pneumatic cuff	DVCT, seconds—toe stands (×10)	VFT (AMVP), seconds
Femoral vein (n = 30)	8 (2-33)	4 (2-6)[a]	NA
Popliteal vein (n = 30)	12 (3-52)	3 (1-5)[a]	NA
VFT DFV (n = 55)	NA	NA	78 (20-200)[a,b]

AMVP, Ambulatory venous pressure; *DFV,* dorsal foot vein; *NA,* not applicable.
Values are presented as median (range).
[a] $P < .0001$.
[b] Versus DVCT of femoral and popliteal valves.

DISCUSSION

Key findings. Direct pressure measurements in the saphenous and DFVs were simultaneously recorded yielding a complete pressure profile shown in Fig 2 and Table IV. The pressure profiles were different; critical AMVP parameters—the pressure nadir, percent drop, and VFT—were significantly different between the two systems. Because of these differences, AMVP recorded through the DFV did not reflect the pressure events in the saphenous system. Furthermore, CID, a key component of the pressure profile were different in the three compartments (posterior tibial vein, saphenous vein, and DFV). The femoral and popliteal valves closed after calf ejection and remained closed only for a relatively short period of time (Table III). The femoral valve reopened first, followed by the popliteal valve a few seconds later, reestablishing flow in the upper femoropopliteal segments while the distal tibial veins remained collapsed without flow for a much longer duration (Fig 3).

Polycameral model of calf venous pump. The calf pump mechanism is best viewed as consisting of three key compartments interconnected by a valved system: (1) the deep compartment consisting of the posterior tibial veins fed by the foot pump, (2) the superficial compartment primarily consisting of the GSV and branches draining into the deep system through perforators, and (3) the DFV, part of the superficial venous network on the dorsum of the foot. The last is of little clinical-pathologic significance because the dorsum of the foot is infrequently involved in venous stasis changes.[17] It was included here as it is used as a proxy for the entire limb in the AMVP test.

The anatomic and functional aspects of these compartments are well described in the literature.[8,11,18,19] A major difference among them is arterial inflow. Seventy-five percent to 90% of the blood supply goes to the deep compartment packed with muscle draining out through the deep axial veins; only 10% to 25% goes to the skin drained by the GSV and superficial veins. The DFV drains part of the foot pump and dorsal foot skin with relatively meager arterial inflow; it empties into the GSV. The superficial and deep systems are interconnected by numerous perforators in the leg (75-100), some with valves, others without.[20] The gaiter area drains partly into the superficial system and also into the deep system via the perforators. The pressure in the deep system is slightly (1-2 mm) higher than the superficial system at rest owing to the higher flow.[1,3] This keeps the perforator valves closed in the resting state. There are seven to nine valves in the GSV, approximately 19 valves in the posterior tibial vein and numerous valves in the DFV; foot veins as small as 1 mm in size have valves.[11] Valves are more numerous and more closely spaced in the caudal portions of the leg veins.[21]

The calf pump mechanism. The calf and foot muscles are the prime motivator of flow in the veins of all three compartments.[1,11] The calf pump acts directly on the

Table IV. Simultaneous recording of saphenous and dorsal foot vein (*DFV*) pressures (N = 47)

Parameter	Normal reference values	Saphenous vein	DFV
Supine pressure, mm Hg	<11	10 (4-18)	11 (4-20)
Erect base pressure, mm Hg	<100	98 (83-109)	93 (69-112)
First peak, mm Hg	>40	107 (58-122)	110 (85-130)
AMVP			
Percent drop	>50	54 (35-78)	73 (38-90)[a]
Venous refill time, seconds	>20	36 (5-102)	77 (28-200)[a]

AMVP, Ambulatory venous pressure.
Values are presented as median (range).
[a] $P < .0001$.

Table V. Column interruption duration (*CID*)

Vessel (method)	No.	CID, seconds
Posterior tibial vein (duplex)	28	92 (27-180)
GSV vein (duplex)	28	73 (10-230)
GSV vein (pressure)	28	41 (5-94)
DFV vein (pressure)	28	77 (28-200)

DFV, Dorsal foot vein; *GSV,* great saphenous vein.
Values are presented as median (range) unless otherwise specified.
Duplex CID of GSV versus pressure CID of GSV: $P = .08$.
Duplex CID of posterior tibial versus duplex CID of GSV: $P = .6$.
Duplex CID of posterior tibial versus pressure CID of DFV: $P = .005$.

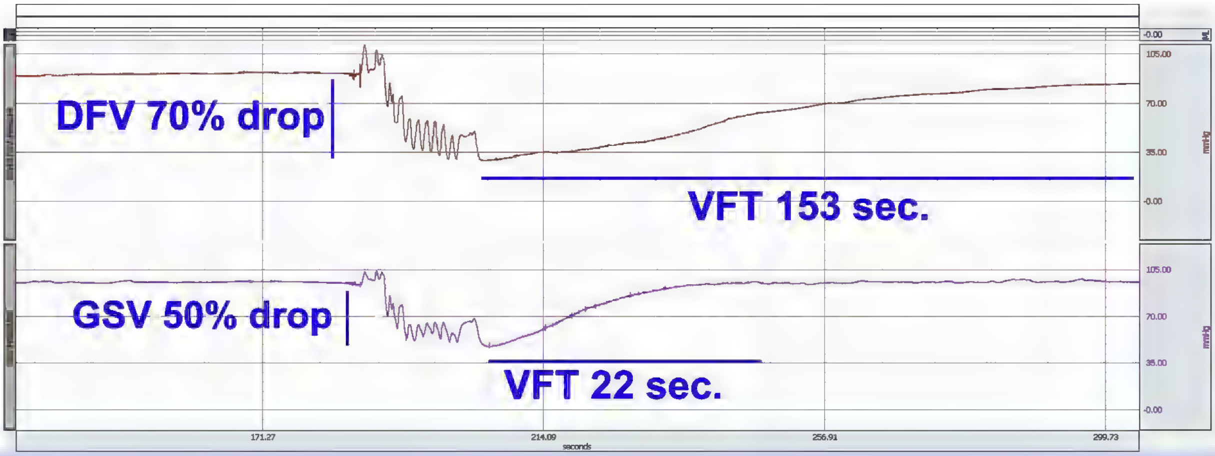

Fig 2. Simultaneously recorded pressure curves in the dorsal foot vein (*DFV*) (top curve) and the great saphenous vein (*GSV*) (bottom curve) in a volunteer. Notice the difference in percent decrease and venous refill time (*VFT*) in the two veins. See text.

deep system, compressing deep veins and tributaries; motive effect is indirect on the superficial system with outflow occurring through connectors with the deep system.[11] The foot venous pump functions as a priming pump for the calf pump.[19,22,23] It ejects mainly through the posterior tibial vein at the ankle; some outflow also occurs through several valveless foot perforators connecting to the DFVs. The saphenous outflow is normally smaller in caliber (roughly one-half the size) than the popliteal vein and therefore offers exponentially more (16×) resistance ($1/\pi r^4$) per the Poiseueille equation. We estimated that most of the deep venous outflow occurs through the popliteal vein and only a small fraction ejects through the GSV. There is no significant

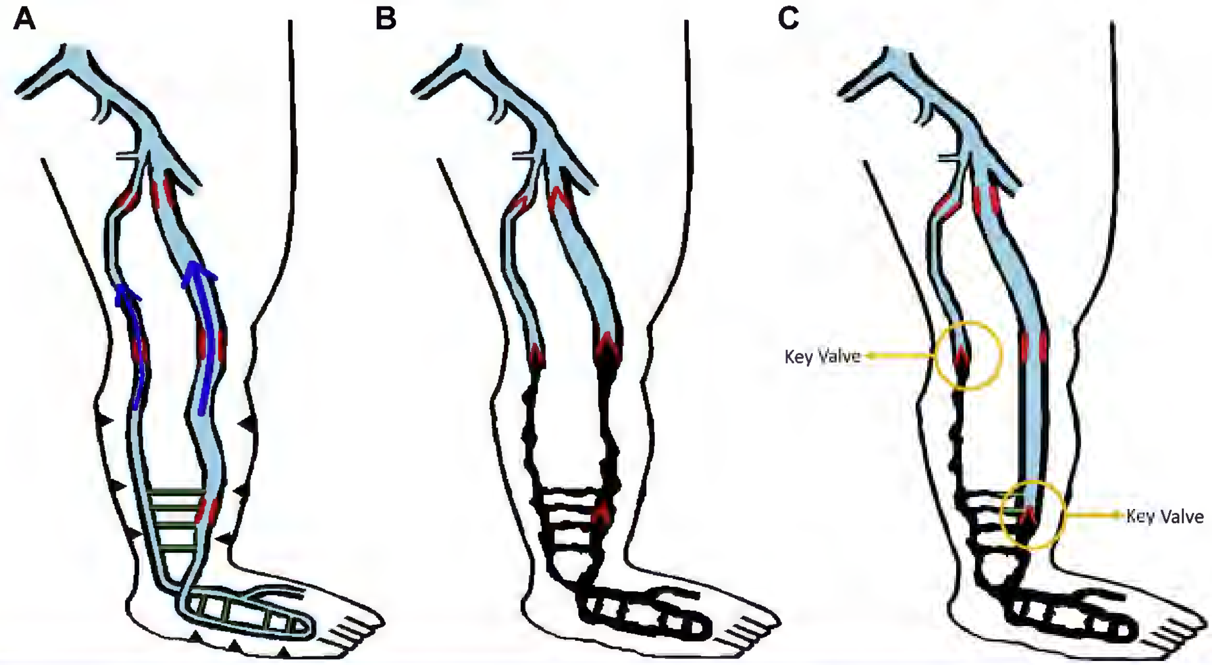

Fig 3. Calf pump dynamics. **A,** Calf ejection produces flow both in the deep and the superficial systems. The resistance to flow is higher in the great saphenous vein (GSV), resulting in lesser flow than in the deep axial veins. **B,** After the ejection is completed, valves in both outflow channels above the knee close temporarily for a few seconds. **C,** The saphenofemoral valve reopens soon after, allowing upward flow in the thigh portion of the great saphenous vein (GSV). The key valve in the GSV at or near the knee level remains closed with collapse of the saphenous segment below. In the deep system, the femoral valve reopens first, followed by popliteal valve a few seconds later, allowing flow in the upper femoral-popliteal axis. The key valve or valves in the lower tibial vein remain closed with collapse of the segments below. The dorsal foot vein (DFV) also remains collapsed.

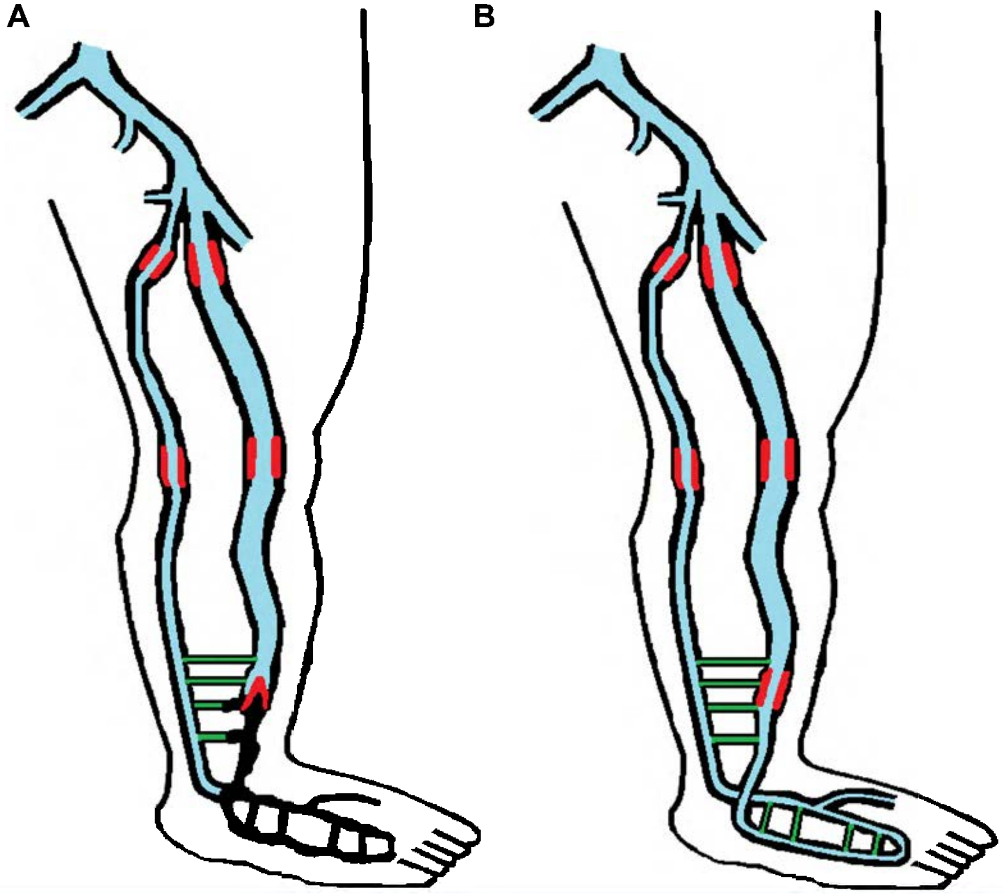

Fig 4. Column restoration occurs first in the great saphenous vein (GSV) followed by the tibial vein **(A)**. The dorsal foot vein (DFV) is the last to recover in the majority of volunteers **(B)**. See text.

ejection through valved calf perforators if the valves are competent.[18] An additional protective mechanism is that the perforators are compressed at the fascial ostium as they exit during muscular contraction.[18]

After calf systole is completed, the femoral and popliteal valves close but reopen a few seconds later owing to drainage from large muscular tributaries in the thigh and calf (Fig 3). Tibial valves in the lower third of the calf remain closed much longer than the popliteal valve. The tibial veins remain collapsed for nearly 2 minutes resulting in column interruption, although there is considerable individual variation. The saphenous segment below the knee also remains collapsed with column interruption for a significant duration (Table V). CID is longer in the tibial veins than in the GSV. Duplex tibial CID was shorter than pressure-derived DFV CID (same limb) in the majority; that is, tibial veins generally reconstitute flow sooner than the DFV (Figs 4 and 5).

Static and dynamic pressures in the erect posture. Orthostatic resting pressure at the foot level is frequently described as representing the pressure exerted by a column of blood extending from the foot to the heart. In fact the column is not static but dynamic with continuous flow even at rest. Dynamic flow mechanics are different from static.[24]

The normal erect venous pressure at rest is approximately 80 mm Hg and consists of three components: (1) A mean filling pressure of approximately 8 mm Hg also known as the dead man's pressure that is surprisingly constant among individuals and even across species; (2) a dynamic pressure of approximately 3 mm Hg generated by the cardiac pump (vis a tergo), which varies somewhat among individual veins depending on regional differences in arterial inflow (eg, superficial and deep veins at rest); and (3) a very large gravity component of approximately 70 mm Hg related to height (which is likely the cause of the sex difference in resting pressure noted in this study).

During calf pump contraction, a substantial new dynamic pressure component is generated. The additional dynamic pressure component is three to five times the basal vis a tergo. An increase of 10 to 25 mm Hg in the popliteal and GSVs occur during calf ejection for this reason.[2,8,11] The pressure increase will be different in the two veins because of different resistances and ejection volumes.

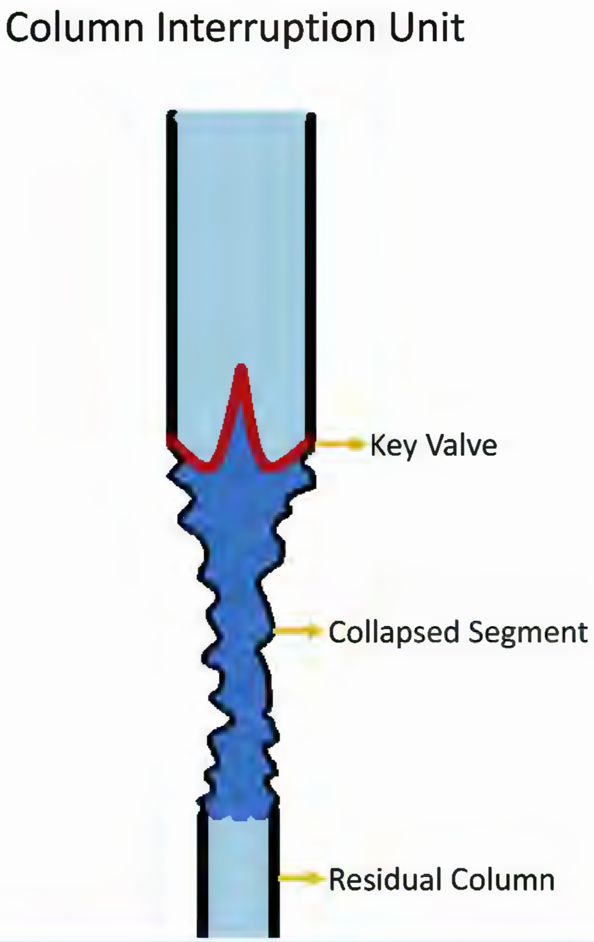

Fig 5. Column interruption unit. The key valve closing after calf ejection divides the flow. Pressure reduction through column interruption is the result of vein segment collapse below the closed valve. There is a residual column that is higher in the great saphenous vein (GSV) compared with the tibial vein. This pressure gradient may allow drainage flow from the superficial to the deep system during calf diastole. The mechanics of uncollapse and flow restoration is a complex process with many counterintuitive features. See text.

Hydraulics of column interruption. The calf muscle is rich in vascular components. The calf pump activity is often described in plethysmographic terms such as ejection fraction, residual fraction, and so on. However, column interruption occurs exclusively within the two axial veins of the superficial and deep systems. Sideline vascular volume in the rich calf network has little direct influence on it.[25,26]

The column interruption unit consists of a key valve and the collapsed venous segment immediately below (Fig 5). Closure of the valve divides the column into two. It is the collapsed vein segment below that results in pressure reduction.[7,27] A collapsed vein segment will not transmit column pressure, effectively interrupting it.[7,28,29] The fluid mechanics of segment collapse and its restoration are complex involving many counterintuitive flow charecteristics.[7,25,27,29-32]

The column pressure decrease is greatest when column interruption is closer to the ankle level, which eliminates most of the column pressure. The key valve(s) in the tibial veins are in the lower third of the leg (gaiter area). The key valve in the GSV is higher, at about the knee level.[11]

There is a dramatic decrease in the gravity component during calf diastole owing to column interruption. The pressure nadir represents a total of the mean filling pressure (approximately 8 mm Hg) + vis a tergo (approximately 3 mm Hg) + the residual column height (gravity component) below the column interruption. The median pressure nadir in the GSV in the current study was 46 mm Hg placing the level of column interruption at about the knee level in line with other reports.[6,11] The gravity component in the GSV is nearly cut in half owing to column interruption. Direct pressures in the tibial vein near the ankle in healthy volunteers have not been documented. Current duplex findings suggested that column interruption in the tibial vein occurs in the lower third of the leg. Column restoration occurs from inflow interacting with capacitance, compliance, and residual volume in the collapsed segment.[27,33] The latter factors are different in the superficial and deep systems. CID therefore differ between the two systems. CID in the DFV is substantially different from the CID in the GSV and the tibial veins as well.

The foregoing explains why the pressure profiles in the three compartments differ during various phases of calf pump action.

CVD pathology. CVD pathology can involve one or more components of the polycameral system. This includes valve reflux, caliber and compliance changes, focal stenosis, dilatation, and reflux of perforators. Arterial inflow may be affected as well.[34] These features degrade the polycameral model into more like a unicameral model. Hemodynamically, these abnormalities are likely to be reflected in reduced CID in the GSV and tibial veins. If the perforators are large, the CID in the two systems will tend to become the same.

VCT versus CID. Clinical and research interest in venous pathology has largely focused on proximal valves. VCT, or reflux time, is now a standard measure of reflux severity. Reflux of the saphenofemoral valve is the focal point in assessing saphenous reflux. In the deep veins, reflux severity grading also involves proximal valves (femoral and popliteal) with tibial valves included only if they are involved in continuity with proximal valves (axial reflux). This study suggest that these proximal valves in the GSV and deep veins do not contribute to column interruption, the desired result of calf pump action. They may provide perimeter defense against coughing and Valsalva pressure effects.

In the GSV, reflux below the knee is likely more important than saphenofemoral valve reflux duration. With increasing reflux duration, the CID decreases; when reflux duration is longer than CID, pressure gradients favoring private circulation described by Bjordal[35] exist. CID rather than VCT is probably a better measure of grading reflux severity in the superficial and deep systems.

The key distal tibial valves allegorically play the role of the Praetorian guards—the last defense of the vulnerable gaiter area against venous hypertension. Several authors have emphasized the functional importance of these valves based on clinical and teleological grounds.[8,21,36] The CID of tibial veins in this study was surprisingly long, exceeding 2 minutes in several limbs, although there was considerable variation. Duplex-derived CID elicited with pneumatic cuff ejection in the GSV tended to be longer (ns) than pressure-derived CID with tip-toe exercise in the same limb. Calf ejection with pneumatic cuff (used for duplex CID) is known to be more effective than toe stands (used for pressure-derived CID), partly explaining the difference.[11] A more likely explanation for the disparity is the difference in the sensitivities of current instrumentation that measure pressure (transducers) versus flow (duplex). Sensitivity spectrum of color/B-flow have steadily improved but probably still lag behind modern transducers near the lower limits of specifications. However, duplex CID measurement seemed to be reproducible with a low coefficient of variation. It may be a useful tool when interpreted within its own frame of scale.

The clinical use of AMVP measurement has steadily decreased. A noninvasive substitute is likely to find greater use. The duplex CID methodology described here has such potential, but awaits validation in the clinical setting.

CONCLUSIONS

AMVP measured through the DFV does not reflect pressure changes that occur in the GSV in normal individuals questioning its status as the gold standard in calf pump dynamics. Critical parameters of ambulatory pressure measurement are best explained on the basis of column interruption that occurs with calf pump action. A duplex method of measuring CID is described.

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AUTHOR CONTRIBUTIONS

Conception and design: SR
Analysis and interpretation: SR, WW
Data collection: SR, WW, CM
Writing the article: SR, WW
Critical revision of the article: SR, WW, CM
Final approval of the article: SR, WW, CM
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