Plethysmographic features of calf pump failure in chronic venous obstruction and reflux

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ABSTRACT

Background: Calf pump failure (CPF) is a common concept in chronic venous disease. Dorsal vein pressures were originally used to define the pathophysiology. More recently, an abnormal ejection fraction (EF) and residual volume fraction (RVF) with air plethysmography (APG) have been substituted for its diagnosis. The relationship between reflux and calf pump function has been studied extensively. Reflux is thought to be the main cause of CPF, although other mechanisms may play a secondary role. Data mining in our dataset revealed that CPF is frequently found in nonrefluxive limbs—an unexpected finding. We analyzed the APG features of CPF in nonrefluxive limbs of a large cohort of patients investigated for chronic venous disease in our clinic. Data from refluxive limbs (control) seen over the same period was included for comparison. Venous obstructive pathology was variably present in both subsets. Iliac vein stent outcome in CPF limbs from both subsets is included. The role of obstruction in CPF is currently unknown.

Methods: Records of 13,234 limbs in 8813 patients evaluated for suspected chronic venous disease over a 22-year period were analyzed. Prestent and poststent data in 406 CPF limbs (129 nonrefluxive; 277 refluxive) that underwent iliac vein stenting to correct associated stenosis are included. This is a single-center retrospective analysis of prospectively collected data. Duplex and APG data were available for included limbs. A RVF of more than 50% was defined as CPF. A reflux time of greater than 1 second elicited with automated cuffs in the erect position was defined as reflux.

Results: There were 7780 (59%) limbs with reflux and 5454 (41%) that were nonrefluxive. Supine venous pressure, an index of venous obstruction, was elevated in both subsets. The incidence of CPF was 25% in refluxive limbs and 16% in nonrefluxive limbs totaling 2790 limbs. Venous volume and venous filling index were significantly elevated ($P = .0001$) in refluxive limbs compared to nonrefluxive limbs. The EF was diminished ($<$50%) in all CPF limbs except in a small fraction (n = 427 [3%]). Stent correction of iliac vein stenosis corrected CPF, normalizing the RVF in both subsets.

Conclusions: CPF frequently occurs in nonrefluxive limbs with incidence only slightly less than in refluxive limbs. An RVF of more than 50% seems to be a practical definition of a CPF; an EF of less than 50% is associated with a RVF of greater than 50% in 97% of analyzed limbs. Prospective identification of CPF in limbs with chronic venous disease may allow more detailed investigation of its cause (preload, afterload, neuromuscular pathology or joint immobility, etc) and direct more targeted treatment than currently practiced. (J Vasc Surg Venous Lymphat Disord 2022;■:1-8.)

Keywords: Air-plethysmography; Calf pump failure; Venous reflux; Venous obstruction

The calf is an auxiliary pump in the venous circuit. It increases venous flow during periods of high demand. It also serves to decrease venous pressure during orthostasis. There was early realization that subnormal calf pump action results in ambulatory venous hypertension associated with venous stasis symptoms. Calf pump failure (CPF) is used generically in this context. More specific characterization is possible with calf pump mechanics measured by air plethysmography (APG); an ejection fraction (EF) of less than 50% and or a residual volume fraction (RVF) of more than 50 are commonly used as defining thresholds for CPF. Reflux pathology is considered the central element of CPF with many other mechanisms playing an ancillary role.[1] There is a large body of literature relating various reflux parameters to calf pump function in general and CPF in particular.[2-7]

The pressure parameter, however, is the central element in venous pathology. Even though volumetric emptying of the calf veins is at the core, a variety of other factors such as capacitance, compliance, and arterial inflow have an influence on the venous pressure at the calf pump. The pressure-volume relationship in the calf is nonlinear and variable. Precise extrapolation of calf pump pressure from APG in individual limbs is, therefore, not possible.[4,8] Recognition of venous obstructive pathology and its wide prevalence in patients with chronic venous disease is of recent vintage.[9-11] The effect of venous obstruction on ambulatory venous pressure has been studied only in a limited fashion.[4,11] Central venous obstruction seems to be associated with elevation of supine venous pressure ($>$11 mm Hg). Increased resting

From The RANE Center for Venous & Lymphatic Diseases.

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pressure in the erect posture and ambulatory venous hypertension are features of reflux, not obstruction. The relationship between chronic venous obstruction and CPF is unknown.

In a recent retrospective analysis of iliac vein stent outcome, an unexpectedly high incidence of CPF in nonrefluxive limbs was found on data mining.[12] The aim of this article is to provide an analysis of the APG parameters in this nonrefluxive subset and compare it with a case control cohort of CPF in refluxive limbs. The study also includes an analysis of the effect of iliac vein stenting on CPF in limbs (with and without reflux) performed to correct coincident symptomatic intravascular ultrasound examination-proven venous obstruction. This is a single-center retrospective analysis of prospectively collected electronic medical record data.

ARTICLE HIGHLIGHTS

- **Type of Research:** Single-center retrospective analysis of prospectively collected data in a large cohort with chronic venous disease.
- **Key Findings:** Elevated residual volume fraction with calf pump failure (CPF) occurred frequently in nonrefluxive limbs though the incidence was somewhat less than in refluxive limbs (16% vs 25%) among 13,234 limbs investigated for chronic venous insufficiency; CPF was relieved in all 518 limbs after iliac vein stenting.
- **Take Home Message:** CPF occurs in approximately 20% of chronic venous disease limbs with or without reflux and should be investigated for other factors such as obstruction, neuromuscular disorders, and restriction of joint motion.

METHODS

Patients

A total of 13,234 limbs in 8813 patients with suspected chronic venous disease seen in our tertiary referral center from 1999 to 2021 were analyzed. Only limbs with duplex and APG data were included. There were 7780 (59%) limbs with duplex reflux and 5454 (41%) limbs without reflux. CPF was defined as having an RVF of greater than 50%. There were 1932 limbs (25%) in the refluxive group and 858 limbs (16%) in the nonrefluxive group had CPF.

Tests

APG. A commercially available instrument (ACI Medical, San Marcos, CA) with modified protocol described by Christopoulos et al was used.[4,13] The following APG parameters were obtained: venous volume (VV), EF, RVF, recovery time (RT) and venous filling index (VFI_{90}). The EF is obtained after a single tip-toe stand and RVF after 10 tip-toe stands per protocol. The definition of CPF in the present article is an RVF of more than 50%. An EF of greater than 50% is excluded from this definition but is separately designated as calf pump dysfunction (CPD).

Duplex ultrasound examination. Reflux prevalence was measured using a color duplex ultrasound machine (LOGIQ S8: GE Healthcare, Wauwatosa, WI) per standard protocol. Patients were evaluated in the erect position with quick inflation-deflation cuffs to evoke reflux within the lower extremities. Reflux was monitored directly over the valve station, not elsewhere in the segment below. Reflux was defined as reverse flow for more than 1 second in duration. The 1-second threshold has been in use in our laboratory since 1995 and was retained for data consistency. Recent Society for Vascular Surgery/American Venous Forum guidelines have adopted the less stringent 0.5-second reflux duration threshold for superficial reflux.

Supine venous pressure. Supine venous pressure recorded through arm or leg vein was available in a large number of limbs in both subsets.

Iliac vein stenting. Patient selection, technique, perioperative test and treatment protocols, and outcome have been described in detail elsewhere.[14,15] Long-term follow-up included clinical examination and tests (duplex ultrasound examination, APG) for venous assessment and stent surveillance. These were performed after stenting at 6 weeks, 3 months, 6 months, and yearly thereafter.

Data analysis. Data were contemporaneously entered into an electronic medical record program (MedInformatix, Los Angeles, CA) and analyzed retrospectively. Prestent data were compared with poststent studies obtained at the last available follow-up.

Statistical analyses

All statistical analyses were performed using commercial software Prism, version 9 (GraphPad, San Diego, CA). Chi Square, Paired and unpaired two tailed t test as applicable were used. A *P* value of less than .05 was considered significant.

Permissions

Informed consent from patients for all tests and procedures was obtained. Deidentified data were extracted from a registry with institutional review board approved protocol.

RESULTS

The demographics of the entire refluxive and nonrefluxive groups and the CPF subsets in each are shown in Table I. There were no clinically meaningful differences between the test and control groups though some were statistically significant. The median body mass index (BMI) was elevated in the entire patient set analyzed. Venous clinical severity score and CEAP clinical scores were largely similar. Post-thrombotic pathology was dominant over nonthrombotic limbs with a 2:1 ratio in both the refluxive and nonrefluxive subsets. A prior history of deep vein thrombosis (DVT) was elicited only in

Table I. Demographics of refluxive and nonrefluxive subsets (n = 13,234 limbs)

Parameters	Nonrefluxive limbs (n = 5454 [41%])	Nonrefluxive CPF limbs (n = 858 [16%])	Refluxive limbs (n = 7780 [59%])	Refluxive CPF limbs (n = 1932 [25%])
Age, years	57 (11-100)	56 (14-100)	58 (12-100)	60 (15-100)
Gender male:female ratio	1073:2666 (1:3)	153:587 (1:3)	1807:3267 (2:3)	541:1061 (1:2)
Laterality left:right:bilaterals ratio	2693:1046:1715 (3:1:2)	337:285:118 (3:3:1)	4009:1065:2706 (4:1:3)	706:578:324 (7:6:3)
Previous DVT	528/3739 (14%)	101/740 (14%)	1104/5074 (22%)	398/1603 (25%)[a]
Previous DVT episodes	1 (1-5)	1 (1-3)	1 (1-6)	1 (1-5)
MTS:PTS	317:581 (1:2)[a]	56:108 (1:2)	651:1018 (3:5)	156:262 (1:2)
BMI	32 (16-68)	29 (16-63)	30 (18-65)	30 (18-64)
VCSS	5 (0-20) n = 2709	5 (0-20) n = 443	6 (0-24) n = 3030	6 (0-22) n = 803
CEAP Clinical Class (no. of limbs)[b]	n = 3002	n = 759	n = 3560	n = 554
C0-2	622 (17)	99 (18)	775 (26)	204 (27)
C3	1252 (35)	219 (40)[c]	867 (29)	241 (32)
C4	1395 (39)	195 (35)[c]	999 (33)	222 (29)
C5	82 (3)	12 (2)	140 (5)	37 (5)
C6	209 (6)	29 (5)	221 (7)	55 (7)

BMI, body mass index; *CPF*, calf pump failure; *DVT*, deep vein thrombosis; *MTS*, May Thurner Syndrome; *PTS*, post-thrombotic syndrome; *VCSS*, venous clinical severity score.
Values are median (range) or number (%).
[a] $P < .005$; Incidence of DVT in patients with CPF is significantly higher than DVT in patients without CPF.
[b] Limbs with available data.
[c] $P = .05$. The incidence of PTS in patients without CPF is significantly higher than PTS in patients with CPF.

a small fraction (14%) of nonrefluxive limbs. A history of DVT was obtained more often (22%-25%) in refluxive limbs. Reflux was superficial in 45%, deep in 21% and combined in 34% of the limbs. The median follow-up in stented limbs was 4 years (range, 0-21 years).

The APG parameters for the refluxive and nonrefluxive groups as a whole and their respective CPF subsets are shown in Table II. Supine venous pressure in available limbs is included. The calf pump venous capacitance (VV) is approximately 78 mL in nonrefluxive limbs, but

Table II. Air plethysmography (*APG*) parameters in calf pump failure (CPF) in limbs with and without reflux

APG parameter (normal threshold)[a]	Nonrefluxive limbs n = 5454 (41%)		Nonrefluxive limbs with CPF (n = 858 [16%])		Refluxive limbs (n = 7780 [59%])		Refluxive limbs with CPF (n = 1932 [25%])	
VV (85 ± 36)	78 ± 36		79 ± 40		100 ± 49[b]		116 ± 57[b]	
EF >50%	58 ± 23[c]		35 ± 19[d]		54 ± 22[c]		35 ± 16[d]	
RVF <50%	30 ± 21[c]		65 ± 16[d]		36 ± 24[c]		67 ± 20[d]	
VFI 90, mL/s <2.3	1.2 ± 1.5[c]		1.4 ± 3.2[c]		2.5 ± 2.2[d]		3.1 ± 2.8[d,e]	
RT	13 ± 8		13 ± 8		11 ± 6		10 ± 6[f]	
Supine pressure, mm Hg (% ≥11: % < 11)	15 ± 31 $P = .3856$	72%[c]:28%[d]	14 ± 9	70%[c]:30%[d]	14 ± 8[b] $P < .0001$	68%[c]:32%[d]	13 ± 7	63%[c]:37%[d]

EF, Ejection fraction; *RT*, recovery time; *RVF*, residual volume fraction; *VFI*, venous filling index; *VV*, venous volume.
Values are mean ± standard deviation.
[a] Commonly accepted normal threshold; value for some parameters not established.
[b] $P < .0001$; the VV in the refluxive group is significantly greater than in the nonrefluxive group; the VV in refluxive CPF limbs is significantly greater than the parent refluxive group and also greater than CPF nonrefluxive limbs.
[c] Values within normal limits.
[d] Abnormal values.
[e] VFI_{90} significantly greater in refluxive CPF limbs vs limbs in parent refluxive group.
[f] RT in refluxive CPF limbs significantly shortened than limbs in parent refluxive group and also limbs in nonrefluxive CPF limbs.

Table III. APG Parameters in calf pump dysfunction (*CPD*) in limbs with and without reflux (n = 13,234)

APG parameter (normal threshold)[a]	Nonrefluxive limbs (n = 5454)			Refluxive limbs (n = 7780)		
	Limbs with CPF (n = 858 [16%])	Limbs with CPF and CPD (n = 700 [13%])	Limbs with CPF but without CPD (n = 158 [3%])	Limbs with CPF (n = 1932 [25%])	Limbs with CPF and CPD (n = 1663 [21%])	Limbs with CPF but without CPD (n = 269 [3%])
VV (85 ± 36)	79 ± 40	82 ± 39	68 ± 46	116 ± 57	116 ± 56	116 ± 63
EF >50%	35 ± 19[b]	29 ± 11[b]	70 ± 18[c]	35 ± 16[b]	31 ± 11[b]	63 ± 15[c]
RVF <50%	65 ± 16[b]	64 ± 14[b]	70 ± 21[b]	67 ± 20[b]	67 ± 19[b]	68 ± 27[b]
VFI 90 mL/s <2.3	1.4 ± 3.2[c]	1.4 ± 3.6[c]	1.2 ± 1.0[c]	3.1 ± 2.8[b]	3.1 ± 2.7[b]	3.2 ± 3.0[b]
RT	13 ± 8	13 ± 8	12 ± 7	10 ± 6	10 ± 6	11 ± 6

APG, Air plethysmography; *CPF*, calf pump failure; *EF*, ejection fraction; *RT*, recovery time; *RVF*, residual volume fraction; *VFI*, venous filling index; *VV*, venous volume.
Values are mean ± standard deviation.
[a]Commonly accepted normal threshold; value for some parameters not established.
[b]Abnormal values.
[c]Values within normal limits.

was significantly increased to approximately 100 mL in refluxive limbs. The VFI_{90} was significantly increased and the RT shortened in the refluxive limbs. The EF and RVF are within normal limits in the two large groups as a whole. Supine venous pressure was elevated (normal, ≤11 mm Hg) in the majority of limbs in both refluxive and nonrefluxive subsets and in the respective daughter CPF populations. VV was significantly contracted to less than 60 mL in 26% of the entire group of limbs.

The RVF and EF were in the abnormal range in CPF subsets of both refluxive and nonrefluxive limbs. VV was significantly elevated even more in the CPF subset of refluxive limbs over the parent group; the VFI_{90} was significantly further increased and the RT was prolonged even more as well in this subset. The mean reflux segment score was 2 and axial reflux was present in only 6% of these CPF limbs of the refluxive group, meaning that reflux overload was modest and was unlikely the only factor in pump failure. The mean supine venous pressure was not significantly different between parent and daughter subsets of either the refluxive or nonrefluxive CPF limbs.

Table III shows CPF and CPD detail in the dataset. CPF incidence is higher in the refluxive group than in the nonrefluxive group (25% vs 16%) CPD (EF <50%) was coincident with CPF (RVF of >50%) in both refluxive and nonrefluxive subsets in all but 3% of limbs in each CPF subset. Key APG parameters are similar in CPF with or without CPD in both refluxive and nonrefluxive groups (not significant).

A plot of ejection volume (EV) versus capacitance (VV) for the refluxive and nonrefluxive limbs and for the CPF limbs as a whole from both groups is shown in Fig 1, *A-C*. The EV seems to be influenced not only by venous capacitance (VV), but also by the contractile efficiency of the venous calf pump. The VV and EV were increased in refluxive limbs with or without CPF. Contractile efficiency was however less in refluxive limbs than in nonrefluxive limbs. This parameter seemed to deteriorate further in refluxive limbs with CPF.

Table IV shows in the APG parameters before and after stent placement in CPF subsets who underwent the procedure to treat coincident iliac vein obstruction. The RVF was normalized and the VV significantly improved (decreased) in both refluxive and nonrefluxive CPF subsets after stent placement; the EF trended higher but did not normalize in either CPF subset, meaning that stent correction of obstruction did not result in complete normalization of the EF.

DISCUSSION

Reflux has been considered the main cause of CPD. However, CPF was also found in 16% of nonrefluxive limbs, though the incidence was less than in refluxive limbs (25%). The venous capacitance (VV) is noted to enlarge significantly in the refluxive subset. This is a known passive compensatory mechanism to offset reflux.[4,16] The VV is further increased in refluxive CPF limbs and is significantly greater than that in the parent subset. CPF limbs have greater reflux than in their parent refluxive group as evidenced by significantly increased VFI_{90}. However, the VFI_{90} level indicates only modest reflux overall in either group.

Supine venous pressure was increased to abnormal levels (>11 mm Hg) in the majority of refluxive and nonrefluxive limbs, suggestive of central obstruction. This finding is in line with the obstruction prevalence in patients with chronic venous disease seen in our clinic.[11] Supine venous pressure was elevated in both CPF subsets and was not worse than in the respective parent groupie. Limbs in the refluxive group appeared to have combined obstruction and reflux.

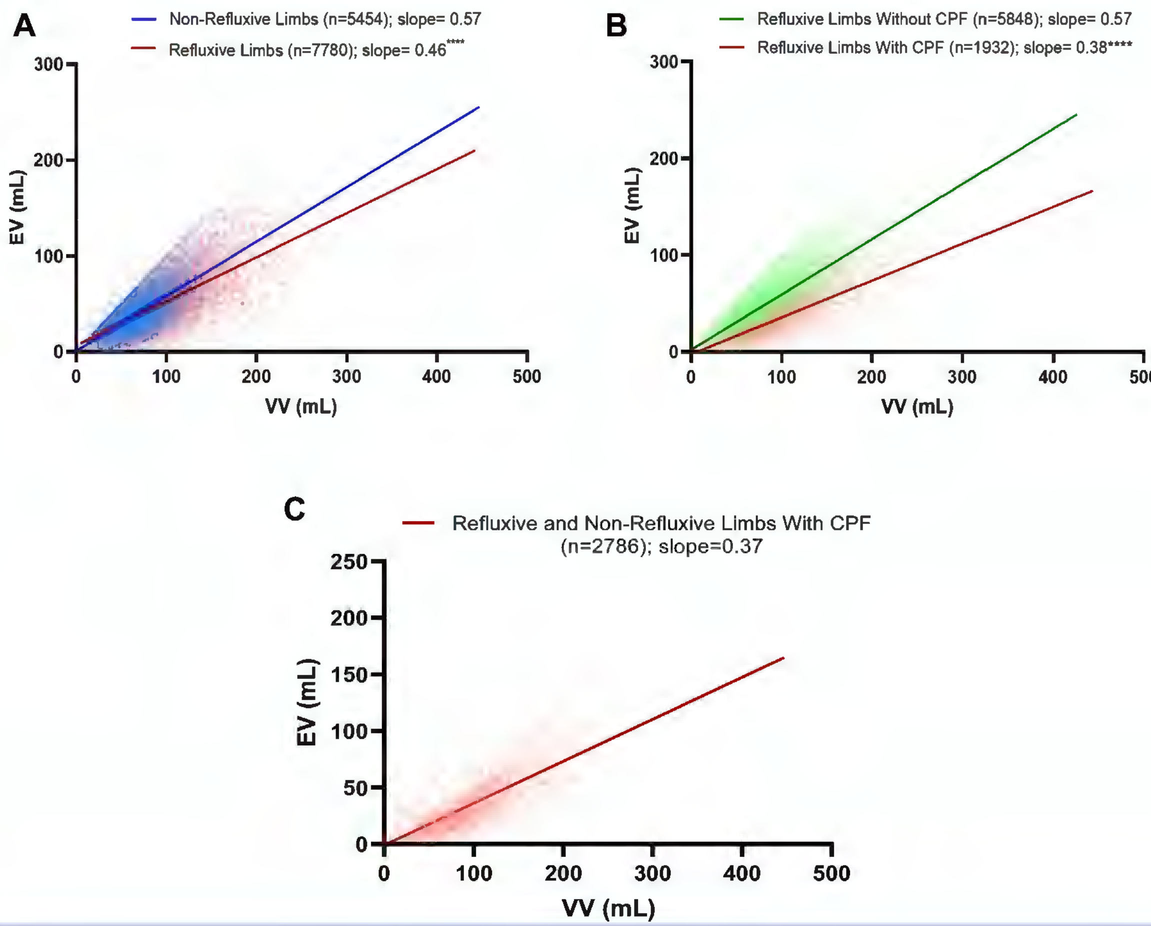

Fig 1. (A). Relationship between venous volume (*VV*) and ejected volume (*EV*) in refluxive and nonrefluxive limbs. EV increases with increasing VV. The VV and the EV in refluxive volumes (red dots) is greater than in nonrefluxive limbs. The slope of the plot reflecting calf-pump efficiency is 0.57. The slope in refluxive limbs is significantly less despite greater range of VV and EV. ****$P < .0001$. See text. **(B)** EV/VV relationship in refluxive limbs with and without calf-pump failure (*CPF*). The slope is significantly less in limbs with CPF. ****$P < .0001$. **(C)** EV/VV relationship in limbs with CPF (refluxive and nonrefluxive limbs combined). The slope is 0.37, which is significantly less ($P < .0001$) than the slope of the combined parent groups without CPF (graph not shown). This finding suggests that the functional efficiency of the calf pump is even less than in the two respective parent groups.

Table IV. Calf pump failure (*CPF*) in stented limbs

	Stented Nonrefluxive Limbs with CPF n = 129			Stented Refluxive Limbs with CPF n = 277		
APG parameter (normal threshold)[a]	Prestent	Poststent	*P* value	Prestent	Poststent	*P* value
VV (85 ± 36)[a]	81 ± 37	74 ± 35	.0186	114 ± 53	101 ± 52	<.0001
EF >50%	32 ± 15[b]	44 ± 24[b]	<.0001	36 ± 17[b]	43 ± 23[b]	<.0001
RVF <50%	66 ± 16[b]	40 ± 22[c]	<.0001	66 ± 16[b]	45 ± 23[c]	<.0001
VFI_{90} mL/sec <2.3	1.4 ± 1.1[c]	1.5 ± 2.0[c]	ns	3.3 ± 2.7[b]	3.4 ± 3.8[b]	ns
RT	13 ± 7	11 ± 6	ns	9 ± 7	10 ± 7	<.03
Supine pressure, mm Hg (% ≥11: % <11)	16 ± 7 73%:27%	12 ± 6 62%:38%	.0230	14 ± 7 67%:33%	12 ± 7 62%:38%	.0259

APG, Air plethysmography; *EF*, ejection fraction; *RT*, recovery time; *RVF*, residual volume fraction; *VFI*, venous filling index; *VV*, venous volume.
Values are mean ± standard deviation unless otherwise noted.
[a]Commonly accepted normal threshold; value for some parameters not established.
[b]Abnormal values.
[c]Values within normal limits.

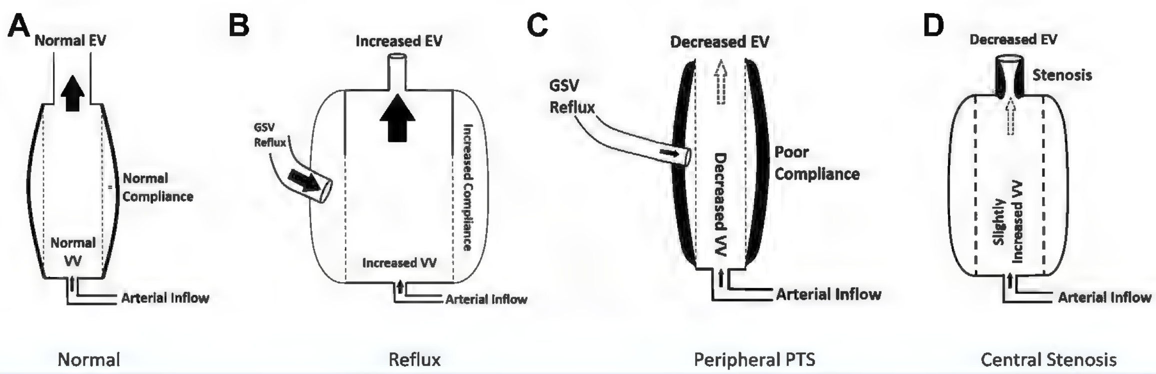

Fig 2. (A) The normal calf pump mechanism consists of a resting volume within (capacitance) within the calf veins. The ejection occurs by a pressure increase in the pump contents by direct compression of the surrounding musculature and some indirect mechanisms that increase the pressure as well. There's a relationship between the resting capacitance and the ejected volume. An ejection fraction (EF) of more than 50% is normal. An increased capacitance usually results in an increased EV, tending to keep the EF constant. Inflow from the arterial side is approximately 2.3 mL/s, the same as the venous filling index (VFI_{90}). After ejection, refill of the capacitance occurs over approximately 17 seconds. **(B)** When there is reflux, the capacitance increases as a passive compensatory mechanism. This tends to dilute the reflux fraction as a percentage of the resting volume. The powerful calf muscles can increase ejection up to three times or more, like the heart. The increased capacitance also results in an increased EV (active compensation). The EF can increase in some patients if the muscular contractile efficiency improves as well. If the reflux is massive, the contractile efficiency may decrease as in heart failure. **(C)** The major pathology in post-thrombotic syndrome is the organization of the clot. The volume of fibrous tissue may result in a physical decrease in pump capacitance. In addition, the contractile efficiency of the muscle pump may deteriorate resulting in decreased volume-pressure relationship (compliance). **(D)** The central stenosis may increase pump capacitance, especially when there are no peripheral post-thrombotic changes (eg, May-Turner syndrome). Capacitance may also increase if inflow from the arterial side increases from an arteriovenous fistula. When the central stenosis is relieved by venous stenting there is decompression of the pump with contraction of the resting volume. *EV*, ejected volume; *GSV*, great saphenous vein; *VV*, venous volume.

RVF, the key APG metric in CPF limbs, normalized after iliac vein stenting performed to correct coincident iliac vein stenosis. The EF improved but did not normalize, suggesting residual calf pump abnormality even after elimination of the central venous obstruction.

A small subset of limbs (3%) had CPD without CPF in this analysis; 97% had both.

Calf pump mechanics. The EF is normally in the range of 50% to 70%, which also increases in response to increased calf capacitance. Like the heart, the powerful calf muscles seem to increase their EV in response to the increased VV to keep the residual volume within normal limits. This active mechanism works in concert with the passive increase in VV that dilutes the reflux fraction.[4,16] The various changes that occur in calf pump mechanics in response to reflux, post-thrombotic changes and central obstruction are illustrated in Fig 2, *A-D*.

The calf pump empties mostly by direct compression of muscular tributaries.[17] Some emptying may also occur by stretching of the muscular and tributary veins that decrease caliber.[18] The powerful calf muscles are capable of generating three to four times the intravenous pressures even in the erect posture.[17] A modest increase in compartment pressures bound by the fascia may play a secondary role in venous outflow.[19] The calf pump works in series with a foot pump below and possibly a thigh pump above to propel venous flow from the lower limb.[20] The complex calf pump mechanism has long been known to be influenced by multiple factors in individual limbs.

In an analysis of 373 limbs with ambulatory venous hypertension, multiple factors that included reflux, arterial inflow, pump capacitance, EF and compliance were found to be contributing components.[1] Because these variables were interrelated, a combination of factors prevailed.

Calf pump capacitance is decreased by as much as approximately 70% in experimental settings when compliance is decreased; not only the stretching, but also the bending mode of the bimodal compliance regimen is affected in the capacitance decrease.[21] An attendant pressure increase can be predicted. In the clinical setting, post-thrombotic disease is the likely the major cause of compliance reduction. The calf pump is known to be frequently involved to a variable extent in cases of DVT.[22] The calf capacitance decrease may also occur with recurrent attacks of DVT that result in thrombosis and attrition of veins in the calf pump network.[21] The VV was significantly decreased (<60 mL) in 26% of limbs in this analysis suggestive of post-thrombotic pathology. A prior history of DVT is notoriously unreliable in this regard as many DVT episodes are silent and a history of clot might have been arterial or cardiac in origin. BMI was increased in all of the patient cohorts, including those with CPF. Counterintuitively, calf pump function seems to be better in obese patients than those with a normal BMI; the EF and RVF were both better in the obese group.[23]

Definition of CPF and its causes. The term "calf pump failure" is poorly defined in the literature.[4] Neuromuscular disorders or ankylosis of the ankle joint that restrict calf muscle contraction mechanically are clearly pathological. The term has been more commonly used to denote functional insufficiency related to pathology involving calf veins. Both a reduction in EF and RVF have been variably used in this context. EF is measured with a single tip-toe calf pump action. RVF is measured with multiple calf contractions, typically 10 tip-toe exercises. RVF is probably more reflective of ambulatory hypertension which also uses 10 tip-toe stands. RVF is probably more reflective of real-life calf activity than the single ejection represented in the EF. An increase in RVF over critical threshold (50%) is used as the defining standard of CPF in this article. A decrease in the EF to less than 50%, termed CPD in this article, does occur, but is associated with an RVF of greater than 50% (CPF) in all but a small fraction of limbs. For these reasons, we suggest that the RVF threshold be adopted as the sole definition of CPF.

Role of reflux and obstruction in calf pump function. The pathology of chronic venous disease in general and that of the calf pump in particular had largely focused on reflux in the last century. Recognition of obstructive pathology is much more recent after venography became prevalent in clinical use in the 1950s.[24] It is widely assumed that obstruction causes ambulatory venous hypertension. This may not be the case. In an analysis of 8868 limbs in 5792 patients referred to our clinic with chronic venous disease, ambulatory venous hypertension was associated with reflux, not obstruction. In contrast, supine venous pressure was associated with intravascular ultrasound examination proven obstruction and did not worsen with an increasing severity of reflux.[11]

RVF may be more affected by reflux than obstruction.[25] A moderate amount of reflux after a single calf ejection can be cleared by subsequent calf contractions. If there is a to and fro type of reflux, where most of the ejected volume refluxes back into the calf after each ejection, the RVF will progressively build up into CPF. The EF is usually in the 50% to 70% range with the remainder remaining behind as residual volume. Complete content clearance (100% pump efficiency) is not possible in the calf or in the heart.

Clinical significance of CPF. The clinical significance of CPF is not clear from this analysis. The clinical profile of CPF limbs (CEAP, venous clinical severity score) was not different from the parent groups. Although obstruction or reflux was present, in respective CPF limbs their severity was not grossly worse than in their parent group.

Prospective identification of CPF would allow detailed assessment of the calf pump much like that in cardiac pump (preload, afterload, muscle failure or restriction) with clinical correlation. Examples of calf pump analogues are shown in Fig 1, *A-C*. The VV/EV ejection curve in Fig 1, *A-C*, shows that the EV varies with the VV. In addition, the slope of the curve is variable, suggesting different contractility in the three subsets. CPF owing to neurological, neuromuscular, or joint restriction have been described.[26-28] These factors were not studied in limbs reported in this retrospective analysis. The EF and RVF may be improved by targeted calf exercise.[29]

CONCLUSIONS

CPF does occur in limbs without reflux though less frequently than in limbs with reflux (16% and 25%, respectively). Venous capacitance (VV) increases in CPF limbs with reflux—a passive compensatory mechanism to reduce the reflux fraction of VV). CPF is associated with reduced EF (EF of <50%) in all but 3% of analyzed limbs. Stent correction of associated iliac vein stenosis seemed to correct CPF. A more detailed study of calf pump mechanics may allow for targeted conservative measures to correct identified deficits before resorting to stent placement.

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AUTHOR CONTRIBUTIONS

Conception and design: SR
Analysis and interpretation: SR, TS, AJ
Data collection: ML, DT
Writing the article: SR, ML, DT
Critical revision of the article: SR, TS, AJ
Final approval of the article: SR, ML, DT, TS, AJ
Statistical analysis: SR, ML, DT
Obtained funding: SR
Overall responsibility: SR

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