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The pressure / volume relationship of the calf: A measurement of vein compliance?

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Objectives. **The role of compliance changes in the patho-physiology of venous disease is not well known mainly because of difficulty to measure compliance of veins in situ. This study suggests a method to determine the calf pressure/volume relationship by utilizing venous occlusion plethysmography combined with dorsal vein pressure.**
Design. **Comparison between two techniques of measuring calf pressure/volume relationship using air plethysmography with validation against popliteal vein diameter changes detected by duplex ultrasound.**
Setting. **Vascular laboratory.**
Materials. **In 6 normal and 6 radiographically confirmed post-thrombotic lower limbs, the calf pressure/volume relationship was determined. The dorsal vein pressure was continuously recorded. Simultaneously calf volume changes were obtained by an air plethysmograph during venous occlusion plethysmography (outflow slope coefficient) and fractionated tilting of the subject from erect to supine position (volume at 40 mmHg). During the tilt, sagittal diameter of the popliteal vein was measured (% change/mmHg = distensibility).**
Results. **The outflow pressure/volume slope coefficient correlated significantly with the volume at 40 mmHg during tilt maneuver (r=0.92) and the popliteal vein distensibility (r=0.86). Variations in arterial inflow, venous outflow obstruction, or reflux did not affect the occlusion plethysmographic method. Plethysmographic changes related directly to venous volume changes, i.e. vein expansion suggesting that the pressure/volume relationship described vein compliance.**
Conclusion. **The result show a direct relationship between the pressure/volume curve of the calf and deep vein distention. Shifts of the pressure/volume curve are likely to be mainly caused by vein wall changes, but other factors (e.g. condition of surrounding tissue, reduced venous volume) may also contribute and this needs further investigation.**

KEY WORDS: Plethysmography - Compliance - Venous disease - Veins.

Vein compliance changes in different types of venous disease and their effect on calf pump function and different hemodynamic tests are not well known. Vein wall properties probably play a much larger role than previously anticipated.[1] The main obstacle for advancement is the difficulty to measure the wall compliance of veins in situ.

To obtain reliable pressure/volume relationships it is important to measure the volume and pressure simultaneously.[2] Earlier studies utilized indirect strain gauge methods, but without any venous pressure measurements.[3-6] Later foot volumetry with simultaneous dorsal vein pressure measurements was used. [7] This study indirectly demonstrated a lower foot-vascular system compliance, i.e., a high elastic modulus in limbs with varicose veins compared to normal legs. There was no comparison to actual changes of the vessel geometry or vein volume. The greater «stiffness» observed with advanced venous disease was attributed to the sclerotic skin changes of the ankle region. More recently, venous compliance was assessed by measuring calf volume by strain-gauge technique and dorsal vein pressure during the up-slope of venous

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occlusion plethysmography.[8] A calculated elastic modulus was determined. The elastic modulus was reduced in patients with simple varicose veins, i.e., the veins were more compliant. No validation of the technique was offered.

This study describes two techniques to measure the pressure/volume relationship of the calf using air plethysmography and simultaneous dorsal vein pressure measurement. An attempt is made to validate the findings against direct popliteal vein diameter changes detected by ultrasound scanning.

Materials and methods

This study involved 12 limbs in nine persons. Six legs were clinically apparently normal with no signs or symptoms of venous disease. The remaining six limbs had post-thrombotic vein wall changes of the calf extending above the popliteal vein segment as shown by ascending phlebograms. In addition, all of these limbs had varying degrees of venous reflux (venous filling index [9] was 3.5 to 10.9 ml/s compared to ≤ 2.0 ml/s in healthy legs). The reflux was mainly due to deep axial vein reflux to below the knee in four limbs and a combination of long and short saphenous vein incompetence in one limb. Local varicosities and incompetent perforators were observed in 5 limbs.

Venous pressure was measured through a 23 gauge scalp needle inserted into a dorsal foot vein. This was connected to a transducer (P10EZ, Gould Inc., USA) placed at the level of the cannulation and the signal continuously recorded on a polygraph (Model 7E, Grass Instrument Co., USA).

The calf volume was measured with an air plethysmograph (APG-1000, ACI Medical Inc., USA). With the subject in supine position, the leg was initially emptied by elevation to at least 45 degrees. The air bag was adapted on the leg and the foot lowered to 30° elevation five minutes later. At this point the plethysmograph was calibrated. The volume changes were displayed on the same polygraph as above. The calf volume measurement includes the whole venous volume of the leg, i.e., differentiation between contribution of the superficial and deep venous systems to this volume is impossible.

Sagittal and transverse diameters of the proximal femoral and popliteal veins were measured on a frozen image using software available in the duplex Doppler ultrasound machine (Acuson 128 PV, probe 531 Linear).

All limbs were investigated in three ways:

1. After fitting the air bag over the calf, an occlusive cuff was fixed around the thigh. The subject was in supine position throughout the procedure. Volume changes were recorded during venous occlusion (cuff pressure 70 mmHg) until the volume curve leveled off (inflow) and after instantaneous release of the cuff (outflow). Simultaneous dorsal foot vein pressure measurement was performed and recorded on the polygraph.

2. The subject was placed on a tilt table in supine position. The air bag was fitted and the plethysmograph calibrated as above. Foot vein pressure and volume changes were recorded tilting the patient from 0 to 7.5°, 15°, 22.5°, 30°, 45°, 60°, 75°, 90° erect and then back again. At each level sufficient time was allowed for full stabilization of the volume and pressure.

3. The subject was placed in prone position on a tilt table and then lowered in the same increments as above and raised again. Continuous foot vein pressure was measured. At each level sufficient time was allowed for full stabilization of the volume and pressure. The sagittal and transverse diameter of the popliteal vein at the level of the knee joint was determined. The ultrasound probe was kept continuously in place and its position outlined on the skin. By measuring the distance from the ultrasound probe site to the dorsal foot vein puncture site and knowing the angle of tilt, the vertical hydrostatic pressure could be calculated. This value was then subtracted from the reading given by the pressure transducer, thus estimating the pressure at the site of vein diameter measurement.

All three tests were performed twice in each patient and the mean result was used. Since pressure and volume curves were recorded simultaneously a pressure/volume relationship during expansion (inflow) and collapse (outflow) could be constructed. Standard methods were used to calculate correlation coefficient and perform linear regression analysis.

Results

The three different modes of investigation resulted in individual data shown in Figure 1. The result

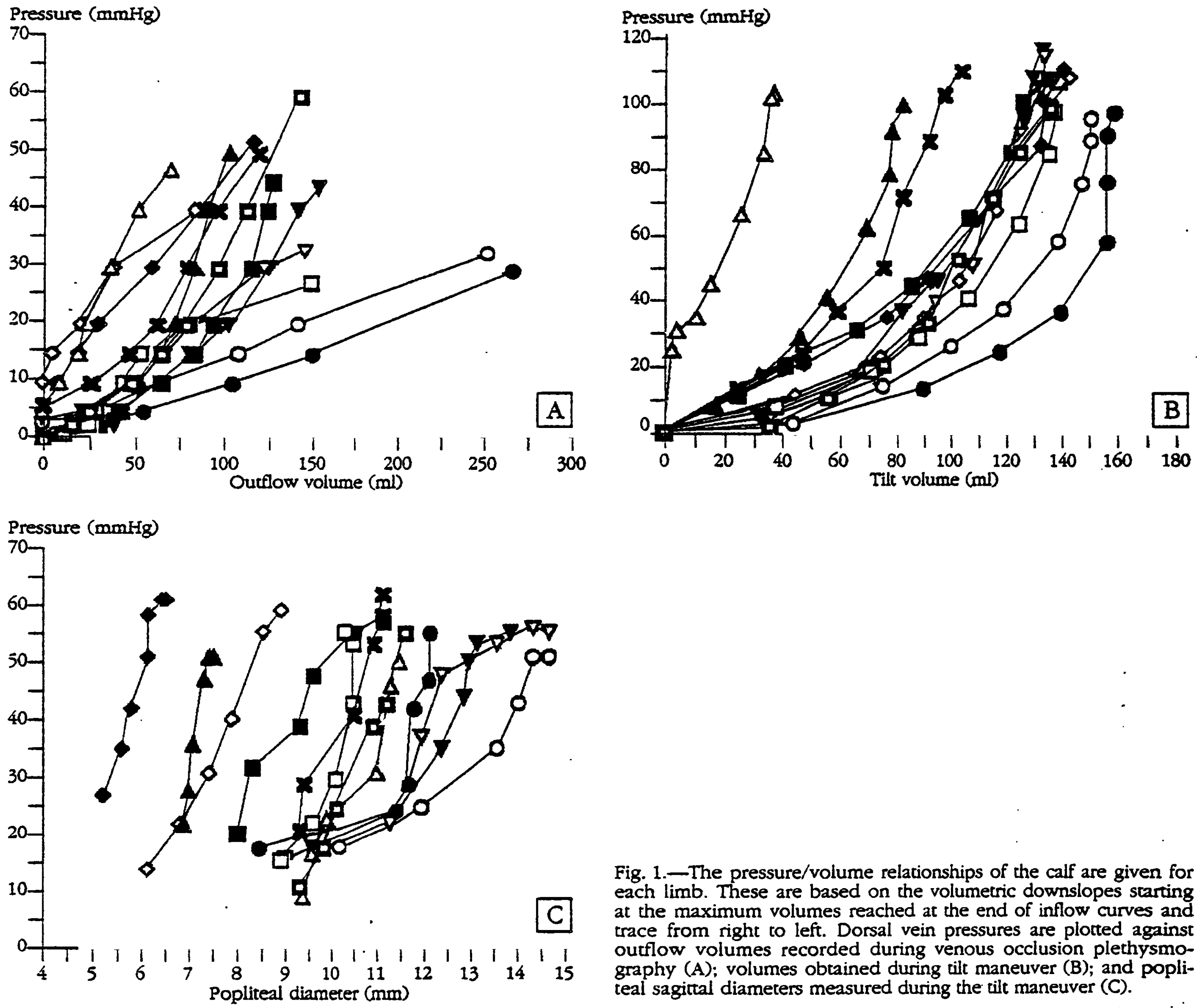

Fig. 1.—The pressure/volume relationships of the calf are given for each limb. These are based on the volumetric downslopes starting at the maximum volumes reached at the end of inflow curves and trace from right to left. Dorsal vein pressures are plotted against outflow volumes recorded during venous occlusion plethysmography (A); volumes obtained during tilt maneuver (B); and popliteal sagittal diameters measured during the tilt maneuver (C).

are depicted in all 12 limbs showing the range of outflow pressure/volume curves encountered. All the curves represent down-slopes starting from a maximum volume at the top right. Thus, the graphs represent the collapse of the calf volume or decrease of the vein diameter.

In order to be able to compare the curves for any correlation the following calculations were made:

1. As the calf volume and the dorsal vein pressure curves were recorded simultaneously on the multi-channel polygraph, the volumetric and pressure curves could be compared directly and used for estimation of the pressure-volume relationship during expansion (inflow) and collapse (outflow) of the calf. The inflow and outflow curves of two limbs are plotted as a counterclockwise loop in Figure 2. The lower portion of the loop represents inflow and the upper outflow. The ending inflow volume and the beginning outflow volume are the same and are plotted as a single point to the top right.

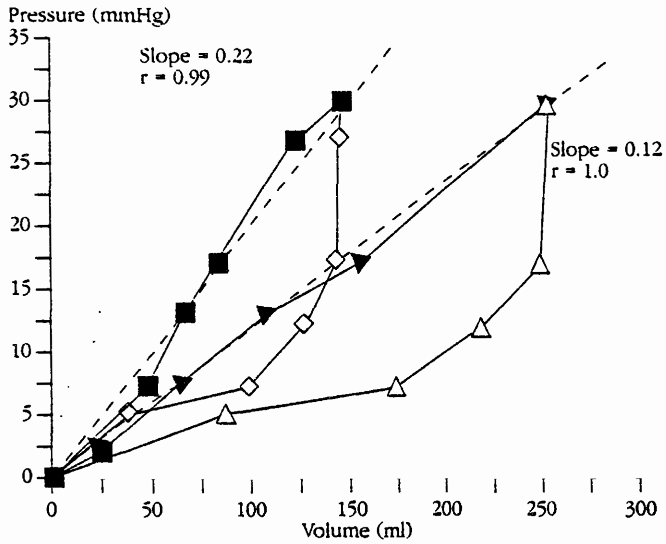

Fig. 2.—Typical inflow and outflow pressure/volume loops during occlusion and after cuff release in two individual legs. Easch loop is traced counterclockwise and consists of an inflow curve (open) and an outflow curve (filled). The lower inflow part is strongly curvilinear. The outflow curve starts at the maximum volume reached at the end of inflow and traces right to left. Note that this portion of the loop is markedly less curved. The fitted straight line (dashed) is superimposed with r-values and slope coefficients given.

The up-slope was curvilinear and varied markedly, likely influenced by the individual variation in arterial inflow and induced outflow obstruction. The downslope starting from a near maximum volume was considered to better reflect a comparable point of full vein distention. Contrary to the inflow curve, the outflow curve exhibited a very gentle curve. The points of the down slope could be fitted to a straight line with a statistically significant r-value in all limbs (Fig. 1, Table I). The average r-value was 0.97±0.02 (SD).

Each individual line could be described by linear regression analysis using the formula: P = kV + c, where P is venous pressure, k is the slope coefficient (describing the angle of the fitted line to the x axis), V is calf volume, and c a constant (y axis intercept) equal to zero, when the line passes through origo. Therefore, each pressure/volume outflow curve obtained at occlusion plethysmography could be described by a calculated slope coefficient (varying from 0.07 [high compliance] to 0.64 [low compliance]) which could be used for comparison of individuals (Table I).

TABLE I.—*Results of the calculations described in the text derived from the three pressure/volume relationships for each of the 12 limbs.*

Limb No.	Slope coefficient (Occlusive cuff test)	ml volume at 40 mmHg (tilt test)	% diameter increase popliteal vein (tilt test)
1	0.07 (r=0.97)	142	1.71
2	0.09 (r=0.97)	122	1.54
3	0.20 (r=0.95)	108	1.19
4	0.22 (r=0.99)	91	1.19
5	0.32 (r=0.98)	89	1.34
6	0.35 (r=0.97)	98	1.15
7	0.39 (r=0.96)	78	0.91
8	0.39 (r=1.00)	84	0.74
9	0.39 (r=0.97)	63	0.54
10	0.42 (r=0.97)	95	0.34
11	0.47 (r=0.92)	56	0.21
12	0.64 (r=0.99)	10	0.47

2. Each volume curve obtained during tilt (Fig. 1B) was characterized by its volume value at 40 mmHg (range 10 to 142 ml) after adjusting the curve to go through zero. The 0 to 40 mmHg pressure interval was chosen because this was the most common pressure range observed during the occlusion plethysmography. A lower volume reflected a greater shift of the curve to the left, leading to a steeper curvilinear slope (indicating a low compliance).

3. The average lengths of the sagittal and transverse diameters with the subject in supine position were equal in both the common femoral and the popliteal veins (10.2±2.5 *vs* 10.1±2.0 mm and 8.5±1.8 *vs* 8.9±1.9 mm, respectively mean ± SD). This indicated that the deep veins appeared circular in the supine position and were not collapsed. Only the sagittal diameter of the popliteal vein (Fig. 1C) is used in the calculation below. The popliteal sagittal vein diameter curves did not go through zero. However, the compliance can be defined by the equation: $C = (\Delta D/D) x (1/\Delta P) x 100$, where C is compliance (percent diameter change per mmHg), Δ D is diameter change for pressure change Δ P, and D is the original diameter. [10] The difference between supine and 45° erect position was used in each patient. The average increase of calculated popliteal vein pressure was 26±4 (SD) mmHg and of popliteal vein diameter 2.0±1.3 (SD) mm. The calculated average % increase of vein diameter per mmHg was 0.94±0.49 (SD). A high percentage change of the diameter per mmHg pressure represented a high compliance.

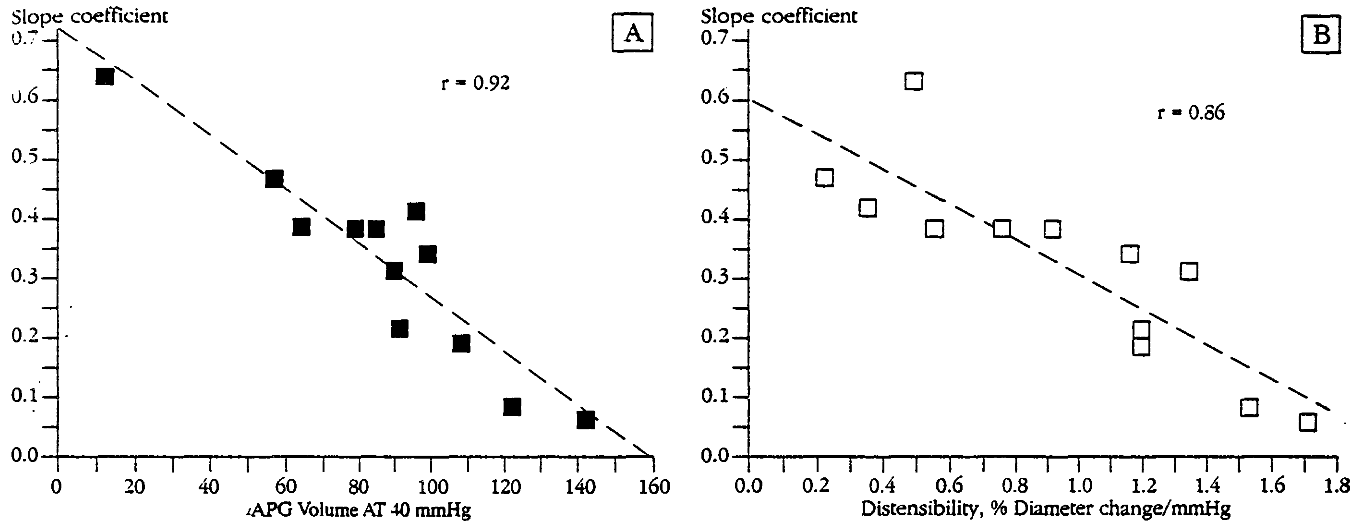

Fig. 3.—Linear correlation between slope coefficients of the pressure/volume outflow curve during venous occlusion plethysmography and the tilt volume at a dorsal vein pressure of 40 mmHg (A); and between the same slope coefficients and the distensibility of the popliteal veins (B).

The values for each limb are given in Table I. The correlation coefficient (r-value) was calculated for the slope coefficient of the pressure/volume outflow curve obtained after occlusion plethysmography *vs* volume at 40 mmHg during the tilt maneuver *vs* % popliteal vein diameter increase per mmHg during tilt (Fig. 3). The slope of the pressure/volume outflow curve following occlusion plethysmography was closely related to the calf volume increase measured during the tilt maneuver (r=0.92; p=0.0001). The volume changes during tilt are entirely due to increased hydrostatic pressure and not affected by venous reflux, arterial inflow and any outflow obstruction, since a steady state was reach at each increment measurement.

The diameter increase per mmHg in the popliteal vein correlated significantly to the tilt volume increase (r=0.76; p=0.0039). This relationship suggested that the pressure/volume changes we observed were related to changes of venous volume. There was also a significant correlation between slope coefficient and the popliteal vein distensibility (r=0.86; p=0.0004) (Fig. 3).

The results suggested a lower compliance in 5/6 patients with post-thrombotic legs compared to so called normal limbs. Compliance also varied widely within the «healthy» group of limbs (slope coefficient 0.07-0.39).

Discussion and conclusions

There is increasing evidence that changes in the vein wall and calf pump function play a vital role in the patho-physiology of venous disease.[1] The difficulty is the lack of reliable methods to study the pressure/volume relationship of the vein in situ in different venous diseases and its effect on hemodynamic tests. Unlike the artery with its high transmural pressure, the vein is much affected by external pressure and forms a functional unit with its surrounding tissue.[2] Air plethysmography and ultrasound scanning are unique tools that make possible the measurement of volume change in absolute numbers and the actual visualization of the vein in situ non-invasively.

There was a surprisingly good correlation between the findings of the three different modes of measurements. The down slopes (outflow curves), which started from a maximal volume with fully dilated veins, were considered to better reflect a comparable point in each individual limb and therefore used for comparison. The measured femoral and popliteal veins appeared circular and not collapsed with the patient in supine position, suggesting true expansion of the veins without any change of vessel configuration.

In contrast to the dynamic occlusion plethysmography, the tilt table tests were static tests, only dependent on increased hydrostatic pressure, since the volume and pressure were allowed to stabilize at each measuring point. The pressure/volume relationship obtained with the tilt table or the outflow volume curve at occlusion plethysmography did not differ significantly. This indicated that venous outflow obstruction, the presence of venous reflux and dynamic changes of arterial inflow, if any, during the plethysmographic outflow method did not critically affect the result. In theory, there should be no such influence on the pressure/volume relationship. The number of limbs is small and further studies on the possible influence of these factors on the detection of the calf pressure/volume relationship should be performed.

Ludbrook & Loughlin have indirectly shown that in normal limbs the increase of calf volume during tilt is mainly due to venous expansion of intramuscular veins deep to the deep fascia. [11] Although the scanning of the popliteal vein may be difficult in post-thrombotic limbs and only the main vessel in the popliteal fossa was measured, there was a clear relationship of the pressure/volume curve obtained with plethysmography to those measuring the sagittal vein diameter, i.e. venous volume. This suggested that the plethysmographic volume changes are mainly due to vein expansion and thus the pressure/volume curve describes vein compliance.

However, venous compliance as it is measured in this study may not only depend on alteration of the vein wall, but the condition of surrounding supporting tissue may also contribute. Fluid accumulation or fibrosis may vary among normal subjects and certainly in patients with chronic venous insufficiency. Although in a comparison between groups of post-thrombotic limbs of different clinical severity class, no significant differences were reported. [12]

As in all plethysmographic methods, the actual baseline venous volume is not known. Only relative volume changes are measured. Even if base line calf volume was measured, there are variations in the relative contribution of venous volume and surrounding tissue, and the relative distribution of the total leg venous volume in the superficial and deep systems can not be measured. Therefore, a smaller venous volume in the calf may shift the pressure/volume relationship to the left without any change in the vein compliance. Voluminous compliant varicosities may disguise a stiffer deep vein and thus underestimate the vein wall compliance. To our knowledge there is no practical method available to measure actual venous volume of each individual calf.

In all three examinations, the results in the two small groups of limbs suggested a lower venous compliance in post-thrombotic limbs as compared with healthy limbs. This observation agrees with the known fibrotic changes of the vein walls secondary to phlebitis and later developing venous hypertension. [7, 13] Although this lower compliance is likely to be the main explanation for the abnormal pressure/volume relationship, other factors (e.g. reduced venous volume due to residual thrombi) may also contribute. It is also apparent that so-called "healthy" limbs have greatly varying compliance with a direct continuum to values found in diseased limbs. The number of limbs is limited and firm conclusions not possible until further studies are performed.

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