Observations on the calf venous pump mechanism: Determinants of postexercise pressure

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Purpose: We investigated the factors determining postexercise pressure and the relationship of venous valve closure and venous column segmentation to ambulatory venous pressure changes.
Methods: Valve closure and venous segmentation were observed during dynamic ascending phlebography in 40 nonrefluxive limbs and by duplex imaging in 25 normal limbs in healthy volunteers. Simultaneous volume (air plethysmography) and pressure studies during calf exercise were also carried out. Some studies used a simple mechanical model comprised of a collapsible latex tube ("calf pump") and a graduated "popliteal" valve.
Results: The femoropopliteal venous column above the popliteal valve remains unsegmented and continuous during ambulatory venous pressure changes in response to calf muscle contraction. Therefore ambulatory venous pressure changes cannot be explained purely on the basis of hydrostatic column pressure changes. Postexercise pressure appears to be determined by a complex set of factors: (1) physical segmentation of the venous column *below* the popliteal valve (i.e., tibial valve closure); (2) tube collapse below the closed valve, which further aids in the breakup of the hydrostatic column pressure and dampens the effect of any reflux through or around the closed valve; (3) ejection fraction, which influences the degree of tube collapse; and (4) the interaction of the resultant pressure forces with the wall properties of the venous pump.
Conclusions: The mechanism of ambulatory venous pressure reduction is complex and multifactorial. The importance of venous wall characteristics as a determinant of postexercise pressure has not been previously appreciated. Changes in venous wall property after a thrombotic process, for example, could conceivably influence ambulatory venous pressure and recovery time in the absence of reflux. (J VASC SURG 1993;17:459-69.)

Two long-accepted concepts in venous hemodynamics are that (1) venous pressure under static conditions largely represents hydrostatic forces of the venous blood column, and (2) segmentation of the venous blood column occurs between valves after calf pump action. In a motionless extremity, the venous pressure recorded at the foot level corresponds to the hydrostatic pressure exerted by a column of blood extending from the foot to the heart level. It is commonly assumed that the pressure changes that occur during ambulatory venous pressure measurement represent alterations in the height of the blood column that occur with segmentation between valves. A closer examination of this simplistic concept, however, leads to difficulties in reconciling pressure changes that occur with calf muscle contraction. For example, in the individual of average height, the foot venous pressure decreases in step-wise fashion (Fig. 1) with each calf muscle contraction from about 90 mm Hg to about 40 mm Hg or less.

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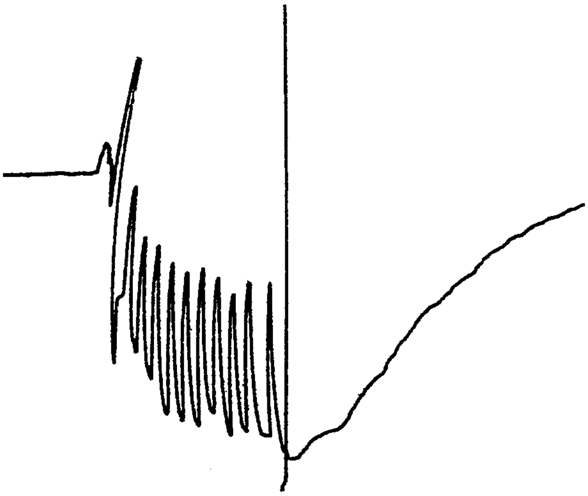

Fig. 1. Ambulatory venous pressure tracing in a healthy limb. Descending limb of pressure curve appears to come down progressively with oscillations induced by calf pump action. Recovery phase of pressure curve is gradual without stair-step increases.

From its nadir, the pressure recovers gradually to preexercise levels during an extended period (20 seconds or more). If the decremental phase of ambulatory pressure during calf exercise represents diminishing height of the segmented blood column above the venipuncture, one can imagine that this is a result of sequential valve closures proceeding from a cephalad to a caudad direction in the lower limb. In anatomic terms, the order of sequential valve closure would be as follows: common femoral vein valve followed by superficial femoral vein valve, popliteal valve, and so on, in the caudad direction. The ambulatory pressure at its nadir represents the shortest height of the segmented venous column being measured during exercise. A moment's reflection on the nature of the calf pump mechanism makes it clear that the sequential order of valve closure from femoral to popliteal in a caudad direction with calf muscle contraction is simply not possible. More than likely, the popliteal or tibial valve closes before the others, inasmuch as the reversal of flow necessary for valve closure[1] probably occurs much more vigorously at the tibiopopliteal level with calf exercise compared with the superficial femoral or common femoral vein levels. If indeed the popliteal or tibial valve closes first, the process of blood column segmentation will be rapid. Assuming that the hydrostatic pressure exerted by the lowest column represents postexercise pressure, one should expect a precipitous drop in the ambulatory venous pressure with the very first calf pump action rather than the stepwise reduction that one sees. The femoropopliteal venous segment contains an average of three to four valves located at intervals of about 10 to 15 cm along the course of the vein.[2,3] During the recovery phase of the ambulatory venous pressure measurement, restoration of the segmented venous column into a single column extending from the foot to the heart should proceed in a stair-step fashion ranging from 7 to 15 mm Hg increments until the column grows from the popliteal level to about the level of the groin. Because functional valves are rarely present above the groin,[3] when the blood column has grown to this height during the recovery phase there should be a sudden jump in ambulatory venous pressure of about 20 to 30 mm Hg, representing the instantaneous growth of the blood column from the groin to the heart level. Such stair-step changes do not occur during the recovery phase of the ambulatory venous pressure measurement (Fig. 1), which suggests that the venous segmentation theory, at least in this form, is simply not valid. It is apparent that changes in ambulatory venous pressure cannot be interpreted simply in terms of changes in venous column height alone that may accompany valve closure.

To obtain a better understanding of the pressure changes and the order of valve closures that occur with calf venous pump mechanism, we undertook pressure and imaging studies on live subjects. We also constructed a simple mechanical model to simulate the calf venous pump as described below. This model yielded unique insights into the determinants of the postexercise pressure, especially as related to the behavior of a vertically positioned collapsible tube.

MATERIAL AND METHODS

Studies on volunteers and healthy limbs. A commercially available color-coded duplex scanner was used to image valve action during calf muscle exercise in the erect position.

Air plethysmography was carried out according to the method of Nicolaides and Sumner[4] with a commercially available instrument.

The technique of dynamic ascending phlebography was similar to the technique of ascending phlebography described previously.[5] Dye was injected with the subject in a 60-degree semierect position. Valve movements were observed as the subject exercised the calf muscle during dye injection.

Ambulatory venous pressure measurements were carried out as described previously.[6] A dorsal vein of the foot was cannulated for pressure measurements. Because of rapid equilibration, the recorded pressures from this vein are similar if not identical to mean deep venous pressures.[7]

Mechanical model of calf venous pump. The model (Fig. 2) consisted of a graduated fluid-filled system with a ⅞-inch diameter latex Penrose tube (Argyle Division, Sherwood Medical, St. Louis, Mo.) (12 inches high × 1⅜ inches wide) representing the calf pump. A second drain outside the first one was required as a reinforcing sleeve to prevent hydrostatic disruption. This two-ply arrangement did not prevent the pump from functioning as a collapsible tube. A ½-inch ball valve (simulating the popliteal valve) with a lever for the closure mechanism was calibrated volumetrically by timed flow measurements (average of four flow measurements for each setting) at a constant head of pressure. For example, a 5% valve opening represented a valve setting that allowed 5% of the timed volume flow through a fully open valve. Arterial input was provided by a side arm at the lower end of the Penrose drain connected to a check valve allowing only unidirectional flow. A reservoir providing a hydrostatic pressure of 90 mm Hg supplied the arterial input. An additional 20 mm Hg pressure was added to the reservoir fluid by an air pump to simulate the postcapillary pressure available to the venous system from arterial inflow. Ambulatory venous pressure was measured at the lowest point of the fluid-filled system. Resting pressure was adjusted to 90 mm Hg, adjusting the height of the venous reservoir to provide a suitable hydrostatic venous column. The valve was located 19 inches above the transducer because 3½-inch long connections were used at either end of the latex pump for assembly. The model was studied with calf pump ejection fractions ranging from 10% to 100%. Manual compression of the latex tubing was used for ejection. The ejected volume could be controlled by monitoring the graduated venous reservoir during ejection. The latex tube contained 105 ml of fluid at rest. A complete set of ejection fraction studies was obtained for valve positions ranging from fully open (100%) to fully closed (0% open) at 10-degree ejection fraction increments. For each combination of ejection fraction and valve position, at least four separate measurements of preejection and postejection pressure, recovery time, and arterial inflow were recorded. Arterial inflow was calculated by monitoring the volume reduction in the graduated arterial reservoir during the inflow phase. Terminology commonly used with ambulatory pressure measurement is used with the model also for ease of discussion, with the clear understanding that the parameters may not be identical.

Statistics. Statistical analysis of pressure curves obtained with the model were carried out by the Kruskal-Wallis method[8] for analysis of variance by ranks.

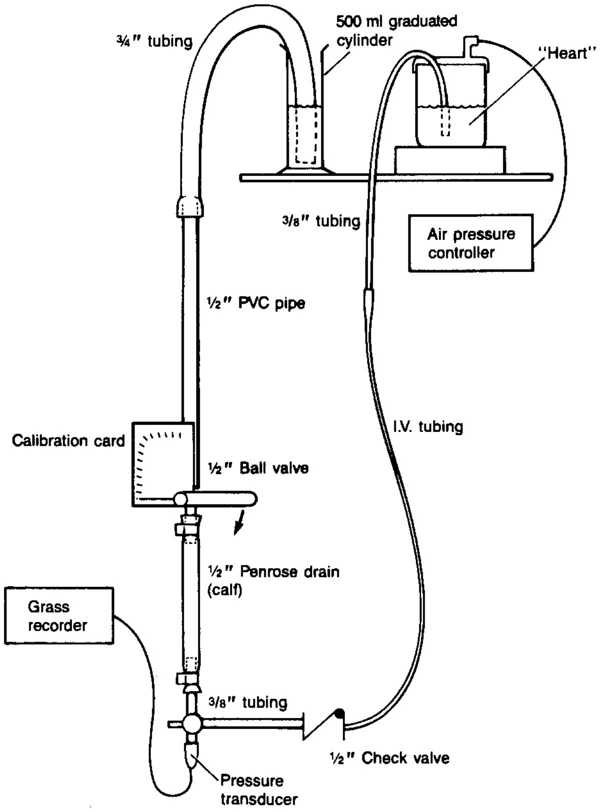

Fig. 2. Diagram of mechanical model used in experiment. *PVC,* Polyvinyl chloride; *IV,* intravenous.

RESULTS

Imaging studies. Twenty-five normal, healthy limbs were examined by duplex scanner to ascertain popliteal and femoral valve action. The examination was carried out with the subjects standing. To avoid leg movement during imaging, manual compression was used to empty the calf veins. This maneuver produces pressure changes in the foot similar to those of the traditional toe-stand technique.[6,9] Satisfactory image quality of the popliteal valve was obtained in nine of these limbs. A posterior tibial valve approximately 6 cm below the knee joint line was well visualized in one thin athletic individual. The femoral valve with satisfactory image quality was observed in six limbs during calf muscle emptying. Imaging observations can be summarized as follows: the popliteal valve closed momentarily after calf emptying in three limbs, reopening almost immediately. In the remaining six limbs the valve leaflets appeared to flutter, never closing completely after calf compression. The movement of femoral valve cusps was even less pronounced and complete valve closure was not observed in any of the six limbs examined. In the single individual in whom the posterior tibial valve was imaged successfully, sustained valve closure for periods ranging from 18 to 52 seconds was observed after calf emptying.

Thus it appears that the femoral valves seldom close completely after calf muscle action. The popliteal valves do close in some limbs, but only momentarily; the period of closure is certainly a mere fraction of the normal recovery time observed for the restoration of postexercise pressure to resting levels.

Dynamic ascending venography. Forty extremities in 28 patients were examined in a semierect (60-degree) position. Twelve of the extremities examined were normal opposite limbs in patients with a single symptomatic limb. Subjects were asked to push their feet against the footboard repeatedly to exercise their calf muscles during the examination. Segmentation of the venous column after calf muscle exercise resulting in an hourglass appearance[10] was not observed in any of the 40 limbs studied. Narrowing of the popliteal vein, as well as the posterior tibial vein, after calf muscle contraction was frequently observed. Correlation of the findings with imaging studies was not attempted because different groups of limbs were involved.

Height of the hypothetical venous column. In 39 limbs with normal postexercise pressure (i.e., <50 mm Hg), the height of the hypothetical segmented venous column after calf muscle exercise was measured as follows: Ambulatory venous pressure measurements were initially carried out through a dorsal foot vein venipuncture with the transducer at the level of the venipuncture. After recovery of venous pressure to resting levels, the transducer was moved up the leg in a cephalad direction to a point at which the pressure read by the transducer equaled the maximum pressure drop obtained during ambulatory venous pressure measurement. For example, if the pressure declined from a resting level of 90 to 40 mm Hg with calf exercise, the transducer was affixed to a point on the leg at which a pressure reading of 50 mm Hg was obtained. This point, representing the top of the hypothetical segmented venous column at its nadir, was located above the knee at the midthigh level in 34 limbs. It was located below the knee in only five limbs. This finding is clearly inconsistent with the common belief that the popliteal valve closes after calf exercise, resulting in venous segmentation, and the segmented column pressure represents postexercise pressure; the segmented column height could not be higher than the closed popliteal valve located behind the knee.

The above series of observations clearly indicates that the basis of venous pressure changes occurring with ambulation is complex, and the explanation of the declining height of the hydrostatic column with exercise is far too simplistic.

Air plethysmography during calf exercise. Simultaneous ambulatory venous pressure measurement and air plethysmography[4] were studied in 14 normal limbs. Simultaneous timed measurements indicated that 90% recovery of the calf volume had taken place at a point at which the ambulatory venous pressure was still at or near its nadir after calf exercise (Fig. 3, *A*).

Mechanical model

Reproducibility. The mean coefficient of reproducibility for postexercise pressure measurements and recovery time for the model was 97% and 96%, respectively. Mean coefficient was calculated from individual values obtained for these parameters from different valve opening and ejection fraction settings.

Pressure-volume relationship. Simultaneous volume and pressure recordings were made in the model with the following settings: (1) ejection fraction 80% and (2) valve opening 5%. After ejection, 75% of volume recovery had taken place in the Penrose tube even while the postexercise pressure remained at or close to its nadir, as shown in Fig. 3, *B*. This is analogous to the findings in healthy limbs (Fig. 3, *A*). The pressure rise in the system was the result of the last 25% of the volume filling of the Penrose tube. The pressure-volume relationship is thus asynchronous and nonlinear. This phenomenon is characteristic of thin-walled collapsible tubes.

RESULTS

Postexercise pressure. The distinctive properties of a vertically positioned collapsible tube as employed in the model are particularly evident in the postexercise pressure curves presented in Fig. 4. It was found that the lowest postexercise pressure curve was obtained with 0% valve opening (i.e., when the valve was completely closed and there was no reflux). Even a 1% valve opening (reflux) resulted in a higher postexercise pressure curve compared with the one obtained with the valve fully closed. Thus even a slight degree of reflux had an adverse, measurable impact on postexercise pressure ($p < 0.008$). However, further increases in reflux (valve opening) beyond 1% did not result in a proportionate increase in the postexercise pressure. There was little difference ($p > 0.09$, difference not significant) in postexercise pressures for a wide range of valve settings from 1% to 100% under varying ejection fractions. Thus the postexercise pressure was sensitive to reflux but was insensitive to the degree of reflux. Differently

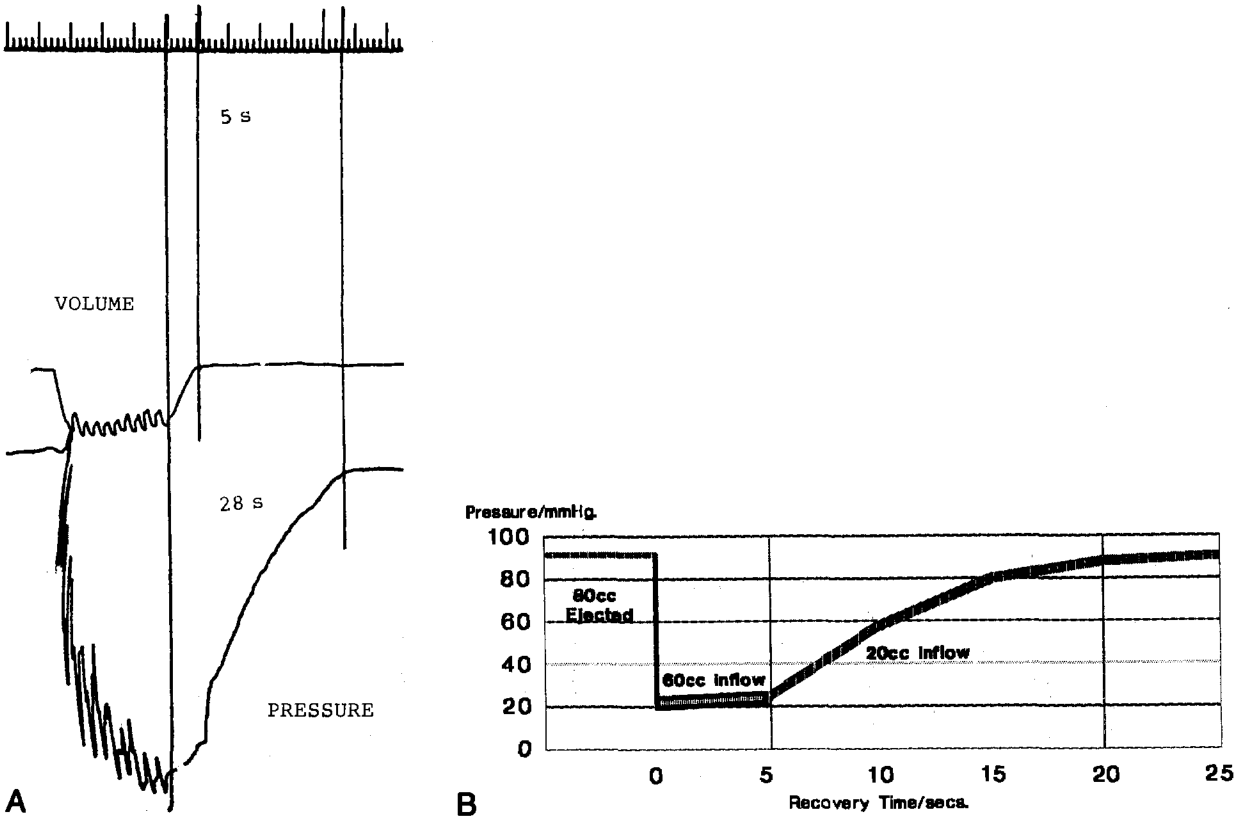

Fig. 3. A, Simultaneous plethysmographic and ambulatory venous pressure tracings in a healthy limb. Note that 90% of ejected volume has been recovered in 5 seconds, whereas ambulatory venous pressure is still close to its nadir. Recovery time for ambulatory venous pressure is 28 seconds. **B,** Similar relationship between volume and pressure is noted in mechanical model. After ejection, 75% of volume recovery takes place, whereas postejection pressure is still at or near its nadir.

stated, a reduction in the degree of reflux, even a substantial one short of total elimination of reflux, will not yield an improvement in the postexercise pressure.

The postexercise pressure plotted for varying ejection fractions is not a straight line but curvilinear. This is characteristic of collapsible tubes that have a two-regimen compliance.[11,12] During the initial regimen, large-volume changes take place with comparatively little pressure change as a result of bending of the collapsible walls of the tube without an increase in the perimeter of the tube. This is represented by the horizontal portion of the curve. The steeper part of the curve is represented by the second regimen when compliance is related to stretching of the wall of the distended tube with an increase in its perimeter. In this regimen, relatively low-volume changes produce a much higher pressure change (i.e., just the opposite of the first regimen). Thus the curvilinear postexercise pressure curve is interrelated to the compliance characteristics of the collapsible tube in both the bending and stretching regimens. Several aspects of the curvilinear postexercise pressure curve should be stressed. For ejection fractions of 10% to 50%, the postejection pressure varied inversely (i.e., the higher the ejection fraction the lower the postexercise pressure). This is represented by the steeper slope of the postexercise pressure curve. Ejection fractions greater than 50% had little influence on the residual pressure; postejection pressure was nearly the same for the range of ejection fractions from 50% to 100%, as represented by the horizontal portion of the pressure curve in Fig. 4. This is partly a function of the 3½-inch long polyvinyl chloride tubing below the Penrose tube (Fig. 2), which contributed a significant proportion of the residual hydrostatic column pressure for ejection fractions greater than 50%. This is also partly a result of a peculiar characteristic of vertically positioned collapsible tubes. In a rigid tube the postejection column

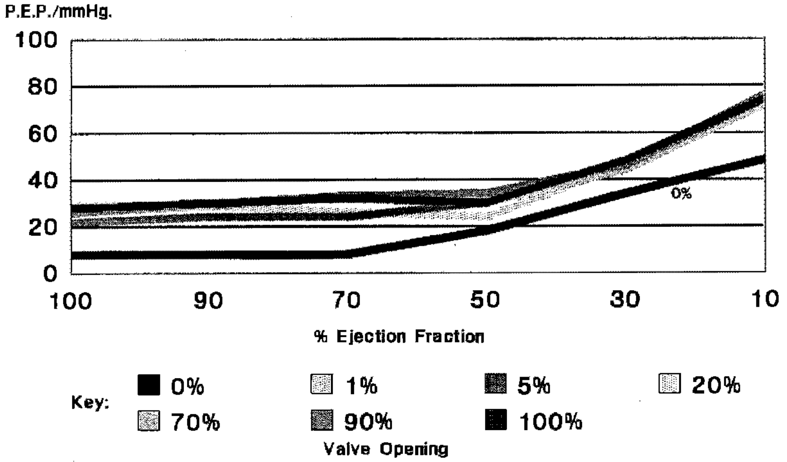

Fig. 4. Relationship between postexercise pressure *(PEP)* and ejection fraction. Data for several valve positions are graphically represented. Note that even a 1% valve opening yields a higher postexercise pressure compared with 0% valve opening. Also note the steepening postexercise pressure curve for ejection fractions 10% to 30% and the near-identical postexercise pressure values for valve positions greater than 0% opening and ejection fractions ranging from 50% to 100%. See text for explanation.

height and the resultant postejection pressure are linearly related to the ejection fraction. On the other hand, volume reduction from increasing ejection fraction will have a relatively diminished effect on column height in a vertical collapsing tube because these variables are related in a nonlinear fashion. Because the column height tends to diminish with increasing ejection fraction in the bending regimen, there is increasing collapse of the tube because the degree of collapse is related to the pressure exerted by the residual column height. Because the degree of collapse is extremely sensitive to column height in this regimen, volume changes associated with increasing ejection fractions result largely in progressive collapse of the tube, with relatively minor reductions in the column height itself. This is responsible for the horizontal nature of the postexercise pressure curve for ejection fractions of 50% and greater observed in the model.

The postexercise pressure differential between 0% valve opening and 5% valve opening is shown in Fig. 5. The line represents the effect of reflux from 5% valve opening on postexercise pressure. The differential is once again curvilinear, similar to absolute postexercise pressures recorded in Fig. 4. The steeper portion of the curve again represents the interaction of the reflux pressure component with the wall property of the latex tube during the stretching regimen. Therefore a given degree of reflux will have a particularly adverse effect on postexercise pressure in this regimen when the ejection fraction is small (i.e., 30% or less). Increasing the ejection fraction beyond 30% mitigates this adverse effect substantially by moving the collapsible tube into the bending regimen. Further increases in the ejection fraction beyond 30%, however, do not result in further progressive improvement in the postejection hypertension generated by reflux (i.e., the portion of the curve for ejection fractions >30% is flat) (Fig. 5).

Recovery time. Recovery time in the mechanical model was influenced by both valve opening (reflux) and ejection fraction (Fig. 6). Valve openings of 1% and 5% resulted in progressive decrease of recovery times compared with 0% valve opening (valve closed, no reflux). Increasing the valve opening beyond 5% resulted in very short recovery times. Increasing the valve opening beyond 5%, therefore, had little additional measurable effect on recovery times. Increasing the ejection fractions resulted in prolongation of recovery times. This effect was clearly noticeable for valve settings of 0%, 1%, and 5%, as shown in Fig. 6. The influence of ejection fraction and recovery times was less noticeable for valve settings beyond a 5% opening because of the very short recovery times observed.

Arterial inflow. Arterial inflow (total volume in milliliters) increased with higher ejection fractions and longer recovery times (Table I).

The arterial limb of the model had a hydrostatic column equaling 90 mm Hg. An air pump was used

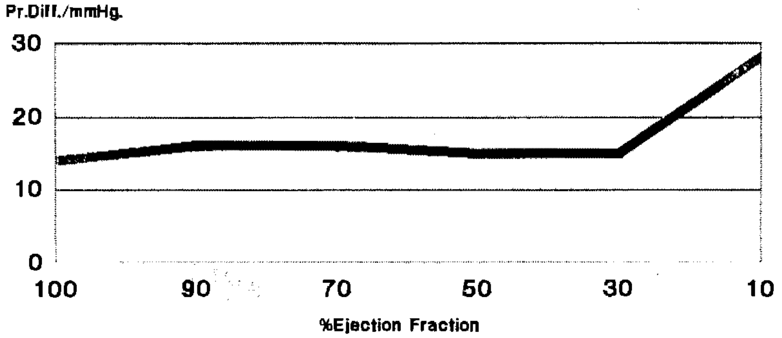

Fig. 5. Contribution of reflux (valve opening) to postexercise pressure. Postexercise pressure differentials *(PrDiff)* between 0% and 5% valve openings are plotted. Differential represents pressure contribution of 5% reflux. Steepening of curve starting at 30% ejection fraction represents interaction with wall property of Penrose tube during stretching regimen. A 5% valve setting was chosen for this illustration because higher valve settings had oscillation-induced artifacts in data points because of very short recovery times.

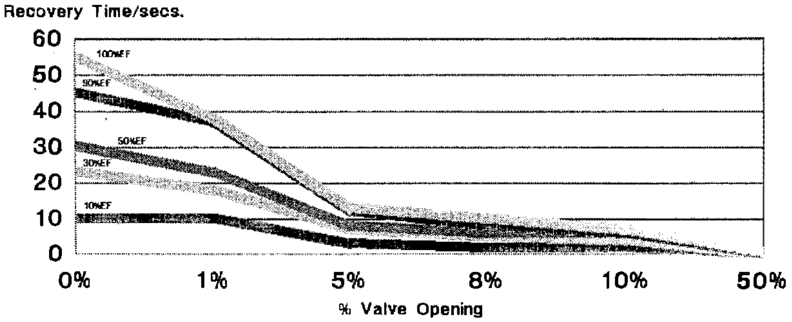

Fig. 6. Relationship between recovery time and valve opening.

to provide additional pressure to the system in step-wise increments from 0 to 40 mm Hg, resulting in a total arterial limb pressure varying from 90 to 130 mm Hg. The effect of this variable arterial limb pressure on the venous side (hydraulic pressure[13]) was studied as follows: The Penrose tube was emptied of fluid (100% ejection fraction) and the valve was completely closed (0 degrees open) so that the only fluid input into the drain was through the arterial limb. The instantaneous pressure change at the Penrose tube resulting from the variable arterial pressure input as described is shown in Table II. Because the Penrose tube is collapsed, most of the arterial input pressure is dissipated (presumably from viscous flow resistance), with only a small fraction showing up as measurable pressure at the lower end of the Penrose model. When the Penrose tube is full (0% ejection fraction) and the valve is open (100% open), flow is established in the system from the arterial to the venous reservoir such that pressure changes from varying the arterial input pressure are minimized substantially (Table II). A small increment in the hydraulic pressure is noticeable when arterial input pressure is raised incrementally with an open valve.

DISCUSSION

Ambulatory venous pressure measurement is traditionally considered the "gold standard" in assessing venous function of the lower limb. Even though it is commonly assumed that the ambulatory pressure changes are related to venous segmentation, the extent of such segmentation and its relationship to postexercise pressure have not been defined precisely. The series of studies reported herein suggests that the factors determining postexercise pressure and recovery time are more complex than generally perceived.

Table I. Relationship between ejection fraction* and arterial inflow

	Arterial inflow (ml) by ejection fraction	
Recovery time (sec)	*10%*	*90%*
3	4	10
6	9	15
10	11	21

*Ejection fractions with identical recovery times were compared to eliminate the latter's influence as a factor.

Table II. Relationship between arterial input pressure (hydraulic pressure) and instantaneous pressure measured at the bottom of the Penrose drain

	Instantaneous Penrose pressure (mm Hg)	
Arterial input pressure (mm Hg)	*Valve closed, Penrose empty*	*Valve open, Penrose full**
90	12	5
110	19.5	7
130	26	10
150	–	12
170	–	14

*Flow is established in the system from the arterial to the venous reservoir.

Absence of column segmentation above the popliteal valve. Observations with venous imaging and dynamic ascending phlebography clearly suggest that there is no segmentation of the venous column above the popliteal valve during calf muscle contraction. The femoropopliteal vein segment cephalad to the popliteal valve appears to retain continuity as a single venous blood column during and after calf pump action. This is consistent with the well-established observation[7,9,14-16] that popliteal venous pressure is affected only minimally by calf muscle contraction. The hourglass appearance of this vein from segmentation as depicted frequently in diagrams to illustrate valve action[10] is not discernible in vivo by dynamic ascending phlebography or duplex imaging (at least in response to calf muscle action). Although some form of functional segmentation of the venous column below the popliteal valve level after calf contraction appears probable, it is not clear whether this is the result of valve closure alone or a combination of valve closure and vein collapse. In the absence of apparent venous segmentation cephalad to the popliteal valve, the pressure changes that occur with calf muscle exercise become impossible to explain purely on the basis of hydrostatic column height changes, as already noted.

Sumner[10] has offered a solution to reconcile infrapopliteal venous segmentation and ambulatory venous pressure changes. This is depicted in Fig. 7. In the resting position (Fig. 7,*A*), the tibial valve is open and the pressures above and below the open valve, as well as at the foot level, correspond to the hydrostatic column pressure. After calf muscle contraction, partial emptying of the calf veins occurs, resulting in tibial valve closure, collapse of the upper portion of the tibial vein, and column segmentation below this point (Fig. 7, *B*). The postexercise pressure recorded at the foot level corresponds to the hydrostatic pressure exerted by the segmented venous column. With arterial inflow, the segmented venous column gradually grows to touch the valve. The pressure relationships at various points of interest during this stage are as depicted (Fig. 7, *C*). Only hydrostatic pressure forces are involved at this point. The top of the segmented column touching the valve will have a hydrostatic pressure of 0 mm Hg and, consequently, the valve will remain closed as a result of the pressure differential above and below the valve. The venous segment below the closed valve will gradually get distended with arterial inflow. At some stage a compliance pressure of 30 cm may be recorded immediately below the closed valve from continuing arterial inflow. A corresponding pressure of 60 cm of blood would be recorded at the foot level at this stage (Fig. 7, *D*). This would represent a column height pressure of 60 cm, placing the top of the hypothetical column somewhere at the thigh level, well above the closed tibial valve as shown in Fig. 7, *D*. The valve will not open until the tibial venous segment gradually distends from arterial inflow to generate a pressure of at least 91 cm of blood at a point immediately below the closed tibial valve (Fig. 7, *E*). Although this explanation is consistent with all of our observations in the patients reported herein, it should be pointed out that this solution incorporates forces other than hydrostatic column pressure alone: the hydrostatic pressure immediately below the closed tibial valve will be 0 if the valve provides for effective isolation of the hydrostatic column above from the one below. Generation of compliance pressure from arterial inflow is required to achieve a pressure of 91 cm of blood in the illustrated example to open the tibial valve. A significant role for vein wall compliance is therefore implicit in this explanation.

The mechanical model. The mechanical model used in this study is particularly useful in appreciating the distinct behavior of a vertically positioned collapsible tube and the complex forces that influence postexercise pressure and recovery time. The model

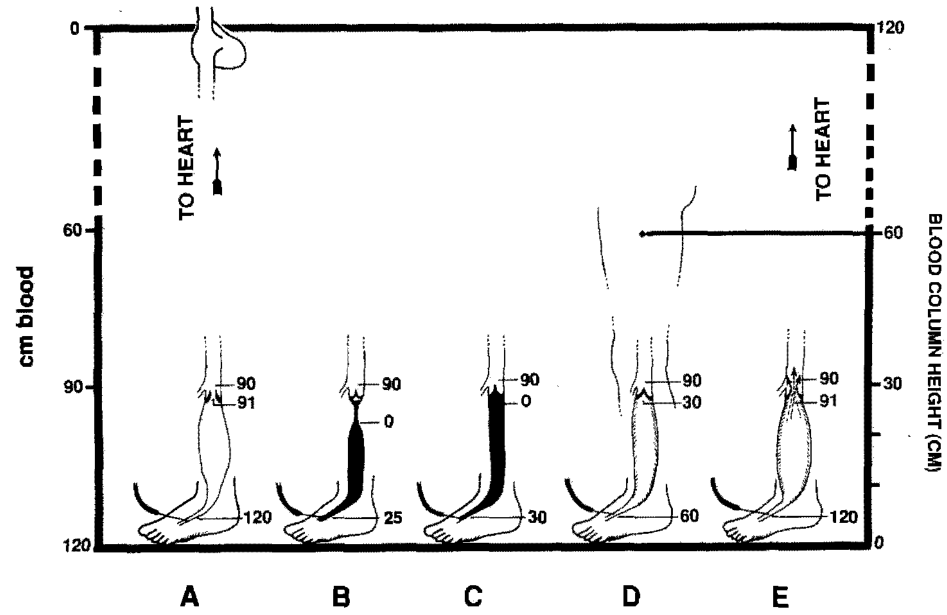

Fig. 7. Scheme of nominal pressure relationships related to tibial valve closure after calf muscle contraction. Hydrostatic pressure forces alone will be insufficient to open closed tibial valve. Generation of compliance pressure by distention of tibial vein segment by arterial input is necessary for valve opening. See text for details.

suggests that postexercise pressure is influenced by ejection fraction, arterial inflow, and reflux. Most important, these inputs are profoundly influenced and shaped by the lumen geometry and wall properties of the collapsible tube. Minimal pressure changes occur in the collapsible tube until it fills to a circular shape that may represent as much as 70% or more of the original volume of the distended latex tube (bending regimen).[11,12] Pressure changes are much more prominent beyond this point, with stretching of the latex wall (stretching regimen) representing the last 30% of volume increment. An interesting feature of the latex tube in the bending regimen is its tolerance to a wide range of reflux (valve opening) and ejection fractions in terms of the resulting postexercise pressure (Figs. 4 and 5) (i.e., the postexercise pressure tended to remain the same despite increasing reflux or decreasing ejection fraction). The collapsible tube is thus complementary to the calf pump, effectively functioning as a "buffer" to compensate for any deficiencies in valve function or ejection fraction. This buffering action is operative only in the bending regimen of the collapsible tube, however; in the stretching regimen the postexercise pressure tends to rise steeply with reflux (Fig. 5) and decreasing ejection fraction (Fig. 4). Fig. 8 illustrates how tube collapse dampens the restoration of the hydrostatic column pressure. When the latex tube is empty and collapsed, the hydrostatic column above the valve remains largely isolated from the postexercise pressure, even when the valve is open and greatly refluxive. Reflux flow falling down the tube fails to transmit the full hydrostatic column pressure, presumably because it is largely neutralized by viscous flow resistance at this stage. With increased filling of the collapsible tube and slowing of reflux flow, pressure at the lower end of the system begins to approach the hydrostatic column pressure. Only after the latex tube is fully distended and reflux flow has ceased is the hydrostatic column pressure fully restored at the lower end of the system. It is thus clear that the collapsible nature of the tube plays a crucial role in the pressure dynamics that occur in response to ejection and reflux; therefore changes in tube volume and wall characteristics of the pump (i.e., compliance) will profoundly affect postexercise pressure and recovery time even when other parameters such as reflux and arterial input remain unchanged. The model suggests that arterial inflow is not constant but will vary proportionally with ejection fraction. The hydraulic pressure component is slightly higher when the valve is closed than when it is open (Table II).

The mechanical model and calf venous pump in humans. The single-tube univalvular mechanical model cannot compare with the complexity of the

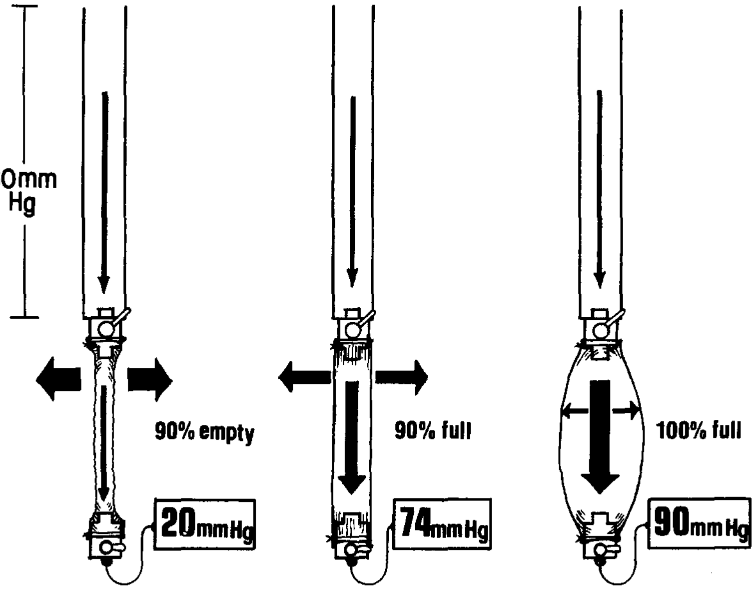

Fig. 8. Diagram illustrates influence of tube collapse on dampening restoration of hydrostatic column pressure after ejection. A 60 mm Hg hydrostatic column is present above a refluxive valve, which is open. Only 20 mm Hg is recorded at bottom of Penrose tube, which is 90% empty and collapsed. Most hydrostatic pressure is dissipated in filling collapsible tube. Thus hydrostatic column is functionally broken even though there is continuity of fluid column through refluxive valve *(far left)*. As filling of Penrose tube progresses, more hydrostatic pressure head is recorded at bottom of Penrose drain. When Penrose tube is 90% full *(middle)*, 74 mm Hg is recorded at bottom of Penrose tube. When Penrose tube is 100% full and distended *(far right)*, hydrostatic column pressure is fully restored; pressure reading of 90 mm Hg is now obtained at bottom of Penrose tube.

multivalvular-multichannel venous system with intact neuromuscular influences in humans. Although veins and latex tubes share the common property of being collapsible tubes, the pressure-volume relationship in the two structures is different. A clear two-regimen behavior is not seen in veins.[12,17] The pressure-volume curve is more gradual in veins as a result of simultaneous stretching and bending throughout the pressure-volume cycle. This may be why the typical hourglass appearance after calf vein emptying was not seen in vivo. Also in the clinical setting, ambulatory venous pressure is typically monitored through a superficial foot vein some distance away from the calf pump. Several valves that provide for unidirectional flow are interposed between the calf pump and the monitoring site. Even though rapid equilibration of mean pressure is known to take place between the monitoring site and the deep veins after calf exercise, it seems that dampening of the pressure wave might occur as a result of closure of intervening valves when a pressure differential is present across the valves. Close examination of the data provided by Ludbrook[9] and others[7,15] who have made simultaneous measurements of superficial and deep venous pressures confirms that such dampening occurs during the up-slope phase of the pressure wave. Dampening might also occur when recovery times are extremely short, reducing the time available for equilibration of pressure between the calf pump and the monitoring site. For these reasons any conclusions drawn from the mechanical model are at best of qualitative significance and cannot be transposed to the ambulatory pressure readings in the clinical setting. Even so, a general understanding of the distinct behavior of vertically positioned collapsible tubes as used in the mechanical model appears essential for the interpretation of ambulatory venous pressure changes. The importance of collapsible tube geometry and wall properties in venous hemodynamics has been appreciated for some time. The crucial role they may play in changes in ambulatory venous pressure, however, has not been investigated or appreciated previously. Some observations with regard to ambulatory venous pressure in patients with reflux remain paradoxical and unexplained. For example, approximately 25% of patients with venous stasis ulceration have ambulatory venous pressures in the "normal" range.[6,18]

Procedures that have been documented to reduce volumetric reflux[19] and heal stasis ulceration[6,20,21] produce only modest improvement in the ambulatory venous pressure, which is seldom normalized after surgery. Clues to an explanation of these perplexing observations perhaps lie in the tolerance of a vertical collapsible tube to a wide range of reflux in terms of the resulting postexercise pressure (Figs. 4 and 5). Ambulatory venous pressure represents the horizontal limb of a curvilinear pressure-volume relationship. Perhaps some other point in the curve in the ascending limb is more representative of the mean pressure seen in an erect individual[22] that may be physiologically more meaningful. This or some other parameter such as recovery time may be a better indicator of calf venous pump dysfunction than ambulatory venous pressure.

In their classic study, Pollack and Wood[23] listed venous reflux, arterial inflow, and calf venous volume as determinants of postexercise pressure. Clearly, vein wall compliance as an additional important determinant should be added to this list. Even though each of the foregoing can presumably affect postexercise pressure independently, most laboratories ignore all but reflux when evaluating ambulatory venous hypertension. More than likely, several of these determinants of postexercise pressure (e.g., valve function, calf venous volume, and wall compliance) are simultaneously deranged in the postphlebetic extremity. An accurate evaluation of the abnormality in each component appears essential for an understanding of the disease process and eventual application of appropriate treatment.

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