Reprinted with permission from
JOURNAL OF ENDOVASCULAR SURGERY, Volume 5, No. 1, February 1998

J ENDOVASC SURG
1998;5:42–51

◆ EXPERIMENTAL STUDY ◆

Tube Collapse and Valve Closure in Ambulatory Venous Pressure Regulation: Studies With a Mechanical Model

Seshadri Raju, MD; Austin B. Green, MS*; Ruth K. Fredericks, MD; Peter N. Neglen, MD, PhD; C. Alexander Hudson, MD; and Keith Koenig, PhD*

Department of Surgery, the University of Mississippi Medical Center; and the *Department of Aerospace Engineering, Mississippi State University, Jackson, Mississippi, USA

Purpose: To determine the role of valve closure and column segmentation in ambulatory venous pressure regulation.
Methods: Using a mechanical model consisting of a graduated adjustable valve and a collapsible tube, we studied the differential effects of valve closure and tube collapse on venous pressure regulation. By utilizing materials with differing wall properties for the infravalvular tube, the influence of wall property changes on tube function and pressure regulation was explored.
Results: Valve closure, per se, does not cause venous pressure reduction. Collapse of the tube below the valve is the primary pressure regulatory mechanism. The nonlinear volume-pressure relationship that exists in infravalvular tubes confers significant buffering properties to the collapsible tube, which tends to retain a near-constant pressure for a wide range of ejection fractions, residual tube volumes, and valve leaks. Changes in tube wall property affect this buffering action, at both the low and high ends of the physiological venous pressure range.
Conclusions: The valve and the infravalvular venous segment should be considered together in venous pressure regulation. Tube collapse of the segment below the valve is the primary pressure regulatory mechanism. An understanding of the hydrodynamic principles involved in pressure regulation derived from this model will provide the basis for construction of more complex models to explore clinical physiology and dysfunction.
J Endovasc Surg 1998;5:42–51

Key words: experimental study, venous valves, venous pressure, venous physiology, venous pump

◆ ◆

The increasing popularity of direct venous valve reconstruction to correct reflux has intensified interest in developing an endovenous approach to the problem. Our understanding of reflux and ambulatory venous pressure regulation, however, remains incomplete. Valve closure and column segmentation are central concepts in venous physiology.[1] Foot venous pressure changes that occur with calf exercise ("ambulatory venous pressure") are commonly ascribed to these mechanisms. While the nonlinear volume-pressure relation-

Address for correspondence and reprints: Seshadri Raju, MD, 1020 River Oaks Drive, Suite 420, Jackson, MS 39208. Fax: 1-601-939-5210.

ship present in collapsible tubes[2,3] is well known in fluid mechanics, it has received little attention in the regulation of ambulatory venous pressure.

We developed a mechanical model utilizing a vertically positioned collapsible tube and a graduated valve to explore the differential effects of valve closure and tube collapse on hydrostatic column pressure in the infravalvular tube.[4] Our preliminary work with this model suggested that the collapsible tube with a nonlinear volume-pressure relationship played an important role in pressure regulation. By using tubes composed of different materials, we have been able to investigate the effects of wall property changes on tube collapse and pressure regulation as well. This article expands upon our earlier work by presenting these new observations.

METHODS

Model Description

A mechanical model, which has been described in detail previously,[4] was devised to simulate some elements of the calf venous pump (Fig. 1). In brief, the model was con-

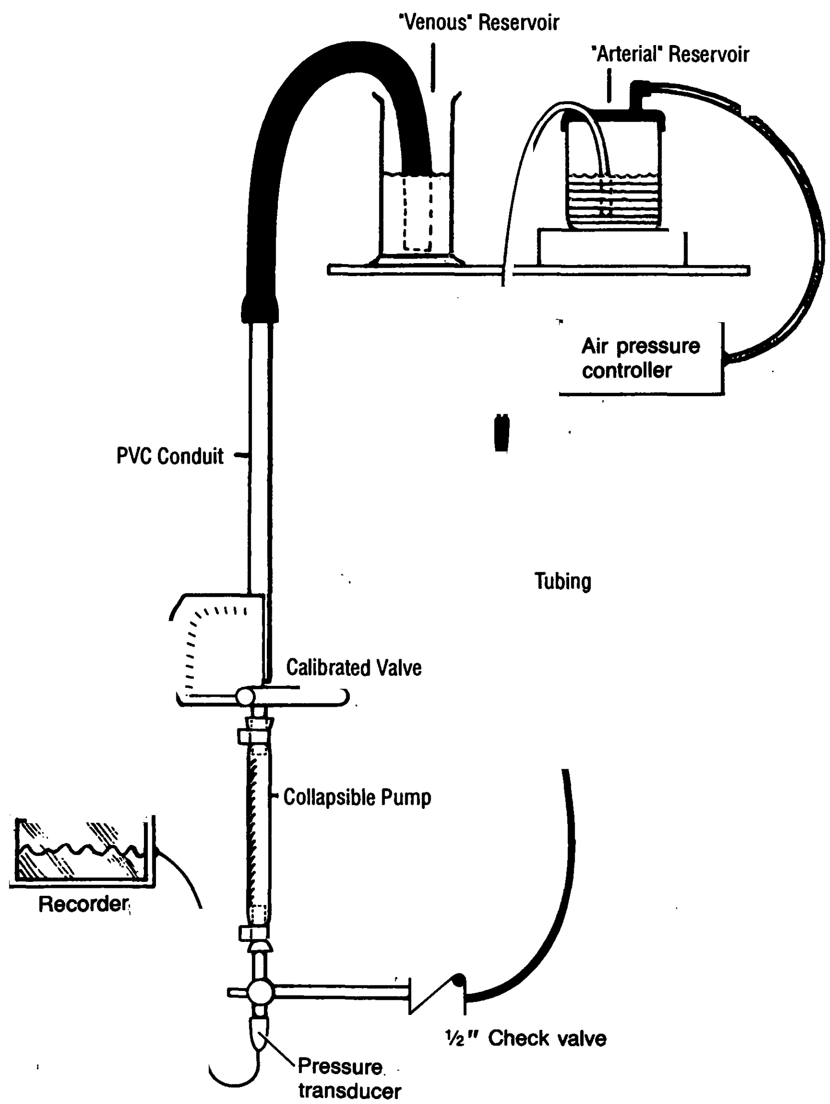


Figure 1 ◆ A schematic diagram of the mechanical model utilized in the experiment.

structed with a 2.2-cm-diameter (double-ply), 17-cm-long vertically mounted collapsible latex tube that functioned as the "pump." A ball valve mounted above the latex tube was calibrated for percentage valve opening by timed volumetric flow measurements through the valve. Polyvinyl chloride (PVC) tubing of sufficient length functioned as a conduit between the valve assembly and a venous reservoir. This conduit between the valve and venous reservoir was rigid and noncollapsible; it remained full at all times, even during emptying and filling of the infravalvular tube segment because of the siphon arrangement at the top near the venous reservoir.

Pressure was measured at the bottom of the latex pump by means of a standard pressure transducer setup and continuously recorded on a multichannel polygraph. The height of the venous reservoir was adjusted to a hydrostatic pressure reading of 95 mmHg at the bottom. "Arterial" input to the pump was provided by a reservoir located at the same height as the venous reservoir via a fluid-filled tubing incorporating a unidirectional check valve. A "postcapillary" pressure component of 20 mmHg was added to the "arterial" input by a pressure-generating pump. The coefficient of reproducibility established for the model was quite high despite manual compression used for pump ejection; 97% and 96% coefficients were recorded for pressure and recovery time measurements, respectively, after ejection.

Experimental Designs

Several experiments were performed with this model to explore the impact of valve closure and tube collapse on venous pressure regulation. Further, the effects of wall property changes on pump function were investigated by conducting the studies with tubes made of other materials, such as polytetrafluoroethylene (PTFE) and thick rubber.

The PTFE tube, although collapsible, is less compliant than the thin-walled latex material that has been used for some time as a mechanical analogue for collapsible veins in experimental studies. Collapsible tubes, such as latex, exhibit a two-regimen compliance of initial "bending" and later "stretching."[5,6] In the "bending" regimen, the cross-sectional area (volume) of the tube enlarges as the shape changes from dumbbell to circular without increase in its perimeter; in the "stretching" regimen, volume changes accompany an increase in the tube perimeter. PTFE is bendable but has an abbreviated stretching regimen. Thick rubber, on the other hand, is noncollapsible. It has minimal bending characteristics and may stretch very little within the pressure envelope used in these studies.

Column Pressure. After the resting pressure at 95 mmHg was recorded, the valve was completely closed, and the arterial line was clamped to monitor the pressure changes in the closed tube over an observation period of 4 hours. To study a hydrodynamic tube, the arterial line was unclamped, and the valve was kept fully (100%) open. When the tube was 100% full, a resting pressure of 95 mmHg was recorded at the bottom of the system. The tube was then emptied 10% (measured by displacement into the graduated venous reservoir) by manual squeezing and then prompt release; the lowest pressure was reached after the release was recorded. The experiment was repeated, emptying (collapsing) the tube in a stepwise fashion at 10% increments until it was completely empty and collapsed (0% tube volume).

Buffer Function. Volume was ejected from the tube in stepwise fashion from 0% (tube full) to 100% (tube empty). Postejection pressures were recorded with the valve increasingly open after ejection in a stepwise fashion (1%, 5%, 10%, 20%, 30%, etc.), representing increasing degrees of valve leak. This experiment was repeated with the three different tube materials to develop volume-pressure curves for each.

To mimic hyperdistention in the tubes, the valve was closed and the arterial input cut off after the tube was fully distended under the influence of arterial input and the hydrostatic column above. The tube was then hyperdistended by injecting additional fluid volume (ranging from 0.1 to 1 mL) via a three-way stopcock at the bottom of the system.

The buffering capacity of the tubes was also assessed by measuring recovery time, i.e., the time required for the tube to refill through a constant "arterial" input after being emptied.

All individual experiments were repeated at least three times, and data were reported as the mean values.

RESULTS

Effect of Valve Closure on Hydrostatic Column Pressure

Regardless of the tube material, there was no immediate change in pressure when the valve was closed (Fig. 2), and postclosure pressure was identical to the resting pressure for a variable period after valve closure. Thus, there was no reduction in the recorded pressure despite actual physical segmentation of the fluid column caused by valve closure. At this stage, postclosure tube pressure was obviously much higher than the hydrostatic pressure represented by the short fluid column retained in the tube below the closed valve. Thus, there was persistence of pressure "trapped" by valve closure and originally generated in response to the long hydrostatic column when the valve was open.

Although identical pressures were recorded immediately after valve closure for the various collapsible and noncollapsible tubes, marked differences were noted in the subsequent behavior of pressure during the observed time frame. With poorly compliant tubes (thick rubber, PTFE), there was gradual decay of postclosure pressure over the next several minutes and hours, slowly approaching a level approximately equal to the column pressure exerted by the short tube fluid column segmented below the valve (15 mmHg). Pressure in excess of tube fluid column pressure was thus gradually dissipated. With highly compliant 2-ply latex tube, there was no such decay in tube pressure after valve closure; the measured pressure remained at preclosure levels during the 4-hour observation period.

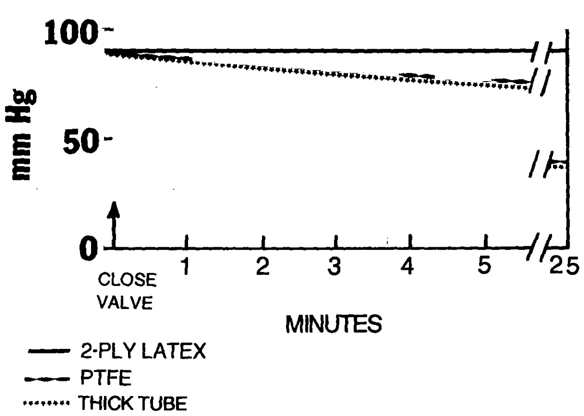


Figure 2 ◆ This graph of the hydrostatic column pressure for different tube materials over 25 minutes shows that there was no instantaneous pressure reduction with valve closure. During the observation period (4 hours), a further gradual reduction in pressure for nonlatex tube materials was seen (see text).

Pressure in excess of the tube fluid column pressure is generated by compliance volume, which may be defined as the volume in excess of tube fluid column volume that would be present in a totally noncompliant tube below the valve. With the valve open, compliance volume accumulates in the tube in response to the hydrostatic pressure exerted by the long column above the valve. Although the resulting compliance pressure generated is identical for the tube materials, their compliance volumes vary markedly, according to their individual compliance characteristics.*

Since the excess fluid volume is relatively minute with PTFE tubing, there is gradual decay of pressure after valve closure toward that represented by the tube column height. This decay results from either stress relaxation characteristics of the materials used in the apparatus or the presence of minute leaks in the apparatus at various points, e.g., the unidirectional valve in the arterial inflow tubing, through which very small amounts of fluid may pass, resulting in degradation of pressure. Studies by one of us at another facility using a more sophisticated model with finer tolerances suggested that structural relaxation of the tube plays a major role in pressure decay. Since water (and blood) are almost noncompressible, even minute volume changes in a closed tube system can result in substantial pressure changes. Hence, because

* The compliance volume for latex is on the order of 1 mL or more. For other less compliant tubing, the compliance volume is < 0.1 mL. This can be demonstrated by the following experiment. With the arterial line clamped throughout, 0.03 mL is withdrawn from the tube after the valve is closed. Little or no pressure drop is noticed in the latex tube setup. On the other hand, a noticeable pressure drop occurs in the PTFE and rubber setups. When the volume is reinjected, pressure is recovered. The compliance volume for PTFE and thick rubber is small. Additional experiments in which the latex was substituted with a rigid PVC tubing resulted in even more rapid pressure decay after valve closure than seen with PTFE and thick rubber. Fluid withdrawal experiments indicate that the compliance volume for PVC is concomitantly even smaller.

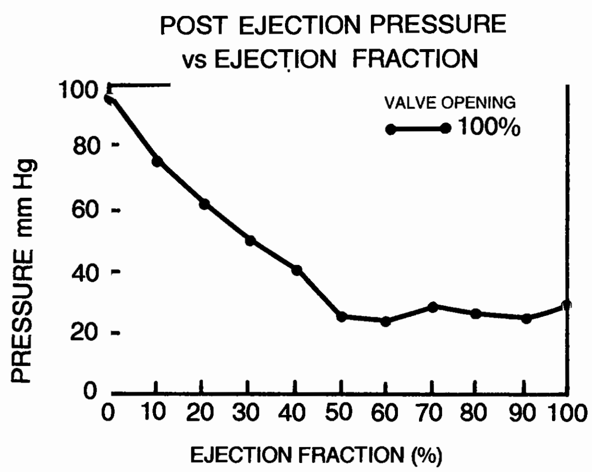


Figure 3 ◆ As the latex tube is progressively collapsed, the hydrodynamic pressure rapidly declines to about 20 mmHg when 30% to 40% of original volume has been emptied. The pressure reaches a rough plateau at this point, and further volume reduction does not result in additional significant pressure reduction. The pressures were recorded with the valve fully (100%) open.

of the relatively large compliance volume for latex, no pressure decay was documented during the observed time frame.

Effect of Tube Collapse on Hydrodynamic Column Pressure

The degree of tube collapse (expressed as tube volume) and the corresponding pressures for latex are shown in Figure 3. As the tube enters the bending regimen, the recorded hydrostatic pressure reaches a plateau. With progressive collapse of the tube, further reductions in the recorded hydrostatic pressure were not noted. Since the valve was kept fully open throughout the experiment,† there was physical continuity of the fluid column in the system across the open valve, including the moment when the lowest pressure achieved was recorded.

† With the valve fully open, pressure recovery is very rapid, i.e., very short recovery time. Nearly identical volume-pressure curves can be generated with the valve partially closed with longer recovery times.[4] The resistance of a partially closed valve begins to exceed viscous flow resistance (see later), affecting residual tube pressure only when the valve is open ≤ 5%. This is a well-known effect seen in tandem stenoses, in which the distal resistance is greater than the resistance of the proximal stenosis.

The explanation for the pressure reduction with tube collapse is probably related to the influence of viscous flow resistance when the tube is partially or fully emptied and fluid rushes through the open valve to fill the tube. The hydrostatic pressure exerted by the fluid column above the valve is variably dissipated in overcoming viscous resistance encountered by this fluid flow, resulting in a reduced pressure at the bottom of the system. The recorded pressure is less than the column pressure that can be expected from the long fluid column in a static system. Note that the pressure reduction is maximized even with partial tube collapse (60% to 70%); further increments in tube collapse add very little pressure reduction. This is related to the pressure differential (hence the fluid velocity and viscous resistance) across the open valve that reaches a maximum with partial tube collapse and remains relatively constant with progressive collapse of the tube.

Buffer Function

The volume-pressure curves for latex at several degrees of valve closure are represented in Figure 4. Postejection tube pressures remained constant or nearly identical in the infravalvular tube despite wide variations in

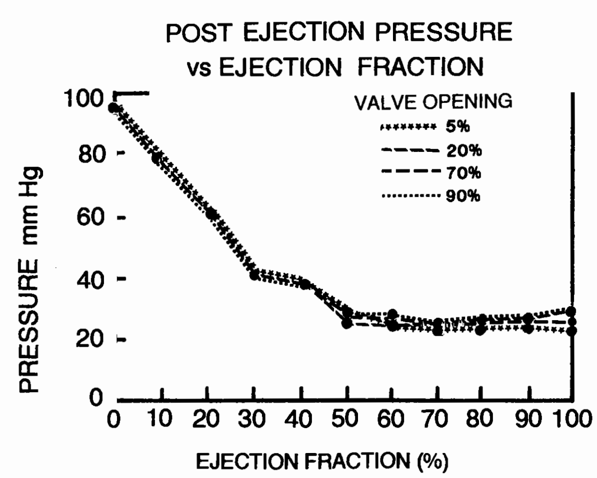


Figure 4 ◆ Buffer function of tube collapse. The latex tube maintains a near identical pressure of approximately 20 mmHg for a wide range of ejection fractions (from about 30% to 100%) and for different valve leak settings.

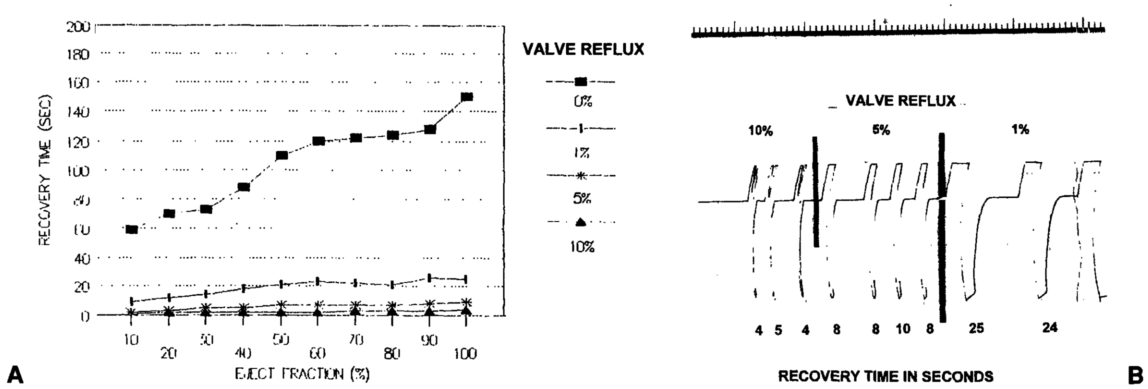


Figure 5 ◆ (A) The recovery time plotted for various ejection fractions with the latex tube. Separate curves for several different venous valve reflux settings are shown. **(B)** A sample pressure tracing for 50% ejection fraction (several separate ejections for each reflux setting) with varying degrees of valve leak (10%, 5%, and 1%). Note the nearly identical postejection pressures. Recovery time, however, becomes progressively shorter as the degree of valve leak increases.

valve leak. This "buffer" function is also in evidence with regard to ejection fractions. Recovery times, however, become shorter with increasing valve leaks and decreasing ejection fractions (Fig. 5).

Tube collapse as it occurs in the bending regimen tends to keep the postejection pressure low and nearly constant (+20 mmHg) for a wide range of ejection fractions (ranging from 100% to 40% for latex). The postejection pressure tends to rise, and buffer function is lost for ejection fractions < 40%, i.e., when the latex is in the stretching regimen.

The buffering capacity of a vertically positioned collapsible tube in the bending regimen is related to the fact that the residual fluid within the tube will maintain a near constant column height despite wide variations in the residual fluid volume. Because column height rather than fluid volume dictates postejection pressure in the bending regimen, a near constant postejection pressure for a wide range of ejection fractions is recorded. The self-leveling mechanism in the collapsible tube is related to the tube law,[7] represented by a typically sigmoid curve with steep volume-pressure relationships at the low and the high ends of the volume envelope (Fig. 6). In the intermediate regions, the curve is flat, i.e., very little pres-

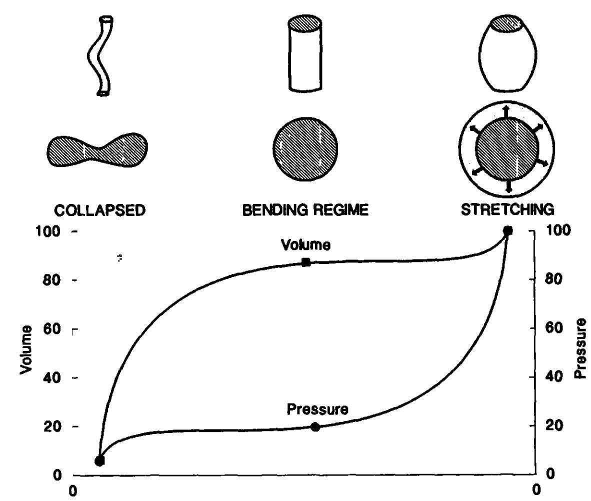


Figure 6 ◆ Diagrammatic representation of the nonlinear volume-pressure relationship in thin-walled collapsible tubes. The volume scale is on the left and pressure scale on the right. Volume and pressure are separately depicted in individual curves. The degree of tube collapse is shown in the upper panel. Large volume increments with relatively little pressure changes occur in the initial bending regimen. In the later stretching regimen, dramatic pressure increases occur with relatively little volume increments (see text).

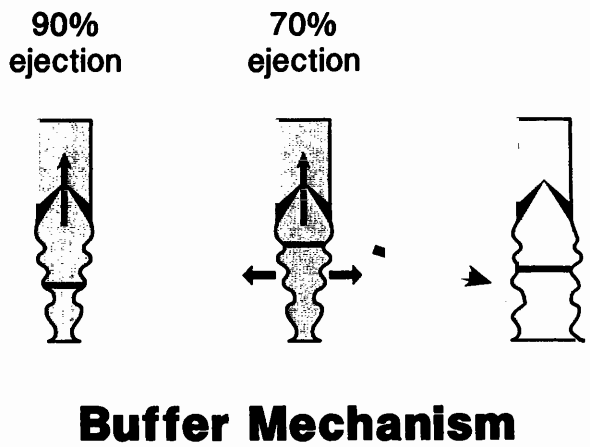


Figure 7 ◆ Because of the nonlinear volume-pressure relationship, a self-leveling mechanism is present in a partially collapsed vertical tube that keeps the fluid column height nearly constant for a wide range of volumes. An initial 10% increment in fluid volume and resulting transient increase in column height will quickly expand the partially collapsed tube, accommodating the increased volume and bringing the transient increase in column height back to near original level. A mere 1.1% increase in cross-sectional area of the tube can accommodate the increased volume of a transient 10% increase in column height from 10 to 11 cm, for example.

sure is required to reinflate the tube. The influence of this self-leveling mechanism on the partially collapsed tube is illustrated in Figure 7.

For other tube materials, the volume-pressure curves were compared to latex. With relatively little emptying, a steep drop in pressure is recorded for PTFE tubing (Fig. 8). Because

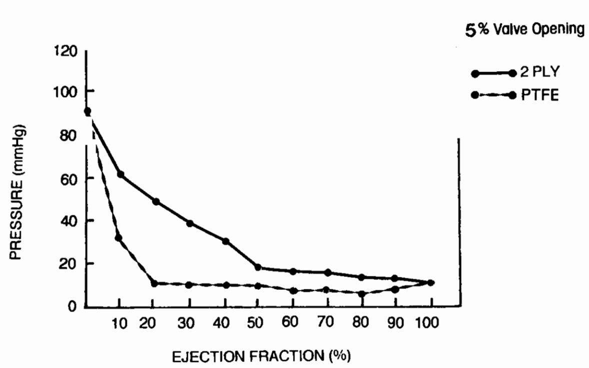


Figure 8 ◆ The volume-pressure curves generated for latex and PTFE tube materials with a 5% valve leak are shown.

TABLE 1
Recovery Time* After 100% Ejection for Various Tube Materials With 0% Valve Opening

Tube Material	Recovery Time (s)
Double Latex	150
PTFE	107
Thick Rubber Tube	59

PTFE = polytetrafluoroethylene
* Time to refill the tube column using "arterial" input.

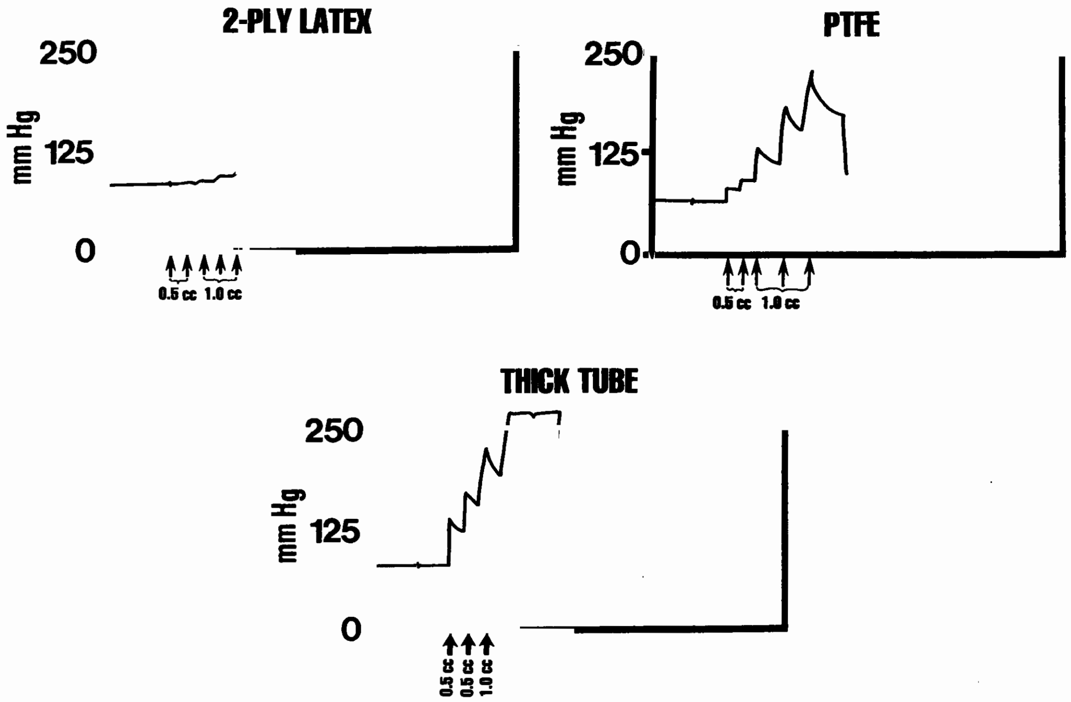
the thick rubber tube is nearly rigid, the buffer action seen in the collapsible tubes could not be demonstrated with the apparatus (the thick rubber tube could not be emptied into the bending regimen without rebounding and interfering with the pressure recordings).

The pressure curves recorded in response to hyperinflation (Fig. 9) demonstrated that poorly compliant materials such as PTFE and rubber yield a much higher pressure in response to hyperinflation than does latex tubing. In terms of recovery times (Table 1), poorly compliant tubes refilled rapidly, despite identical tube volumes and constant arterial input pressure. At the zero valve setting, latex demonstrated the longest recovery time and thick rubber the shortest; PTFE was intermediate between the two.

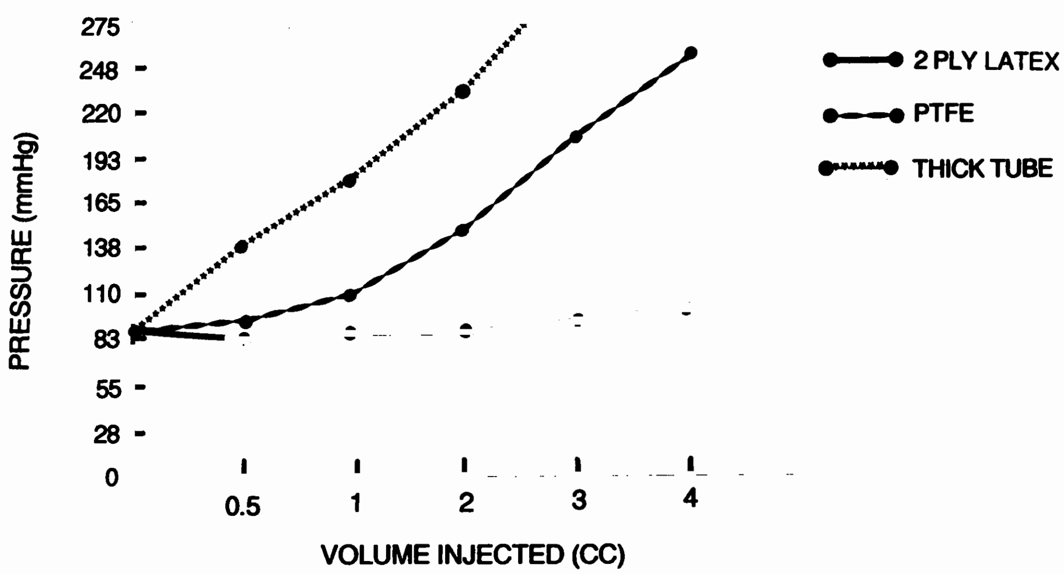
The prolonged recovery time seen in the latex tube is related to the presence of a significant stretching mode, which is absent or shortened in other less compliant tube materials. During the stretching mode, tube filling proceeds at a slower pace because the pressure differential between arterial input pressure and tube pressure is much less than that in the bending regimen. The flow is rapid during the bending regimen because tube pressure is low and the pressure differential is greater. The recovery time for the nonlatex materials is consequently short because most of the tube filling occurs during the bending regimen owing to the nature of the volume-pressure curve (Fig. 8).

DISCUSSION

The model utilized in these experiments is rudimentary, with only a single valve and one tube in contrast to the multitube, multiple valve arrangement in the human calf. More-



A



B

Figure 9 ◆ In the hyperdistention experiments, additional volumes of 0.1 to 1 mL were injected into a distended tube to produce pressure responses. **(A)** The individual pressure curves for the three tube materials showed a minimal pressure rise for latex, while pressure as high as 230 mmHg was recorded for PTFE and even higher for thick rubber tube. **(B)** The hyperdistention volume-pressure relationships are shown for the three tube materials (see text).

over, the latex substitute for the human venous tube in the mechanical model differs from its biological counterpart in significant ways. The volume-pressure relationship is a smoother curve in the vein, and the distinct two-regimen compliance is subdued.[8] Nevertheless, both bending and stretching are important components in venous compliance.[9]

Surgical experience with valve reconstruction indicates that moderately post-thrombotic veins (similar to PTFE) may be bendable even while losing their compliance in the stretching regimen. More advanced post-thrombotic veins encased in fibrous tissue and filled with trabeculae may be nonbendable and poorly stretchable as well. Hence, thick rubber was chosen to mimic these physical characteristics in the experimental setting. However, direct extrapolation of these experimental results to the biological setting is not appropriate, except as pertains to the basic principles demonstrated. Conclusions drawn from these experiments apply only to the single tube below the valve.

The mechanical model clearly demonstrates that valve closure alone will not effect a pressure reduction, even though physical segmentation of the fluid column is achieved. In order for pressure reduction to occur, tube emptying must be accomplished. Tube collapse rather than valve closure thus functions as the main mechanism for hydrostatic pressure reduction. The function of the valve appears to be somewhat secondary, i.e., to maintain tube collapse once it occurs. Both the valve and the tube should, therefore, be viewed as a single unit in venous pressure regulation.

A common misconception is that the venous pressure reduction that occurs with calf muscle exercise results from column segmentation primarily caused by valve closure. The pressure regulatory role of tube collapse in the calf venous pump was suggested initially by Sumner,[7] and the principles of tube collapse have been well studied in fluid mechanics.[2,3] In medical literature, there has been an exclusive focus on valve function and valve reflux with reference to venous dysfunction and chronic venous insufficiency. The rigid ball valve utilized in the model probably transmits little, if any, supravalvular column pressure to the tube below after the valve is fully closed. In the physiological setting, the thin membranous venous valve probably allows some transmission of pressure even when closed. Tube collapse as a hydrostatic pressure brake may, therefore, be even more important physiologically than suggested by these experiments.

Tube collapse evinces other important properties relevant to calf muscle function. It exhibits a pronounced buffer function in the bending regimen, maintaining a near constant low tube pressure for a wide range of ejection fractions and valve reflux settings. Inefficiencies in calf muscle contraction or valve competency are thus compensated for a broad range of these abnormalities.

Wall property changes have important adverse effects on tube function. Changes in wall characteristics that alter compliance may result in a volume-pressure curve that has a limited stretching mode and a prolonged bending mode. The hydrostatic brake function and the buffer function with regard to postejection pressures appear to be unaffected by wall compliance changes and, in fact, may be paradoxically superior to latex because of the predominance of the bending regimen. The recovery time becomes short with wall property changes, however, and the buffering ability of the tube to dampen transient pressure elevations is also adversely affected. This may be clinically relevant. High tube pressure from hyperinflation is encountered during calf muscle contraction and during Valsalva and cough maneuvers. Latex effectively dampens transient pressure inputs while less compliant tube materials are unable to do so.

The volume-pressure relationship in collapsible tubes is nonlinear and asynchronous (Fig. 6). In the latex setup, as much as 70% of the tube fills with little pressure rise. The pressure rises only during the last 30% volume filling in the stretching regimen. This behavior may have physiological import for adequate limb perfusion in the erect individual in whom high ambient venous pressures are encountered. Even with partial tube emptying in response to calf muscle contraction, pressures are dramatically lowered, increasing the arteriovenous pressure difference and facilitating muscle perfusion concomitant with exercise.

A characteristic of tube collapse is a steep drop in tube pressure. Calf muscle exercise, such as tiptoe movements, produces a substantial drop in tibial venous pressure but very little pressure change in the popliteal vein.[4,10] We may surmise that tube collapse in response to calf exercise is confined to infrapopliteal veins. The duration of tube collapse is directly related to the duration of proximal valve closure. Although the tibial valve is seen on duplex imaging to close with calf exercise, the femoral valve does not.[4] If tube collapse of the proximal femoral venous segment in response to calf exercise occurs at all, it is extremely brief in duration. Since tube collapse in the axial conduit interrupts forward blood flow by reducing segmental venous pressure, this arrangement allows cessation of axial flow in the distal (tibial) veins, while maintaining flow in the proximal femoral vein fed by the tributaries from the thigh musculature.

Basic principles of pressure regulation derived from these experiments will be invaluable in constructing and understanding more complex models to simulate calf venous pump function.

Acknowledgment: The authors wish to express their grateful appreciation to Dr. David Sumner, Springfield, Illinois, for providing many helpful suggestions and criticisms in preparation of this manuscript.

REFERENCES

1. Ludbrook J. *Aspects of Venous Function in the Lower Limbs.* Springfield, IL, Charles C Thomas Publisher, 1966:1–136.
2. Shapiro AH. Steady flow in collapsible tubes. J Biomech Eng 1977;99:126–147.
3. Kamm RD, Shapiro AH. Unsteady flow in a collapsible tube subjected to external pressure or body forces. J Fluid Mechanics 1979;95:1–78.
4. Raju S, Fredericks R, Lishman P, et al. Observations on the calf venous pump mechanism: Determinants of postexercise pressure. J Vasc Surg 1993;17:459–469.
5. Attinger EO. Wall properties of veins. IEEE Trans Biomed Eng 1969;16:253–261.
6. Griffiths DJ. Principles of flow through collapsible tubes: Venous hydrodynamics. In: Gardner AMN, Fox RH, eds. *The Return of Blood to the Heart.* London, John Libbey, 1989: 115–126.
7. Sumner DS. Applied physiology in venous disease. In: Sakaguchi S, ed. *Advances in Phlebology.* London, John Libbey, 1987:5–16.
8. Moreno AH, Katz AI, Gold LD, et al. Mechanics of distention of dog veins and other very thin-walled tubular structures. Circ Res 1970;27: 1069–1080.
9. Sumner DS. Mechanical properties of the blood vessel wall. In: Strandness DE Jr, Sumner DS, eds. *Hemodynamics for Surgeons.* New York, Grune & Stratton, 1978:191.
10. Hojensgard IC, Sturup H. Stasis and dynamic pressures in superficial and deep veins of the lower extremity in man. Acta Physiol Scand 1952;27:49–66.