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Studies in Calf Venous Pump Function Utilizing a Two-valve Experimental Model

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Objectives: *to explore the hydrodynamic mechanisms involved in the regulation of ambulatory venous pressure.*
Design: *an experimental model of calf venous pump was constructed with collapsible tubes and valves.*
Material: *the model consisted of a conduit and a pump with an intervening competent valve. Another valve that could allow reflux into the pump was mounted above the pump.*
Methods: *conduit pressure and recovery times were monitored under conditions of different degrees of ejection fraction and reflux into the pump. Model variables included using poorly compliant tubes for the pump, the conduit and for both the pump and conduit.*
Results: *the latex tube exhibited a non-linear volume–pressure relationship and a bi-modal regimen of compliance. This bestowed pressure-buffering properties. Ambulatory venous hypertension resulted when reflux beyond buffering capacity occurred. Substituting less compliant PTFE for latex at the pump had a relatively minor effect on post-ejection pressure and recovery times. Using PTFE at the conduit had a profound but divergent effect on both of these parameters. Conduit capacitance reduction had a similar effect.*
Conclusion: *conduit elastance plays a significant role in the regulation of ambulatory venous pressure in this experimental model. The hydrodynamic principles illustrated by the model may enhance our understanding of the human calf venous pump.*

Introduction

A mechanical calf venous pump model, utilising a single collapsible latex tube with a single proximal valve, was previously described.[1] Studies with that model established that the volume–pressure relationships within the collapsible latex pump were non-linear and exhibited important buffering properties for varying degrees of reflux and ejection fractions. The buffering function derived from the non-linearity of the volume–pressure relationship prevailing in collapsible tubes; a near-constant column height for the fluid that remained after ejection in the vertically-positioned collapsed latex pump was maintained for a wide range of residual volumes. Varying volumes resulting from reflux or decreased ejection were accommodated simply by varying degrees of collapse maintaining the column height nearly constant, resulting in a near-constant post-ejection pressure. Buffering of reflux and ejection fraction was lost, however, when post-ejection residual volume in the pump exceeded the point at which the latex was no longer collapsed (bending regimen) and became stretched (stretching regimen). For latex, the transitional point between the two regimens was between 30% to 40% ejection fraction, i.e., as high as 60% to 70% of the original pump volume could be retained as residual volume and buffered after ejection.

While this simple single-valve model was useful in exploring the bi-modal regimen of collapsible pumps, it did not quite simulate the more complex set-up *in vivo*. In the human calf the lower posterior tibial vein serves as a conduit and several large calf muscle veins empty into the proximal tibial vein and the adjoining popliteal vein. The posterior tibial vein harbours several valves. The superficial veins that drain passively into the posterior tibial vein are also part of the conduit system below the calf venous pump. Clinical measurement of ambulatory venous pressure consists of monitoring changes in the dorsal foot vein in response to calf muscle venous pump ejection accomplished by repetitive contractions. It is known, however, that dorsal foot venous pressure corresponds to distal posterior tibial venous pressure due to rapid equilibration.†[2] To better simulate the human calf venous

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†Higher pressures in the superficial veins than in the deep system may, however, equilibrate more efficiently than in the case of inverse pressure relationship, due to the arrangement of valves.

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pump and conduit, the previously described mechanical model was modified into a two-valve system consisting of a lower collapsible conduit and an upper collapsible pump with an intervening competent membranous unidirectional flow valve (uniflow valve). The graduated, adjustable valve in the original model was retained immediately above the pump. Different materials of varying compliance were substituted for latex, both for the conduit and the pump sections. The present report describes a series of experiments in which different combinations of compliance materials were used for the pump and the conduit, and the volume of these two parts of the model was also varied. The arterial input was varied in some experiments as well.

Materials and Methods

The two-valve model consisted of equal lengths (5 inches each) of 7/8 inch 2-ply latex with an intervening membranous valve (Fig. 1). This uniflow valve is commercially available, has a low opening pressure (<1 mmHg), and is commonly used in ventilatory circuits. It is a competent unidirectional valve, allowing passage of fluid or gas from the lower conduit to the upper ~~pump~~ ~~but not~~ in the reverse direction. A graduated adjustable valve that was calibrated according to timed volume-flow measurements was mounted immediately above the pump. When the valve was set at the 5% opening mark in the calibration card, for example, volume flowing through the valve in unit time was 5% of the volume that can pass through the valve in the full open position. The rest of the apparatus consisted of rigid PVC tubing leading from the adjustable upper valve to a venous reservoir mounted at a height sufficient to yield a resting *venous* pressure of 100 mmHg at the bottom of the conduit monitored by a pressure transducer connected to the distal end of the conduit via a three-way stopcock. *Arterial* input was provided by a sideline connected to the bottom of the conduit via the stopcock. The sideline consisted of commercially available polyethylene tubing (I.D. 4 mm) pressurised from an arterial reservoir mounted at the same height as the venous reservoir. The arterial reservoir was pressurised by an air-pump modulated to yield a 20 mmHg *post-capillary* arterial input pressure in addition to the hydrostatic pressure generated by the height of the fluid column in the arterial reservoir and tubing. The system was filled with water. A check-valve mounted on the arterial sideline prevented egress of fluid from the venous side to the arterial side beyond the three-way stopcock. Pressure changes in the conduit were monitored via the chart recorder in response to graduated emptying of the pump. The pressure *in the pump* was monitored by a sideline connected to the bottom of the pump immediately above the membranous valve to another three-way stopcock. The transducer was mounted at the same level as the conduit transducer so that the volume pressure curves in both the pump and conduit had the same pressure range, for the convenience of comparing the shape of the volume pressure curves. In the resting state, the pump contained a volume of 50 ml. Emptying was carried out in 5 ml increments by manual compression of the pump. This was accomplished by monitoring the outflow into the graduated venous reservoir at the end of each compression manoeuvre. For example, a 10 ml ejection was accomplished by carefully squeezing the latex pump manually until the resulting outflow incremented the graduated venous reservoir volume by 10 ml and then the pump compression was quickly released.‡ Volume pressure tracings for the pump and for the pump/conduit combination, where volume changes *in the pump* ejection fraction were plotted

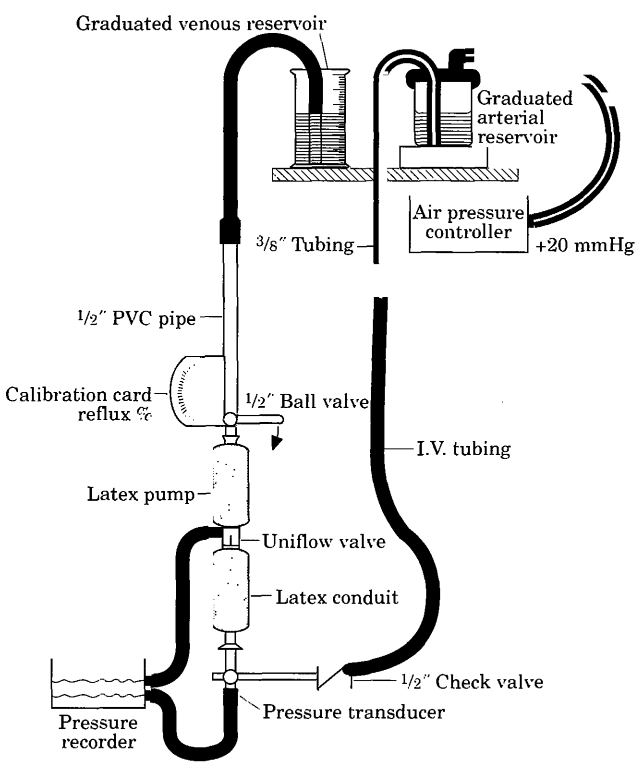

Fig. 1. Two-valve, two-tube model utilised in the study. See text for description.

‡Pressure-volume curves generated by this manual pump compression method compared quite favourably to the curves generated by a more sophisticated model, constructed at the Aerospace Engineering Department at Mississippi State University, consisting of mass flow measurement devices and an automated pneumatic compression device for emptying the pump.

against post-ejection pressure *in the conduit*, were available for analysis. Recordings were made for 1%, 5% and 10% valve leak, set at the adjustable valve mounted immediately above the pump. Since some reflux through the valve always occurs before valve closure, even in normal individuals, and interconnecting tributaries may also circumvent valves to a certain extent, a 1% reflux setting was considered physiological and was used as the reference curve in the experiments. For each ejection fraction and valve leak setting, at least four different pressure measurements were recorded and the results averaged. Another parameter monitored was recovery time, i.e. venous filling time (VFT), defined as the time that elapsed between the recording of post-ejection pressure nadir to restoration of resting pressure of 100 mmHg. This was calculated from the strip chart recording and averaged from at least four trials at the same settings. Mean coefficient of variation was 2.9% for pressure nadir recordings at the same settings and 15% for VFT recordings.

The other variable explored in the series of experiments was the compliance of the material used for the pump and as the conduit. This was achieved by substituting 4-ply latex, PTFE, polyethylene and thick rubber for the pump and conduit in various combinations as described in the results section. The materials were fabricated into tubing of identical dimensions to the latex in the resting state in the system and contained the same volume as the latex, both in the pump and the conduit portion. The thick rubber tubing is not collapsible and exhibits an abbreviated stretching regimen. All other materials were collapsible, i.e. they exhibited a bi-modal bending and stretching regimen as they filled; however, the stretching regimen was less than that of 2-ply latex. In decreasing order of stretchability the materials rank as follows: 2-ply latex, 4-ply latex, PTFE, polyethylene, and thick rubber.

The effect of two other variables, namely the size of the arterial input line and the size of the pump and the conduit, were also investigated. For the former, a smaller tube (I.D. 2 mm) was substituted for the standard arterial input line. For the latter, half-inch diameter latex tubing (2-ply) was substituted for the 7/8 inch latex tubing utilised in the standard series of experiments. It had roughly one-third of the capacitance of 7/8 inch latex tubing.

Statistics and Data Analysis

Volume pressure curves were developed with data points entered into an X-Y plot with post-ejection pressure of the conduit on the Y-axis and the corresponding ejection volume of the pump expressed as ejection fraction on the X-axis. Both the volume and pressure in some curves belonged to the pump itself and these are noted as such where they occur. Separate curves were developed for each of the valve reflux settings (1%, 5% and 10%) in different pump–conduit combinations employing different materials. Corresponding recovery times (VFT) for each of the above data points were plotted separately with time on the Y-axis and ejection fraction on the X-axis.

All curves were subjected to regression analysis. A stepwise regression with a 0.05 level for entering the model was used to find the best-fitting model between the pressure-dependent variable and the ejection fraction and the valve settings-independent variables. Linear, quadratic and cubic terms for the ejection fraction and the corresponding three interactions with valve setting were considered for entry into the model. The presence of non-linear elements is essential for pressure buffering. Buffer function in the conduit was analysed in additional ways as well: (1) The pressure volume curve of interest was split at 50% ejection fraction point into a pair; each of the pair was analysed by linear regression model and the slopes were compared by *t*-test. Bi-modal compliance regimen was determined to be present when the slopes were different. Bi-modality is another characteristic of buffer function. (2) Mean post-ejection pressure for each curve for the range 50% to 100% ejection fraction was noted. The lower the value, the better the buffer function. (3) Buffering range is the number of ejection fraction settings that recorded a post-ejection pressure value of 40 mmHg or less. A maximum of nine such data entries are possible for each curve, i.e. for each ejection fraction setting from 10% to 100%. The total number of data points that actually met the criterion were expressed as a percentage of the maximum possible nine for each curve. A higher percentage value denotes better buffer function. (4) Buffering for valve reflux variations was determined to be present if the post-ejection pressure for 5% and 10% valve reflux settings varied less than 15 mmHg from the corresponding pressure for 1% valve reflux setting in the buffering range. (5) Buffering for ejection fraction variations was determined to be present if the post-ejection pressure varied less than 15 mmHg at each ejection fraction data point in the buffering range. (6) Finally, ambulatory venous hypertension[6] was determined to be present if the post-ejection pressure after 50 ml[§] ejection (100%

§In the human calf of 100 ml volume (pump + conduit), 50 ml ejection is expressed as 50% ejection fraction of the total calf volume. In this model with similar volume distribution between pump and conduit 50 ml ejection represents 100% ejection fraction as it is expressed as a fraction of the pump volume alone.

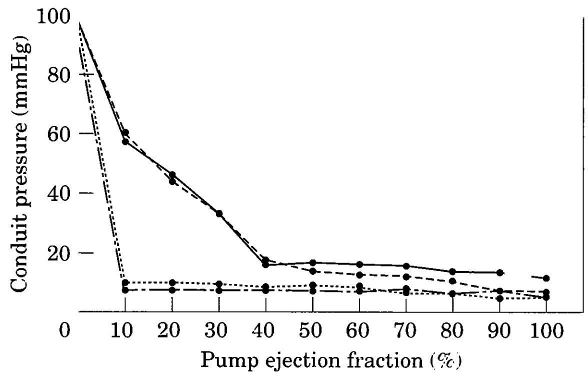

Fig. 2. Comparison of volume pressure curves for 1% valve leak in the pump when materials of different compliance were utilised in the pump. (—) Double latex; (- — -) polyethylene; (- - -) quad latex; (····) PTFE.

EF) was greater than 50 mmHg. Experience with clinical air plethysmography suggests that ambulatory venous pressure with proximal calf exercise is measured at ≤50% residual volume, roughly corresponding to the above parameters. This measurement is an index of buffer function and was chosen for measurement in the model because of this common clinical usage.

Results

The pressure profile in the pump itself in response to progressive ejection for the various pump materials utilised is shown in Fig. 2. The curves are similar to pressure volume curves obtained in the single tube model.[3] All materials yielded a non-linear curve with the less compliant materials, i.e. PTFE and polyethylene, exhibiting a more pronounced non-linearity than did 2-ply and 4-ply latex.

2-ply latex pump/2-ply latex conduit model

The pressure profile in the pump and conduit sections of the basic model with conduit recovery time (VFT) in response to pump ejection is shown in Fig. 3. A representative pressure tracing that illustrates the read-outs utilised in constructing this profile is shown in Fig. 4. Since ejection initially occurred in only the pump section of the device, the pressure changes that occur in the conduit section in response to pump ejection (Fig. 3b) do *not* represent a direct pressure volume curve in the conduit, but rather a pressure profile in the conduit in response to volume changes in the pump section. The pressure profile in the conduit section is analogous to the measurement of ambulatory venous pressure.

The pressure profile in the pump section is characteristically non-linear, similar to that obtained in the single-tube model with flattening of the curve at about 40% ejection. The steeper portion of the curve represents the stretching regimen of latex, and the horizontal portion the bending regimen.[3] The pressure curves for the various reflux settings are virtually superimposed, i.e. reflux-related pressure differences are buffered, which is characteristic of the bending regimen in collapsible tubes. The pressure profile in the conduit is quite different from that seen in the pump.

The curves for the various reflux settings are less non-linear and the pressure differences are not buffered, either for reflux or ejection fraction variations at the pump. Ambulatory venous hypertension was present with 5% and 10% reflux. Most other buffering parameters were poor (Table 1). The recovery time (Fig. 3c) significantly increases with increasing ejection fraction ($p<0.0001$) and significantly declines with increasing reflux settings ($p<0.01$).

Table 1. Conduit pressure buffering in various pump/conduit combinations.

Buffering parameters	2-ply latex/2-ply latex	PTFE/2-ply latex	2-ply latex/PTFE	PTFE/PTFE
Non-linearity	Yes	Yes	Yes	Yes
Bi-modal compliance regimen	No	Partial†	Yes	Yes
Mean post-ejection pressure‡ mmHg for *EF>50%	51	30	30	28
Buffering range %§	11	55	77	100
Buffering¶ for valve reflux	No	No	Yes	Yes
Buffering¶ for ejection fraction	No	Yes	Yes	Yes
Ambulatory venous hypertension	Absent for 1% reflux. Present for 5% and 10% reflux	Present for 10% reflux only	Absent	Absent

* EF = Ejection fraction.
† Present for 1% and 5% valve reflux settings only; absent for 10% valve reflux.
‡ For 1% valve reflux setting. §Percentage of data points among maximum possible 9 with post-ejection pressure of <40 mmHg.
¶ Pressure variation of <15 mmHg from 1% reflux curve for a majority of data points in the buffered range.

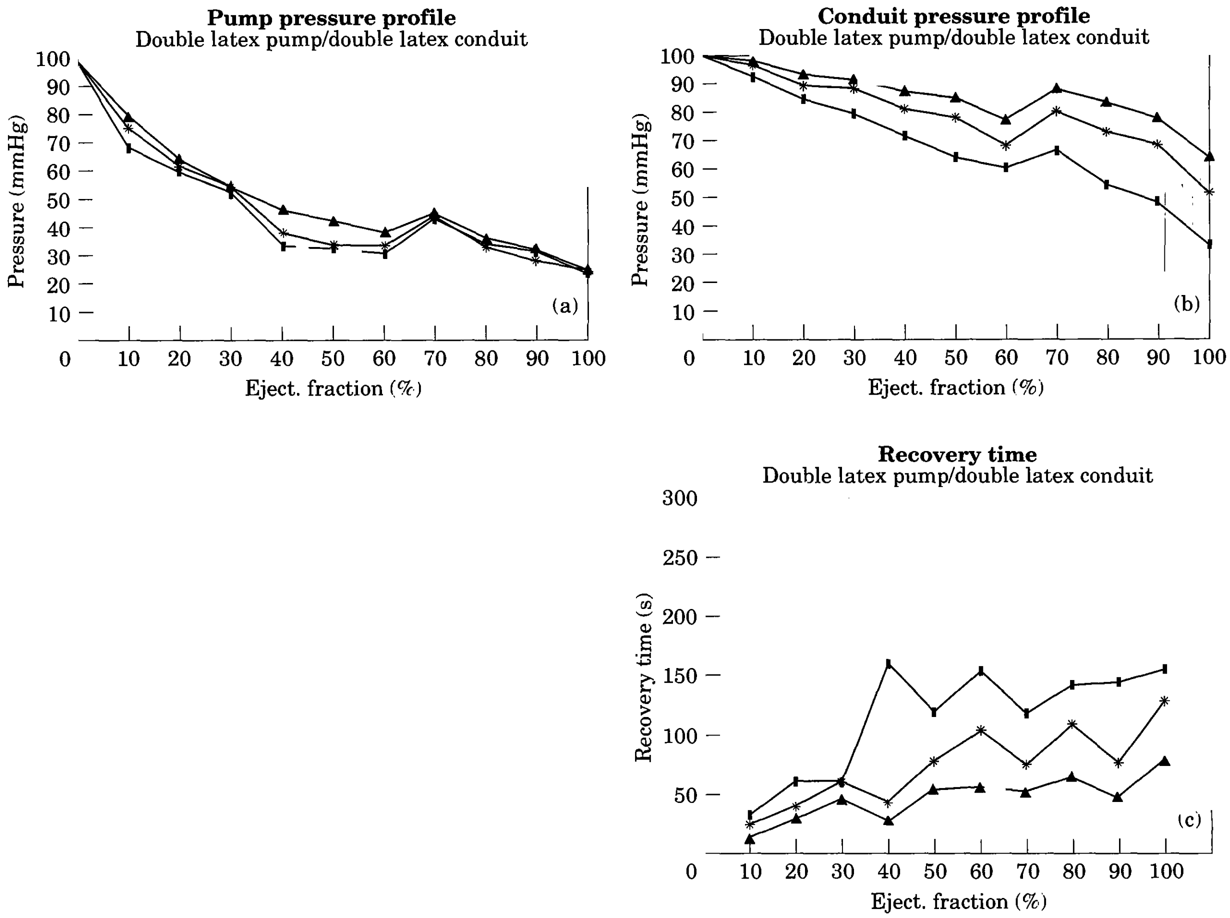

Fig. 3. Pressure profile in the pump (3a), the conduit (3b) and recovery time (3c) for the basic 2-ply latex/2-ply latex model. (▮) 1% valve O; (*) 5% valve O; (▲) 10% valve O.

Changing the compliance of the pump

In this experiment, 2-ply latex was retained as the material for the conduit, but the pump section was changed to either 4-ply latex, PTFE or polyethylene. The pressure profile for the pump, conduit and corresponding conduit recovery times for PTFE pump/2-ply latex conduit combination is shown in Figure 5. Buffering was somewhat better than 2-ply latex/2-ply latex model (Table 1). Ambulatory venous hypertension was present for 10% reflux only. Recovery times (VFT) were not different from the 2-ply latex/2-ply latex model; valve reflux-related VFT differences were significant.

Changing the compliance of conduit only

In this experiment, 2-ply latex was retained as the pump material, but the conduit material was changed to less compliant materials. The pressure profile in the pump and conduit for 2-ply latex pump/PTFE conduit combination with accompanying conduit recovery times is shown (Fig. 6). Buffering significantly superior to the previous two experiments is evident (Table 1) and ambulatory venous hypertension was absent for all reflux settings. This was at the expense of shortened recovery times compared to 2-ply latex/2-ply latex or PTFE/2-ply latex for pump/conduit combinations used in the previous two experiments; ejection fraction or reflux-related differences in recovery time were absent.

Changing the compliance of both pump and conduit

The pressure profile in the pump and conduit and corresponding conduit recovery times for PTFE/PTFE combination are shown (Fig. 7). The pressure profile for the conduit in this experiment was similar to the 2-ply latex/PTFE combination used in the previous experiment, except that the non-linearity of the conduit

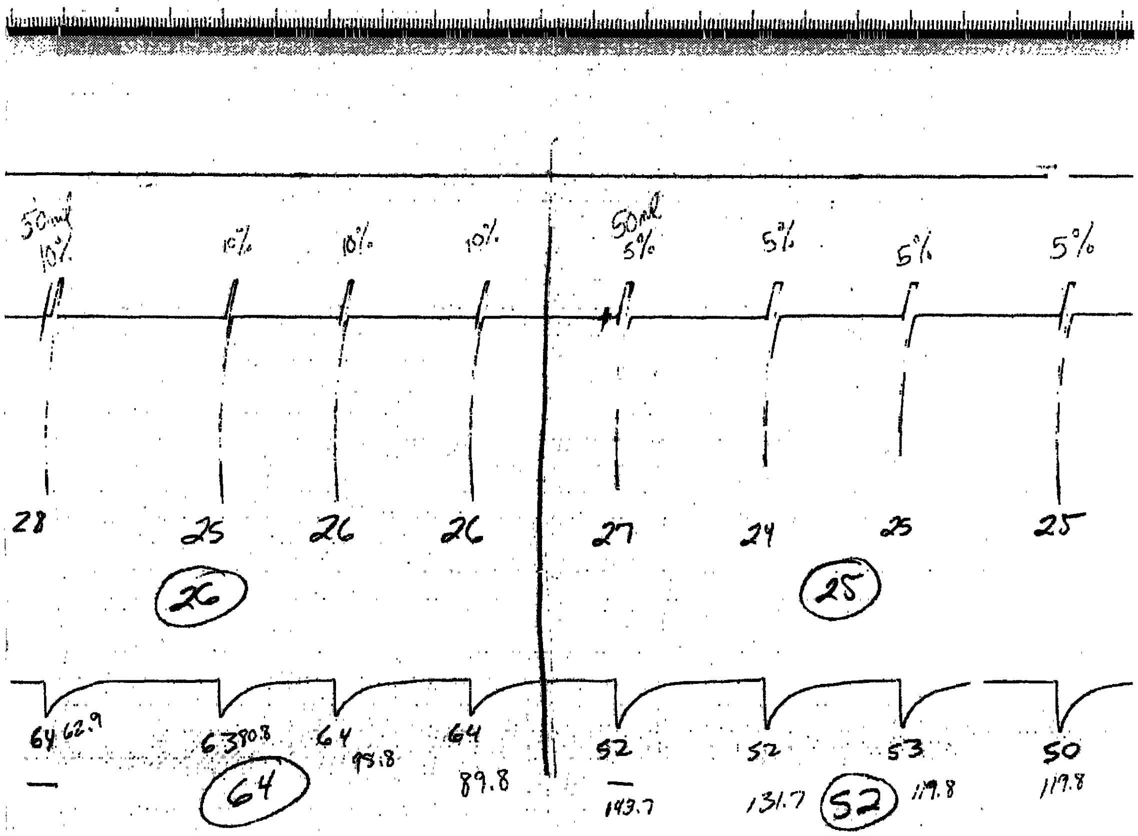

Fig. 4. A representative pressure tracing in the pump (above) and conduit (below) with 2-ply latex/2-ply latex combination. This tracing was obtained at 10% and 5% reflux valve settings. Four ejections each of 50 ml (100% ejection fraction) are shown. Pressure–volume profiles in the previous figure are derived from such data.

pressure profile was even more pronounced and the plateau was reached at 10% ejection of the pump rather than at 30% in the previous experiment. Buffering range was therefore greater (Table 1). Other buffer parameters were similar to the previous experiment. Recovery times, however, were quite short and similar to that obtained in the previous experiment with 2-ply latex pump/PTFE conduit set-up. Recovery-time variations related to ejection fraction or reflux settings were once again absent, as in the previous experiment.

Other pump/conduit combinations

A variety of other combinations for pump and conduit were utilised in this experiment. These combinations included 4-ply latex/4-ply latex, PTFE/4-ply latex, 2-ply latex/polyethylene, polyethylene/2-ply latex, polyethylene/polyethylene, polyethylene/4-ply latex, PTFE/polyethylene, polyethylene/PTFE and thick rubber/2-ply latex for the pump/conduit materials, respectively. The buffering properties and recovery times in the conduit in these sets of experiments appeared to be determined by the conduit material used and the pump material had a lesser effect similar to the experiments using various PTFE and latex combinations. Less compliant materials showed a paradoxical increase in buffering while reducing VFT. These effects were most marked when less compliant materials were used in the conduit position and were much less evident when pump compliance alone was changed.

Reducing the degree of arterial input

In these experiments, 2-ply latex was retained for the conduit but different materials were used for the pump. A smaller arterial input line was used. The pressure profile in the conduit section in this experiment was identical to that obtained in the previous experiments where pump compliance alone was changed. Recovery times, however, were increased by a factor of approximately 3 × for the various ejection

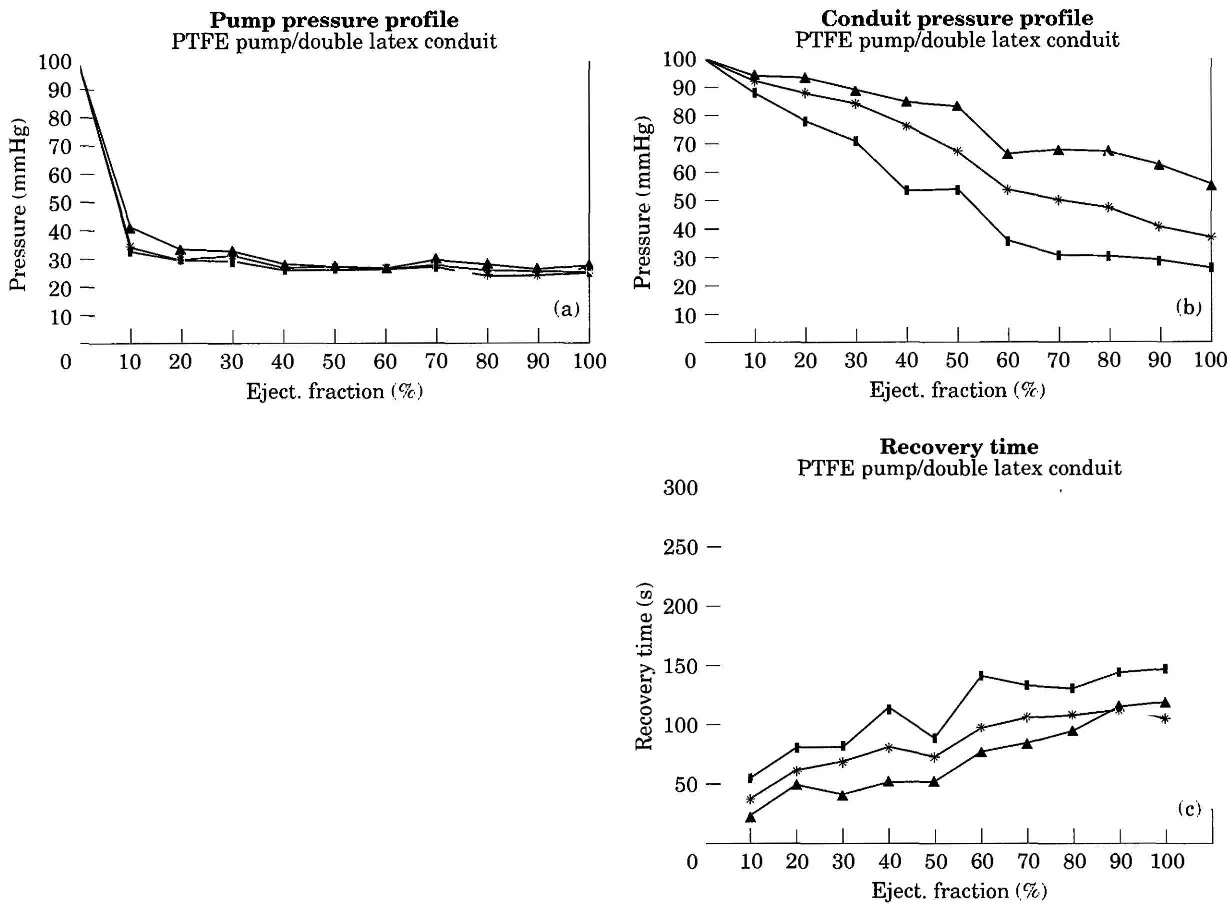

Fig. 5. Pressure profile in the pump (5a), the conduit (5b) and recovery time (5c) in response to volume changes in the pump for PTFE pump/2-ply latex conduit combination. (▮) 1% valve O; (*) 5% valve O; (▲) 10% valve O.

fraction and reflux settings. Relative differences for different ejection fraction and reflux settings were present.

Capacitance changes in pump and conduit

In this experiment the 7/8 inch 2-ply latex tubing of the basic model was exchanged for 1/2 inch 2-ply latex, both for the pump and conduit, which had a capacitance of 32% of the larger tube. Only 2-ply latex was used in this experiment.

Capacitance reduction of the pump tended to increase post-ejection conduit pressure; reduction in conduit capacitance tended to lower post-ejection pressure. In either case, recovery times were reduced and ejection fraction or reflux-related differences in recovery time tended to become minimised. Simultaneous pump and conduit capacitance reduction was no worse than capacitance reduction of the conduit alone with regard to these parameters. In these respects, capacitance reduction was analogous to using poorly compliant material in the conduit.

Differences in pump and conduit pressures and uniflow valve closure

There was a slight time delay between the pump and the conduit in achieving a pressure nadir after ejection of the pump (Fig. 4), the conduit reaching the nadir in pressure a few seconds after the lowest pressure in the pump was recorded. The recovery of pump pressure was more rapid, due to reflux, and occurred earlier than in the conduit. As a result, the uniflow valve between the conduit and the pump, which opened after pump ejection allowing egress of fluid from conduit into the pump, closed at some point after the nadir in the pump was reached, but well before recovery of pressure in the conduit was completed. Recovery of pressure in the conduit after the uniflow valve closed was due solely to arterial input (Fig. 4).

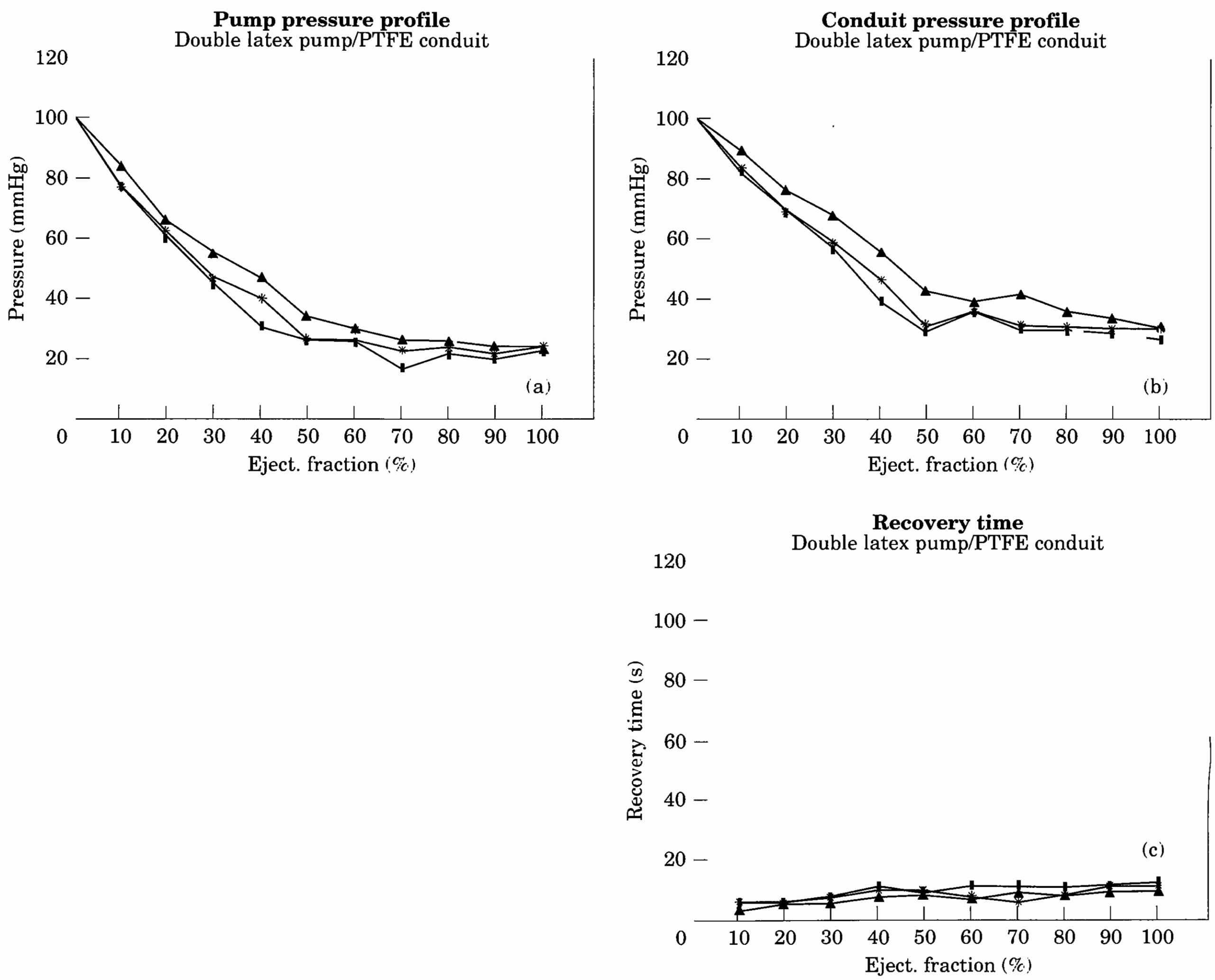

Fig. 6. Pressure profile in the pump (6a), the conduit (6b) and recovery time (6c) in response to volume changes in the pump for 2-ply latex/PTFE combination. (▮) 1% valve O; (*) 5% valve O; (△) 10% valve O.

Discussion

Modelling is an essential part of the investigation of fluid dynamics, as observed behaviour often deviates from the predicted.[4] This is particularly true for collapsible tubes whose bi-modal behaviour has been difficult to resolve in mathematical terms.[5] The previous single-valve model provided insights as to how the non-linear volume pressure relationships, in the bending regimen, can buffer and minimise ejection fraction and reflux-related pressure changes. The current two-tube two-valve model is an evolution over the older one in an effort to better reflect the human calf venous pump. In the context of this model, the superficial system can be considered a part of the conduit leading to the pump section. We have made no provision in this model for a plantar venous pump. The valve above the pump can be set at various degrees of reflux, but the valve between the pump and the conduit is a non-refluxive uniflow valve. Monitoring conduit pressure in this experimental model is analogous to measurement of ambulatory venous pressure through the dorsal foot vein. Variations in the reflux setting of the valve above the pump is analogous to varying degrees of reflux of the popliteal valve. The model consists of approximately 100 ml in total volume between the pump and the conduit, equally divided between them in the steady state. Clinical experience with air plethysmography suggests roughly similar volume distribution in the human calf venous pump.

The current model shows some important differences from the previous single tube model; conduit pressure when compliance was normal (2-ply latex/2-ply latex) was not buffered for ejection fraction and reflux as in the pump. This resulted in ambulatory venous hypertension with most reflux valve settings.

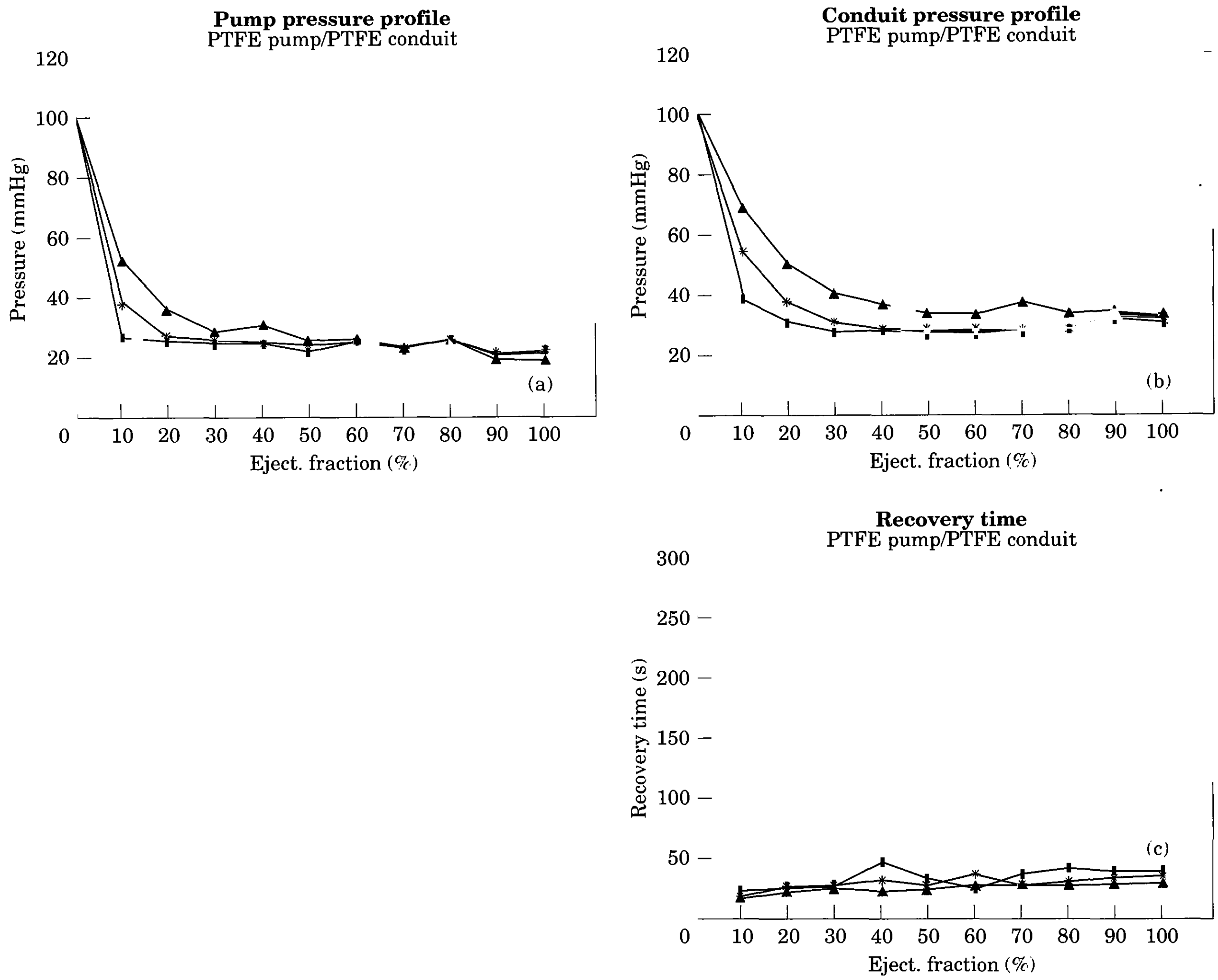

Fig. 7. Pressure profile in the pump (7a), the conduit (7b) and recovery time (7c) in response to volume changes in the pump for PTFE pump/PTFE conduit combination. (▮) 1% valve O; (*) 5% valve O; (▲) 10% valve O.

The change in the compliance or capacitance of the pump had a relatively minor effect on post-ejection conduit pressure, buffering and recovery times. A compliance or capacitance decrease in the conduit, however, had a more dramatic effect, with a marked decrease in recovery time even though the pressure buffering and ambulatory venous pressure paradoxically improved.

Much of the behaviour exhibited by the two-valve model becomes understandable in the light of the following conceptual framework as to how the model works (Fig. 8). If the pump and conduit were to be disconnected from the graduated valve above the pump, the pump walls would be at the transitional area between the bending and stretching regimen, and the walls of the conduit could be slightly stretched under the influence of the hydrostatic column in the pump above it. If the pump and conduit were now reconnected to the apparatus of the graduated valve, the additional column pressure of the long venous column extending from the valve to the venous reservoir would induce additional filling and stretching of the pump and the conduit. This can be referred to as compliance volume. For latex, an additional 30% or so compliance volume will accumulate in the pump and the conduit under the influence of the additional hydrostatic pressure head provided by the venous column above the pump. When the pump is emptied upwards toward the venous reservoir (systole), there is reduction in the pressure in the pump providing a positive gradient for forward flow from the conduit into the pump. The degree and extent of such diastolic inflow into the pump is based on several factors: (1) the magnitude of the pressure gradient, (2) duration of gradient before uniflow valve closes, (3) the compliance volume that must be disgorged from the

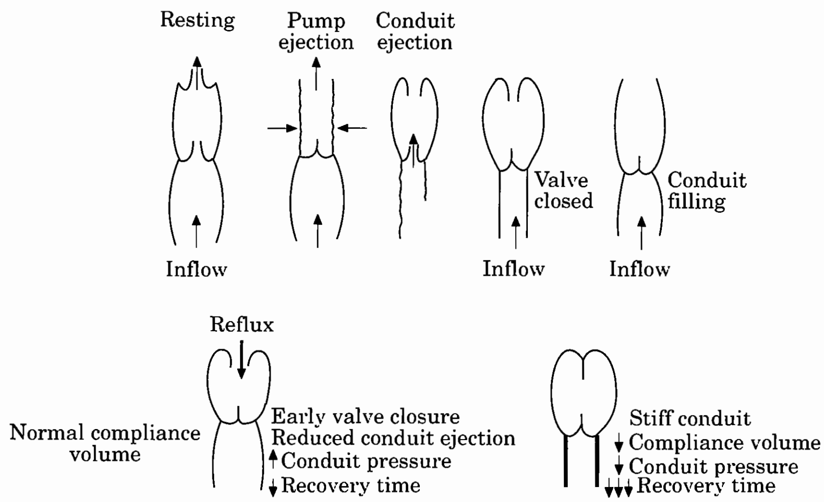

Fig. 8. Schema of interaction between pump and conduit and uniflow valve (see text).

conduit into the pump to dissipate the gradient, and (4) the elastance of the conduit itself that provides the positive head of pressure for forward flow. Although the maximal gradient achieved after pump ejection may not be reduced significantly, any reflux into the pump will largely diminish the duration of the gradient, i.e. time-average gradient will be reduced. The duration of the gradient will also be limited if the capacitance of the pump is diminished. When less compliant materials are used in the pump (Fig. 9), they may actually increase the gradient (due to a highly non-linear pressure–volume curve). This is offset to a certain extent because the increased gradient also increases reflux into the pump from above, thus decreasing the duration of the gradient available for diastolic flow from the conduit. For this reason, compared to the basic 2-ply latex/2-ply latex model, only minor differences in conduit pressure buffering or recovery time were noted when a stiff pump and a normal (latex) conduit were used. The compliance volume of 2-ply latex is large, as much as 40% of the total volume of the tube in the stretched state. If a gradient disappears prematurely because of reflux into the pump, reduced pump ejection or a combination, not all of the latex conduit compliance volume will egress into the pump before the uniflow valve between conduit and pump closes. If there is incomplete egress of compliance volume, the post-ejection pressure in the conduit will be high and the recovery time of the conduit from arterial inflow will be reduced. It is for this reason that, with latex, reflux or reduced ejection fractions at the pump are buffered at the pump, but are poorly buffered at the conduit level, resulting in ambulatory venous hypertension for more reflux valve settings. Such is not the case with poorly compliant conduits, however, and conduit pressures are fully buffered (see below).

A stiff conduit has a smaller compliance volume which is rapidly ejected into the pump after pump systole. Compliance volumes of PTFE and polyethylene conduits were less by at least an order of magnitude than that of latex (approximately 15 to 20 ml for latex; <0.5 ml for PTFE or polyethylene). These very small conduit compliance volumes rapidly egress into the pump with ejection; a nadir of conduit pressure was rapidly achieved, which was little affected by reflux into the pump or reduced pump ejection so long as some pump ejection took place to accommodate the very small conduit compliance volume. As a result, unlike latex, poorly compliant conduits exhibited good buffering for ejection fraction or reflux variations at the pump level. Ambulatory venous hypertension was absent even with 10% reflux. A small compliance volume, however, was responsible for severely limiting recovery time (Figs 6, 9). Adding a stiff pump to a stiff conduit did not further diminish recovery time (Figs 7, 9) which was already shortened owing to the stiff conduit. A stiff conduit has an extremely non-linear volume pressure curve due to an abbreviated stretching regimen and the small compliance volume. For this reason, when a stiff conduit is present, a paradoxically low conduit pressure is obtained after ejection of the pump when the small compliance volume is rapidly discharged into the pump. A stiff pump in addition to a stiff conduit further augments this paradoxical conduit pressure drop by rapidly lowering pump pressure, providing for an even better gradient for the small compliance

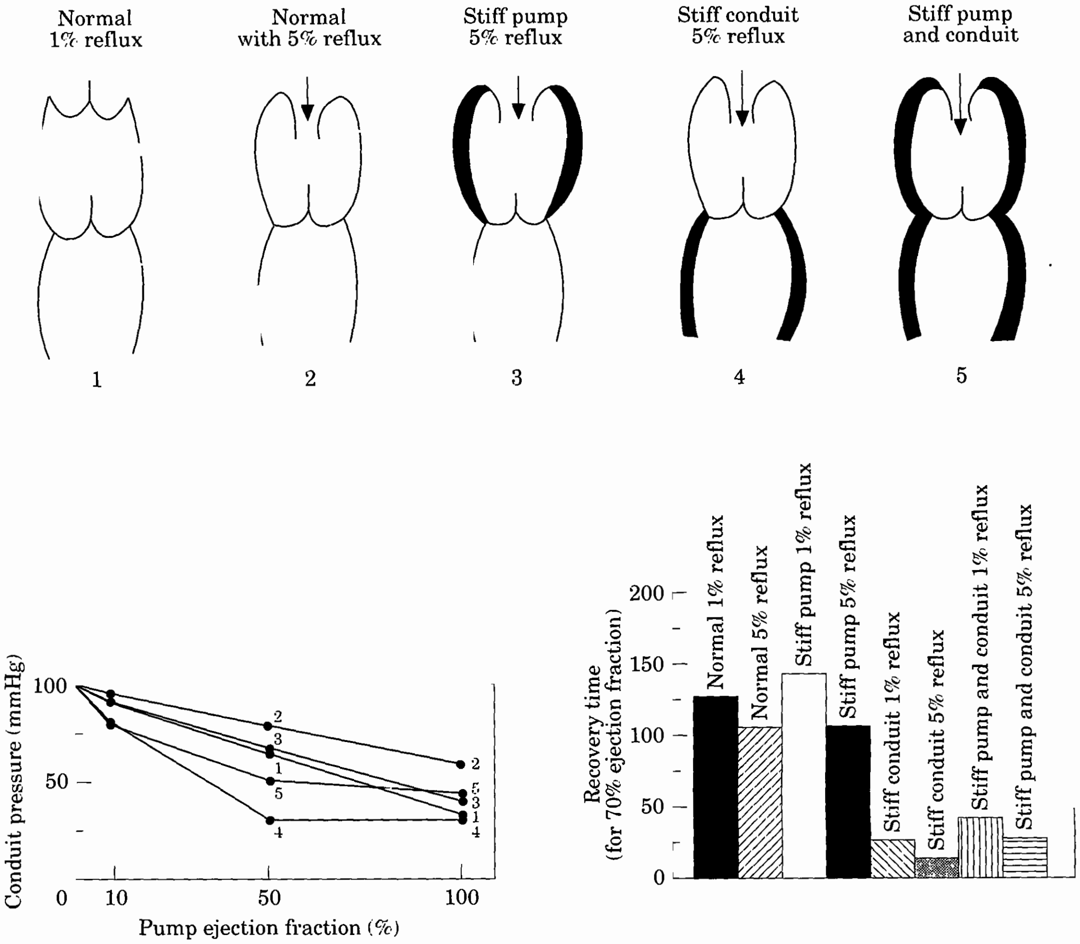

Fig. 9. Comparative conduit pressure profile and recovery times (bottom) (for 70% ejection fraction) for various pump/conduit combinations (top). Stiff pump or conduit = PTFE. A stiff conduit exhibits a paradoxical decrease in conduit pressure with a more profound depression of recovery times compared to a stiff pump. Reflux has a relatively minor effect on recovery time compared to conduit compliance.

volume in the conduit to be discharged into the pump. This paradoxically low conduit pressure, however, occurs at the cost of a severely limited conduit recovery time.

The above findings have implications for post-thrombotic syndrome, in which compliance and capacitance changes at the calf pump or conduit or both occur. Because of the paradoxically low conduit pressure when compliance deteriorates, recovery time appears to be a more reliable indicator of these abnormalities than post-exercise pressure. There is some support for this observation from clinical data.[6] The current model utilises a refluxive valve above the pump but a competent valve between the pump and conduit. While post-thrombotic changes can be segmental similar to the current model, often widespread valve reflux is present. Some types of "primary" valve reflux may also involve reflux throughout the tibiopopliteal venous segments, without any competent valve in the system. A single-tube model with a single refluxive valve as previously described[1,3] may be more representative of these clinical situations than the current model. Even in the single-tube, single-valve model recovery time was profoundly affected by tube compliance and valve reflux, highlighting the importance of recovery time in calf venous pump mechanics.

These experiments also suggest that the flow from the superficial veins into the deep system via perforators is not a passive flow under a favourable gradient, but an active one in which the stretched superficial veins actively decompress (due to the elastance of their walls) into the deep system and release their compliance volume as they deflate into the bending regimen. Thus, the gradient and the emptying of the superficial system into the deep system are governed by the volume/pressure (compliance) relationship prevailing in the superficial (and the deep) system. When superficial varices are present, the veins are dilated and compliance in the bending regimen is increased; but compliance of the varicose veins in the stretching regimen is poor. Compliance volume of varices is likely small, analogous to poorly compliant conduit with equilibration with the deep system occurring after discharge of a very small volume from the varices. Ambulatory venous pressure recovery time is likely to be very short in these cases. Non-elastic compression is not likely to change the haemodynamics, as compliance will not be altered. Highly elastic bandages may, however, transfer their properties to the compressed varices if properly applied.

Biological venous tissue displays a volume–pressure relationship that is less non-linear than experimental substitutes in the study.[7] Stretch relaxation is also present in biological venous tissue. Direct and angioscopic observation of post-thrombotic veins during venous bypass and valve reconstruction surgery indicates that variable compliance changes are present. With mild to moderate changes, the affected veins may collapse (bending regimen) but are unable to stretch (stretching regimen). PTFE used in this experiment has similar characteristics. With more advanced post-thrombotic changes, the affected vein is unable to collapse as well and becomes a rigid tube. A thick rubber tube was utilised in previous experiments[3] to simulate these characteristics. Even though latex and PTFE are acceptable proxies for the normal and post-thrombotic calf venous pump for experimental purposes, they are not identical. The model is not a high-fidelity substitute for the calf venous pump and the purpose is not an effort to create one. Rather, the above hydrodynamic principles exposed by the model help to provide a general insight and perspective in areas that may be important in the function of the human calf venous pump. For example, it has been shown[8] that conduit (tibial) veins in the calf shrink by about 25% to 50% during calf systole. This has been variously interpreted as emptying of the tibial veins by "stretching" and "necking down" during walking movements. Work with our model would suggest a far simpler explanation: the noticed reduction in calibre of the tibial veins was likely due to egress of compliance volume from tibial veins due to tube elastance. Another long-standing concept in ambulatory venous pressure measurement is the belief that dorsal foot vein pressure mirrors deep venous pressure changes during calf exercise.[9] Our experimental model clearly suggests otherwise (Figs 5–7). We have recently recorded simultaneous dorsal foot venous pressure and tibial venous pressure in the clinical setting (Fig. 10); a divergence between the two pressures was apparent in many patients.

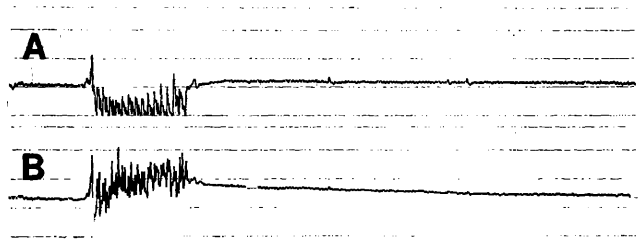

Fig. 10. Simultaneous dorsal foot venous pressure (A) and tibial venous pressure (B) in a patient with leg pain and swelling. Divergent pressure curves were recorded. Note differences in post-exercise pressure and recovery times.

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