

Bioengineering Studies of Periodic External Compression as Prophylaxis Against Deep Vein Thrombosis—Part I: Numerical Studies

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This paper presents the results of a numerical study of the technique of periodic external compression for the prevention of deep vein thrombosis. In the model the veins of the lower leg are portrayed as a continuous system rather than as discrete elements as in previous models. Consequently, we are able to explore the detailed effects of different modes of compression including (i) uniform compression, the simultaneous application of uniform pressure over the entire lower leg, (ii) graded compression, the application of nonuniform pressure, maximum at the ankle and minimum at the knee, and (iii) wavelike compression, a wave of compression proceeding from the ankle toward the knee. These numerical results indicate that the effectiveness of uniform compression is severely compromised by the formation of a flow-limiting throat at the proximal end of the compression cuff that reduces both the rate at which blood is discharged from the lower leg and the total blood volume removed. Both of these detrimental effects can be avoided by the use of either wavelike or graded compression. Both alternate methods are shown to produce more uniform augmentation of volume flow rate, flow velocity, and shear stress, throughout the entire lower leg. In the companion paper, Part II [18] (see following article), these same compression modes are tested using a simple hydraulic model consisting of a single latex tube inside a foam cylinder as a highly simplified representation of a human leg.

Introduction

Methods Used to Prevent Deep Vein Thrombosis (DVT). DVT and pulmonary embolism continue to be two of the more common surgical complications in spite of concerted efforts to develop and implement more effective measures of prevention. Of the considerable variety of prophylactic procedures that are currently in use, most can be classified as either "physical" or "chemical" in their mode of operation. Physical methods include the use of elastic stockings, periodic external compression, electrical stimulation, and early ambulation (Cotton, et al., [6]); they are generally thought to act by producing a more vigorous flow of blood through those parts of circulation most prone to thrombosis, primarily within the lower extremity. Chemical methods include the use of low-dose heparin, warfarin, aspirin, and dextran (Kakkar, [10]); they generally act to inhibit or interfere with one of the steps in the complex process of thrombus growth by altering blood chemistry.

Some methods although moderately successful, are not altogether free of complicating factors. Most anticoagulants,

for example, increase the risk of hemorrhage and, for that reason, are unacceptable in certain clinical situations.

This paper reports on one of a related series of studies on the method of Periodic External Compression (PEC) in which the patient's calf is compressed about once each minute using an inflatable boot or cuff. The effectiveness of PEC has been demonstrated by numerous clinical trials on a wide variety of patient groups. These studies have found, for example, that the incidence of DVT can be reduced from 21 to 8.2 percent in general surgical patients (Clark, et al. [4]) and from 19 to 1.5 percent in neurosurgical patients (Turpie [24]).

Previous Studies. The existing literature contains no comprehensive evaluations of the various modes of compression or of the several compression parameters. Roberts, et al. [20] first presented data showing how peak volume flow rate, as measured in the femoral vein, varies with a single parameter: the rate of application of uniform external pressure. His findings indicate that rapid cuff inflation provides the optimum in flow pulsatility and peak volume flow rate, at least at the point of measurement. He also suggested that a rest period of about 45 s is needed to complete refilling of the deep veins in conjunction with a 10-s

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compression phase; a conclusion also reached by Raines, et al. [19] using venography.

Rohr [21] conducted similar experiments but with only very slow inflations (~ 0.3 kPa/s as compared to 1.3 kPa/s for Roberts). He also concluded that a rapid compression provided the greatest benefit.

Zicot, et al. [26] using a single mercury-in-rubber strain gage positioned at midcalf, made measurements of change in limb cross-sectional area produced by *steady-state* external compression. He noted the anomalous behavior that, above some critical level of external pressure (described as the "collapse pressure") of about 3 kPa the apparent venous volume either continued to decrease, levelled off, or *increased*.

A series of animal experiments was conducted by Ah-see, et al. [1] using two inflation devices with vastly different compression cycles. One inflated and deflated very slowly over a period of 2 min; the other inflated in 3 s and deflated in 20 s, at 3 cycles per min. Rapid compression was most effective for introducing pulsatility to the flow and for producing high peak flow rates, but both methods were found to be comparable in their ability to delay occlusion of implanted steel tubes by thrombin clots.

Thirsk, et al. [23], like Zicot and co-workers, measured changes in *static* venous volume using mercury-in-silastic strain gages, but with six gages positioned along the lower leg, thereby providing information on the relative collapse of different parts of the system in the same individual. All three types of behavior noted by Zicot's group concerning the nature of changes in blood volume at pressures above about 3 kPa could be achieved in one subject at different locations along the leg. It was concluded that the observed variability in apparent compliance could be the result of a physiologic response leading to a change in arteriolar resistance, in combination with the formation of a constrictive throat in the vessel at the proximal edge of the compression zone.

Theoretical studies of external compression by Rohr and by Zicot and associates were based on very simple lumped parameter models. Since neither model went beyond treating the veins of the lower limb as a single lumped volume, neither could distinguish between distal and proximal locations. Therefore, neither could address the central problem of how different *modes* of pressure application (e.g., uniform, wavelike, or nonuniform pressure distributions) compare in terms of those hemodynamic parameters that might be expected to provide a level of protection against DVT.

The literature states in rather vague terms that the primary objective of PEC is to inhibit thrombus growth by reducing venous stasis. In practice, the measure used for selecting cycle parameters has often been flow pulsatility at the femoral vein, a parameter which we show later to be highly unreliable.

Commerically available units vary considerably in their design. They use inflation cuffs which cover either the entire lower leg and foot, the lower leg and thigh, or the lower leg alone; they apply a uniform pressure or apply pressure in a wavelike fashion by means of a segmented cuff; and they inflate more less rapidly. Most units utilize a cycle divided between about 10 s of compression and 50 s of refilling; however, other devices with a much slower rate of inflation are also available.

Motivation for the Present Investigation. Despite the encouraging results from numerous clinical trials, external compression in its present form may not be providing the greatest possible level of protection. Recent studies by Shapiro [22] and Kamm, et al. [13] have provided new and somewhat surprising insights into the detailed fluid dynamics of collapse by external compression of a fluid-filled compliant tube. These insights, and the findings presented in this paper, suggest that *how* pressure is applied may be nearly as im-

portant as whether or not external compression is used at all. Our main objective in the present study is to analyze current methods, and some methods which have not yet been tried, in an attempt to determine which procedure may be most effective.

The Criteria for Preventing DVT. The exact physiologic mechanisms by which PEC prevents thrombosis are not known. However, the several hemodynamic and mechanical factors listed in the foregoing and discussed further in the section "Results and Discussion," are conjectured to limit formation of thrombi or lead to their dissolution:

- High flow pulsatility
- Increased flow velocity
- Increased shear stresses
- Clearance of valve sinuses
- Mechanical stressing of the vessel walls
- Complete periodic emptying of the vessels

These parameters are many, but they are generally not contradictory. Fortunately they are all subsumed in the dictum that the entire length of the veins should be emptied as *fully* and as *rapidly* as possible.

Overview of the Series of Investigations. An ultimate objective is to gain a clear understanding of the hemodynamic events associated with external limb compression. This understanding, when viewed in conjunction with the aforementioned criteria for the prevention of DVT, provides a rational basis for selection of an optimal compression mode. Of the four related studies aimed at gaining this understanding, characterized in the forthcoming, (i) and (ii) are the present companion studies, while (iii) and (iv) are to be published elsewhere.

(i) **Theoretical Model Studies.** In this paper (Part I) the flows induced by external compression are studied in detail using computer simulations. The computer model allows one to explore a wide variety of compression methods and parameter values with greater ease than would be possible by experiment. In addition, the results obtained, in that they describe the detailed flow behavior at each location, provide considerable insight into the general mode of vessel collapse with the various compression procedures.

(ii) **Hardware Experiments on a Simple Model of the Human Leg.** In the companion paper (Olson, et al. [18]), hereinafter identified as Part II, experiments were performed on a model consisting of a single compliant tube imbedded within a foam rubber cylinder. This simple representation of a single vein in the lower leg was useful both for confirming the collapse behavior predicted by the numerical model, and for the development and assessment of various methods of pressure application to be used in physiologic experiments.

(iii) **Noninvasive Measurements on Human Volunteers.** (Hollars, et al. [8]). Using a doppler velocimeter to measure flow velocities in the popliteal vein and mercury-in-silastic strain-gage loops to monitor limb cross-sectional area, a series of compression studies encompassing a broad range of the relevant parameters was conducted. Although the detail of information was much coarser than in either of the two prior studies, comparisons could still be made to determine to what extent the simulations provide a realistic picture of the actual hemodynamic phenomena.

(iv) **Experiments Using Radio-Nuclide Imaging Methods** (Kamm, et al. [12]). Results of the three foregoing studies allowed us to define broadly the optimal parameters of each mode of compression. Further and much more detailed information was gained using radio-nuclide imaging techniques in which the subject's red blood cells were labeled using technetium-99m. By detection of the radioactive emissions in sequential half-second "time windows," accumulated over

many pressure cycles, changes in compartmental blood volume could be observed during the course of compression. Although some overlap exists between these measurements and the totally noninvasive results, these data are much less subject to error and provide a clearer and much more detailed picture of the events occurring at different positions within the calf.

The Model and Simulation Methods

The Different Modes of External Compression. The modes of compression tested in this study fall into three general categories based on the spatial and temporal distributions of external pressure (see Fig. 1):

- 1 *Uniform compression* (Fig. 1(a)) is the application of a single pressure to the entire region of compression simultaneously at all points.
- 2 *Graded compression* (Fig. 1(b)) is the simultaneous application of a nonuniform pressure, falling from a maximum at the ankle to a minimum at the proximal edge of the cuff.
- 3 *Wavelike compression* (Fig. 1(c)) is a progressive application of uniform pressure which starts at the ankle and proceeds proximally in a wavelike fashion.

A fourth possible method, not considered here, is a combination of methods 2 and 3: a wavelike application of a nonuniform pressure distribution.

Unsteady Flow in a Compliant Tube. The objective of external compression, as defined in general fluid dynamic terms, is to empty the vessels most rapidly and most completely. Associated with rapid collapse is a high volume flow rate which, in combination with substantial collapse, simultaneously produces high flow velocity and high shear stress.

In previous studies, we have analysed the collapse of a single, compliant tube subject to a sudden, uniform external pressure (Kamm, et al. [13]). Our findings are summarized in the schematic representation of vessel collapse in Fig. 2. Initially the external pressure is zero and a small steady flow passes through the vessel from left to right (Fig. 2(a)). As pressure is applied, collapse first occurs at the proximal edge of the compression zone where an internal pressure gradient accelerates the fluid (Fig. 2(b)). The vessel collapses at the proximal (knee) end of the vein producing a constrictive throat which tends to limit the subsequent rate of fluid discharge, either by virtue of the large frictional pressure drop in the collapsed vessel or by the mechanism of wave-speed limitation. As time progresses, the region of collapse works its way toward the ankle more and more slowly (Fig. 2(c)). Due to the flow entering at the distal end of the vessel, the final configuration is one in which the area decreases from a maximum at the ankle to a minimum at the knee as in Fig. 2(d).

Although some features of the collapse process depicted in Fig. 2 have been exaggerated for the purpose of presentation, the system of veins in the lower leg are expected to behave in a qualitatively similar way. Thus, the most common mode of pressurization, uniform compression, may be severely compromised, particularly in the deep veins of the mid- and lower-calf, due to the formation of a flow-limiting throat.

The Theoretical Model. The theoretical model used in this study is based upon the one-dimensional equation of motion, conservation of mass, and a static pressure-area law for the tube. The vessel or system or vessels is treated as a continuous system, the distributed compliance of which is a highly nonlinear function of transmural pressure.

Numerical solutions are obtained from the resulting set of partial differential equations using a procedure combining the method of characteristics and a finite difference scheme. The

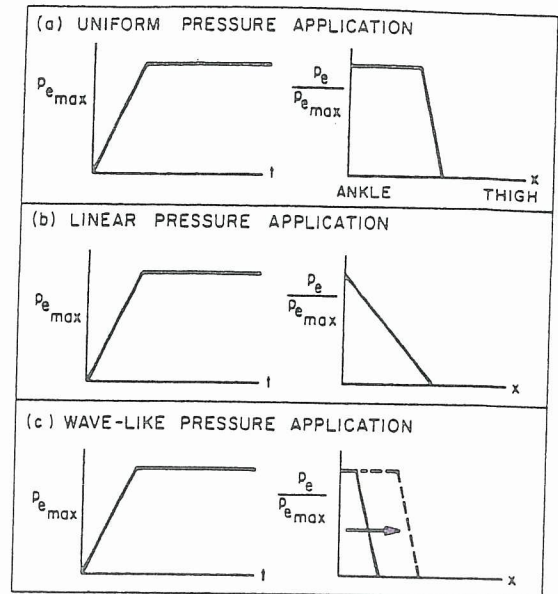


Fig. 1 A schematic representation of the three modes of external compression. On the left, the spatial maximum in external pressure ($p_{e_{max}}$) is plotted against time. The graphs on the right show the spatial distributions of pressure.

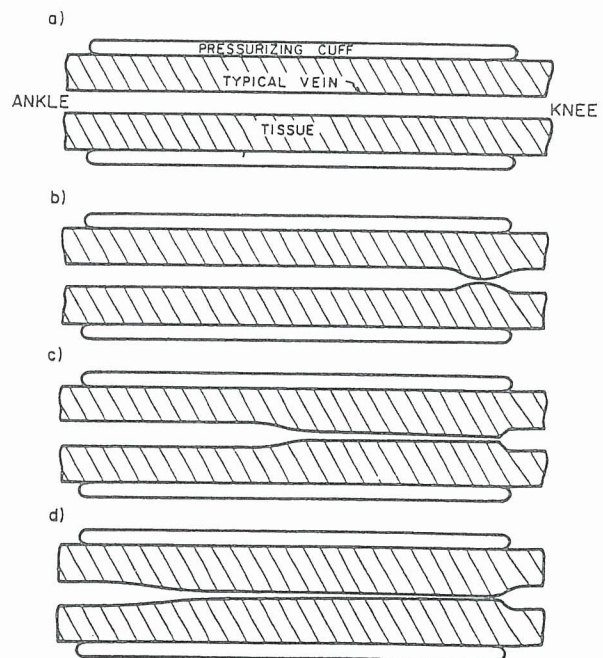


Fig. 2 Geometric changes in a vein during the collapse process, for the pressure cycle of Fig. 1(a) - (a) before the external pressure is applied; (b) shortly after the external pressure is applied; (c), (d) at successively later times during the phase of applied external pressure

validity of the theoretical solutions has been confirmed through a comprehensive series of experiments in which the externally applied pressure, pressure rise time, upstream and downstream conditions, and fluid viscosity were individually varied. In each instance the theoretical model was able to predict, to reasonable accuracy, the transient flows produced by external compression. For details, see Kamm, et al. [13].

Provisions in the theory accommodate most of the complexities associated with modeling the venous system:

- (a) axial variation of cross-sectional area and tube stiffness of the unstressed vessel,
- (b) variations in both time and space of external pressure,
- (c) distributed inflow from tributaries, and

Table 1 Listing of the numerical simulations

Mode of compression	Rise time (s)	$P_{e_{max}}$ (kPa)	Wave speed ^(a) (m/s)	Fig. no. ^(c)
Uniform ^(b)	1/3	4.0	--	5
Uniform	1	4.0	--	
Uniform	1.6	4.0	--	
Uniform	3	4.0	--	
Uniform	5	4.0	--	
Uniform	1	2.7	--	8
Uniform	1	6.7	--	
Uniform	1	9.4	--	
Graded	1	4.0-0 ^(d)	--	
Graded	1/3	4.0-0	--	
Graded ^(b)	1/3	6.7-0	--	
Wavelike	0	4.0	0.2	
Wavelike ^(b)	0	4.0	0.5	

(a) Wavelike compression only
 (b) Tests selected for comparison of "optimal" cycles
 (c) Typical detailed results for each mode
 (d) Denotes the range of maximum pressure from the ankle to knee

division by K_p , a parameter which represents the vessel stiffness or, equivalently, its ability to resist bending deformation (Flaherty, et al. [7]). The axial variations in vessel stiffness can be determined from the distribution $c_o(\xi)$ (given in Fig. 3(a)) using the universal pressure-area law of Fig. 4 and the wave speed relationship $\rho c_o^2 = K_p (P/d\alpha)_{\alpha=1}$.

Values for $c_o(\xi)$ can be determined either from direct measurement of wave speed or computed from pressure-area relationships obtained in vivo. The former suggests values in the range of 1 to 4 m/s for the intact canine abdominal vena cava (Anliker, et al. [2]), values which are consistent with predictions based on the pressure-diameter data of Morris and co-workers [17] for a canine femoral vein in its natural environment. Ludbrook [15] found that muscular veins, in general, have a very small wall thickness-to-radius ratio as compared to other deep veins of the calf and should, therefore, be more compliant. Taking these data into account, a range of wave speed values from 1 to 2.5 m/s was used in the present study (Fig. 3(a)) with a spatial distribution which reflects the greater compliance of the muscular veins and the general tendency toward greater wave speeds in the smaller, more peripheral vessels.

Distribution of External Pressure. Pressure applied to the surface of the leg is transmitted to the vessels beneath via the intervening muscular tissue. Thus, a step change in pressure on the surface of the leg produces a more gradual transition inside the tissue at the location of the deep veins. For our model, we assume that pressure varies over a distance roughly equal to one limb diameter yielding the pressure distribution shown in Fig. 3(b). Support for this approximation can be found in Part II.

Distribution of Fluid Influx from Tributaries. Fluid enters the deep veins of the model in one of two ways; either from the upstream capillary bed, or by way of tributary inflow at points proximal to the knee. Based on measurements made by Roberts and co-workers [20], the mean flow rate through the popliteal vein is approximately 3000 mm³/s. Choosing a mean arterial pressure of 13.3 kPa, the upstream capillary resistance must then equal 4.1×10^9 /kg/m⁴/s. In the femoral and iliac veins, tributary flow increases the resting flow rate from 3000 mm³/s to roughly 7500 mm³/s at the groin. Because the location and relative size of the tributaries may vary, and because influx to the femoral vein exerts only an indirect and minor influence on flow in the more distal calf veins, we assume a constant tributary inflow per unit length, of magnitude 10.8 mm²/s.

The Proximal Boundary Condition. Blood from the calf discharges through the iliac vein into the inferior vena cava. The abdominal and thoracic vena cavae are modeled as two rigid vessels arranged in series and separated by a capacitance

chamber. The more proximal of the two rigid tubes empties into a constant pressure reservoir simulating the right atrium. As a unit, these components account for the inductance, resistance, and capacitance of the system from the iliac veins to the right heart. The values used for length and cross-sectional area of the rigid vessels are: distal to the capacitance, the length is 0.2 m and the area, 1.5×10^2 mm²; proximal to the capacitance, the length is 0.05 m and the area, 1.5×10^2 mm². A value of 1.1×10^{-6} m³/Nt was chosen for the intervening capacitance based on a pressure-volume curve for the human vena cava (Burton [3]). Pressure in the discharge reservoir is 1.0 kPa; a value selected to produce the appropriate pressure in the calf veins under normal flow conditions. The influence of varying each of these parameters separately was assessed in a roughly equivalent experimental system (Kamm [11]), and was found to have little effect on the flows and pressures in the compressed region.

The Numerical Simulations. Calculations were performed to simulate the compression phase of the external compression cycle: that period extending from the onset of compression to the time at which the vessels reach a steady collapsed configuration and the flow velocities become nearly constant with time. No calculations were performed for the refilling phase.

The simulations were grouped into the three categories previously described: 1) uniform, 2) graded and 3) wavelike compression. In each series, the relevant cycle parameters were varied over a range deemed sufficient to illustrate the significance of each and to establish trends.

(i) **Uniform Compression.** The pressure is assumed to rise linearly in time until reaching maximum pressure, then is held constant. Two series of tests were conducted: 1) rise time was varied maintaining a constant maximum pressure; and 2) maximum pressure was varied while rise time was held constant. Note that in the latter series, although the time required to attain maximum pressure is constant, the rate of compression is not.

(ii) **Graded Pressure Application.** In these tests, the time course of the pressure is linear as in (i). The applied pressure, however, is maximum at the "ankle" and falls linearly to zero at the "knee." In this series, both the maximum applied pressure and the rate of pressurization were varied.

(iii) **Wavelike Pressure Application.** Here, the external pressure is applied instantaneously whereas the distribution of pressure is a function of time. The pressure front moves at a constant speed beginning at the ankle and proceeding toward the knee. When the compression wave reaches the knee, the calf is uniformly compressed and remains so for the duration of the cycle. The effect of pressure front velocity is examined.

Table 1 lists each of the varied parameters for the three modes of compression tested.

Results and Discussion

The numerical results show how the following parameters relevant to thrombus formation vary with position ξ and time: (i) the volume flow rate, Q ; (ii) the area ratio, A/A_0 ; (iii) the mean velocity $u = Q/A$; and (iv) a measure of wall shear stress, expressed by a shear rate index, u/R , where R is a characteristic radial dimension [$R = (A/\pi)^{1/2}$].

Uniform Compression (Fig. 5) With this, the simplest and most commonly used compression method, collapse occurs first at the proximal edge of the cuff and then slowly progresses in the upstream direction as the vessels gradually collapse. Qualitatively, this is the same behavior, described in the preceding section, [13] that occurs experimentally in a single compliant tube (Kamm, et al. [13]). The details of the collapse process differ, however. Due to the relatively slow rate of cuff inflation, the occlusive throat does not form until a significant fraction of the vessel network has emptied. Flow rates during this time are low, due not to the presence a constrictive throat, but rather to the low driving pressure. Once the narrow throat develops, emptying occurs very slowly in spite of the much greater upstream pressure. The throat extends roughly from the fully-pressurized region to the unpressurized region and is therefore somewhat less localized in these simulations than in our single tube experiments (Kamm, et al. [13]). Also, the process of becoming choked was less abrupt in the venous model, primarily because the tissue-enveloped vein has a greater wave speed than the latex tube. Thus choking occurs only after viscous flow resistance has already begun to decrease the rate of flow acceleration. Indeed, in some of the simulations employing low external pressures, gradually applied, wave speed limitation never occurred. These effects tend to moderate, but not eliminate, the importance of the flow-limiting throat.

Details of the collapse process are shown in the four graphs of Fig. 5. As demonstrated by the area traces of Fig. 5(b), the vessels are only partially collapsed at the end of the compression period due to the viscous pressure drop in the vessels beneath the proximal edge of the cuff. This limits vessel collapse upstream since the rise in pressure distally is associated with a progressive area increase. This same phenomenon was previously reported in measurements of venous compliance obtained by strain-gage plethysmography (Thirsk, et al. [23]).

The formation of a constrictive throat at the proximal edge of the cuff leads to the behavior exhibited in the other three graphs of Fig. 5. Since $\partial A/\partial t$ is generally negative below the knee, mass conservation dictates that the flow rate is maximum at the knee and falls gradually toward the ankle. Velocity and shear rate, however, both drop precipitously just a short distance upstream of a narrow throat due to the abrupt area change. Thus, while shear rates and velocities are greatly elevated at the knee, the remaining vessels experience a relatively small effect. These observations substantiate the need, when evaluating a particular mode of pressurization, for more detailed information than mere physiologic measurements of popliteal vein flow rate or velocity can provide.

Uniform Compression—The Effect of Rise Time. When pressure is applied at various rates, the general character of collapse remains unchanged; collapse begins at the knee and proceeds distally. In general, a reduction in rise time causes peak flow rate, velocity, and shear rate each to increase at all positions (Fig. 6).

These results, when expressed in terms of pulsatility ($100 \times Q_{\max}/Q_{\min}$ percent), yield values as high as 1300 percent in

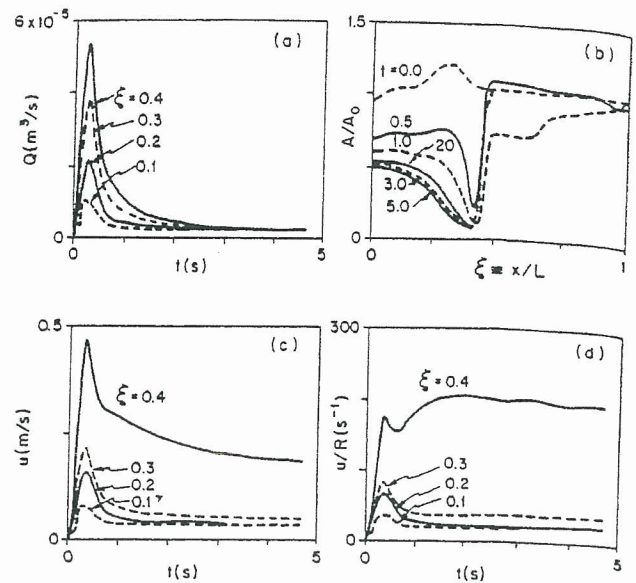


Fig. 5 Results for a uniform compression of 4 kPa with a 1/3-s rise time—(a) flow rate versus time at four positions; (b) normalized cross-sectional area as a function of ξ at six times (times labeled in seconds); (c) flow velocity versus time at four positions; (d) shear rate versus time at four positions

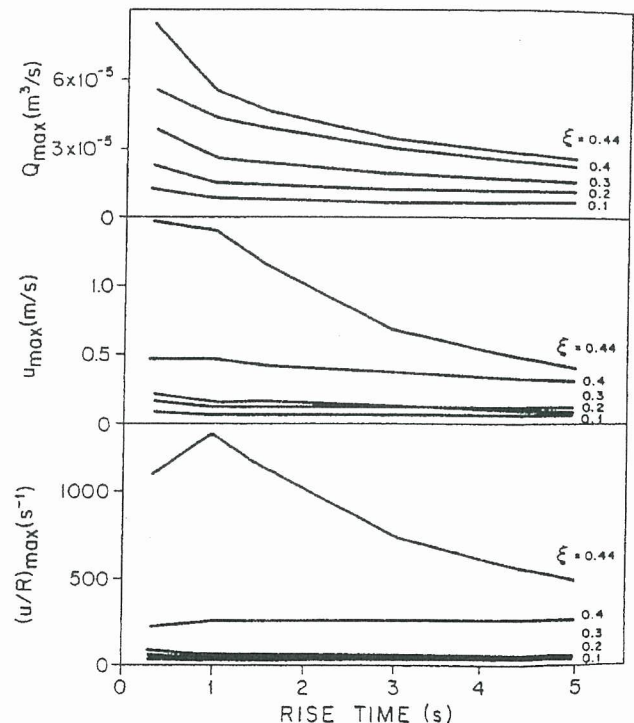


Fig. 6 The effect of rise time in uniform compression on peak values of flow rate, velocity, and shear rate at five different positions within the calf

the femoral vein just above the knee, at a compression rate of about 4 kPa/s. This rate is considerably higher than the range of values tested in the past (1.3 kPa/s, Roberts, et al. [20]), or used in the commercial units now available (typically less than 1.0 kPa/s).

Uniform Compression—The Effect of Maximum Pressure (Fig. 7). As the maximum applied pressure is increased flow enhancement increases, although only slight augmentation is achieved at peak pressures above about 4 kPa. This is con-

sistent with the finding that little additional blood volume can be expelled from the calf for pressures above about 4 kPa (Thirsk, et al. [23]).

The influence of applied pressure may, however, be even less than that suggested by these graphs due to the change in compression rate which accompanies a rise in maximum pressure. Examining the results of Figs. 6 and 7 we find that, although the increase in flow rate is largely due to the change in compression rate, higher pressures do result in some enhancement in velocity and shear rate above that anticipated due to the compression rate influence alone.

The practical import of these data is that the applied pressures must be sufficiently large to cause venous collapse but, because of the trade off between greater flow resistance and larger driving pressures, the gains are very small above about 4 kPa. Thus, in uniform compression, an apparent optimum is reached with rapid pressurization to about 4 or 5 kPa for a supine patient. A compression time of 5 s seems sufficient to reach a new steady state, although this time may vary from patient to patient and may depend upon whether the patient is supine or semi-erect.

The main disadvantage of uniform compression lies in the concentration of high velocities and shears in a relatively narrow region close to the edge of the cuff. Thrombi often originate at more distal locations (Cotton, et al. [5]), particularly in the muscular veins where it would appear that the compression effects are minimal by comparison to conditions at the area throat. An important objective in considering other compression methods was to distribute more evenly these salutary effects.

Graded Pressure Application. The results of Fig. 8 demonstrate the substantial changes in flow rate, velocity, and shear rate index achieved using graded compression. Comparing the curves in Figs. 5 and 8 it can be seen that, although peak values at the knee differ only slightly, each parameter is significantly increased at other locations: by factors of about two and three for velocity and shear, respectively. These improvements are achieved using a graded pressure which, averaged over the calf, is less than the uniform pressure of Fig. 5.

The area profiles in Fig. 8(b) help to explain these differences. By applying maximum pressure at the ankle, collapse occurs there first and proceeds toward the knee. Since the blood need not pass through a constrictive throat, it is expelled more rapidly—and more completely. In essence, the fluid is “milked” from the vessels as the wave of collapse proceeds proximally, thus flow limitation is avoided and the vessels empty in about two seconds as opposed to four seconds in uniform compression. Even the steady-state values of velocity and shear are higher, except at the knee, due to the more uniform collapse achieved with graded compression.

Table 2 shows how the maximum values of flow rate, velocity and shear rate at each location are influenced by changes in pressure rise time and maximum applied pressure. In general, as with uniform compression, rapid application of the greatest pressure provides the most substantial augmentation.

Wavelike Pressure Application. The results produced by wavelike compression are shown in Fig. 9. As the area profiles illustrate, collapse proceeds from ankle toward the knee—following the wave of pressurization—and substantial collapse is produced at every point in the system as the compression front passes. Since, at its final position, the pressure distribution is identical to that of uniform compression, the area profiles eventually coincide. The wavelike mode is, however, clearly more effective in producing near-complete collapse in all vessels.

The point of maximum collapse generally follows the motion of the wave front, except at the highest speeds in

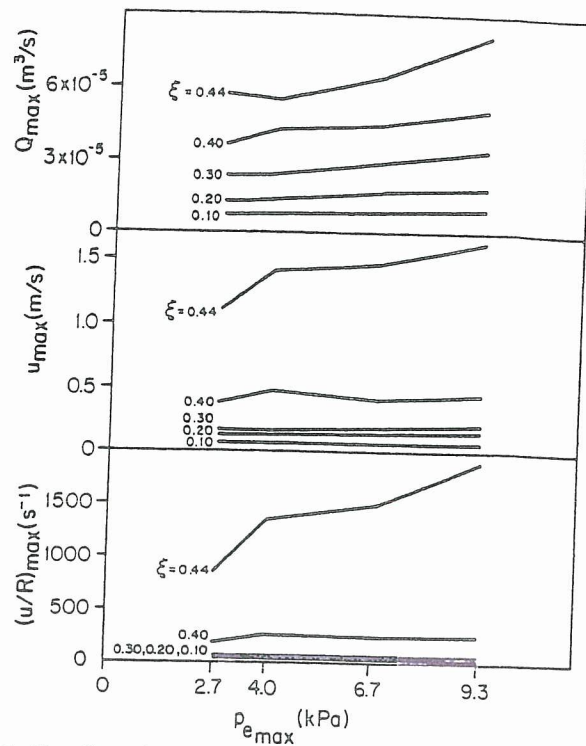


Fig. 7 The effect of maximum applied pressure on peak values of flow rate, velocity, and shear rate at five different positions within the calf

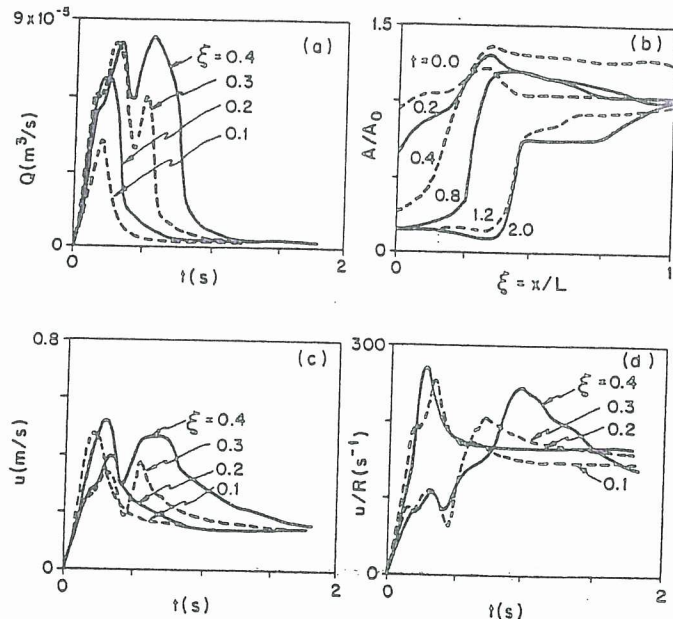


Fig. 8 Results for a graded compression; maximum pressure at the ankle = 6.7 kPa, rise time = 1/3 s—(a) flow rate versus time at four positions; (b) normalized cross-sectional area versus ξ at six times (times labeled in seconds); (c) flow velocity versus time at four positions; (d) shear rate versus time at four positions

which case the compression wave begins to overtake the uncollapsed region. The limiting case of increasing compression front speed is an instantaneous uniform pressure application—similar to the first numerical simulations (Table 1) but with rise time equal to zero. In this extreme, the flow behavior reverts to that of uniform compression with proximal collapse and flow limitation. This limit was not observed, however, because the numerical solutions became unstable beyond a pressure front speed of 0.5 m/s. Intuitively, we might expect the limit to occur when the front speed reaches the local wave speed—approximately 0.6 to 2.0 m/s.

Table 2 Flow parameters for graded compression

(The values of Q , u and u/R are the respective maxima, during compression, at the designated locations, ξ)

Rise time(s)	$p_{e_{max}}$ (kPa)	Parameter	$\xi=0.1$	$\xi=0.2$	$\xi=0.3$	$\xi=0.4$	$\xi=0.44$
1	4.0-0 ^(b)	$Q(\text{mm}^3/\text{s} \times 10^{-3})$	18	29	42	50	51
		$u(\text{m/s})$	0.18	0.25	0.23	0.29	0.39
		$u/R(\text{s}^{-1})$	121	139	126	88	109
1/3	4.0-0	Q	32	49	47	58	61
		u	0.33	0.36	0.26	0.34	0.47
1/3 ^(a)	6.7-0	u/R	175	150	129	118	136
		Q	43	69	82	84	87
		u	0.47	0.52	0.38	0.47	0.64
		u/R	272	256	208	246	219

^(a) Selected for comparison of "optimal" cycles

^(b) Denotes the range of maximum pressure from the ankle to knee

Table 3 Flow parameters for wavelike compression

(The values of Q , u , and u/R are the respective maxima, during compression, at the designated locations, ξ)

Wave speed	$p_{e_{max}}$ (kPa)	Parameter	$\xi=0.1$	$\xi=0.2$	$\xi=0.3$	$\xi=0.4$	$\xi=0.44$
0.2	4.0	$Q(\text{mm}^3/\text{s} \times 10^{-3})$	29	38	48	51	50
		$u(\text{m/s})$	0.22	0.25	0.23	0.32	0.37
		$u/R(\text{s}^{-1})$	379	594	222	189	173
0.5 ^(a)	4.0	Q	75	80	120	149	151
		u	0.55	0.48	0.61	0.80	1.07
		u/R	425	299	391	416	533

^(a) Selected for comparison of "optimal" cycles

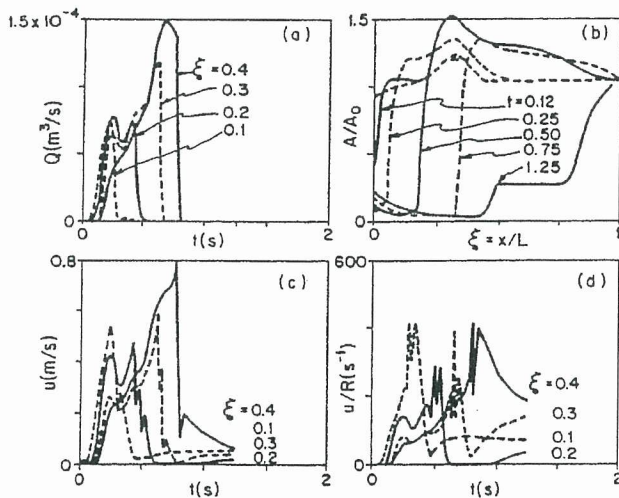


Fig. 9 Results for a wavelike compression; maximum pressure = 4 kPa, wave propagation speed = 0.5 m/s - (a) flow rate versus time at four positions; (b) normalized cross-sectional area versus ξ at six times (times labeled in seconds); (c) flow velocity versus time at four positions; (d) shear rate versus time at four positions

Wavelike compression produces relatively uniform augmentation of flow rate, velocity, and shear stress throughout the entire calf. Thus, the benefits of either wavelike or graded compression are felt at locations deep within the calf where they are likely to be most needed. We emphasize again that if the various methods were evaluated solely on the basis of flow rate measurements made above the calf, these important differences would not be evident.

Table 3 compares the maximum values of flow rate, velocity and shear rate for compression front propagation speeds of 0.2 and 0.5 m/s. Greater enhancement was obtained with the greater speed.

In practice, of course, it may be difficult to produce a true wavelike compression. As discussed in the companion paper (Part II), pressure distributions produced using segmented cuffs differ from the idealized compression wave of the numerical simulation.

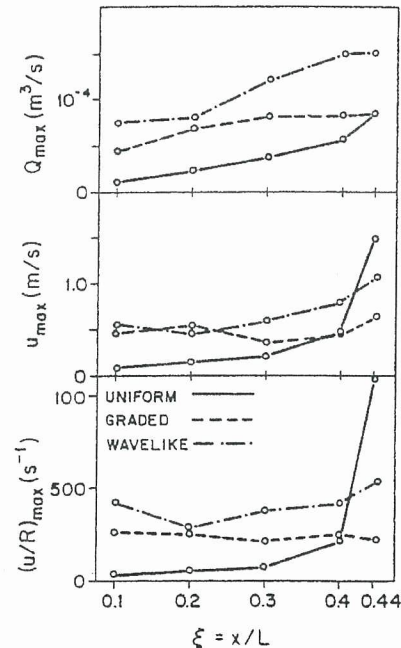


Fig. 10 Peak values of flow rate, velocity, and shear rate at five calf locations for the "optimal" tests of uniform, graded, and wavelike compression indicated in Table 1

Comparison Summary. To compare the three modes of compression, an "optimal" cycle is selected for each mode as identified in Table 1. Since the number of simulations performed was relatively small, these selected cycles are not necessarily optimal with respect to their respective parameters. But judging from the general similarity that exists between all simulations of a particular mode, comparisons of a qualitative nature are certainly valid. Not that the three selected cycles are comparable both in terms of the spatially averaged pressure, and the time scale for full pressurization.

In Fig. 10 the peak values of Q , u , and u/R are plotted against distance of each of these "optimal" cycles. Although uniform compression fares well at $x/L = 0.44$ (the location of

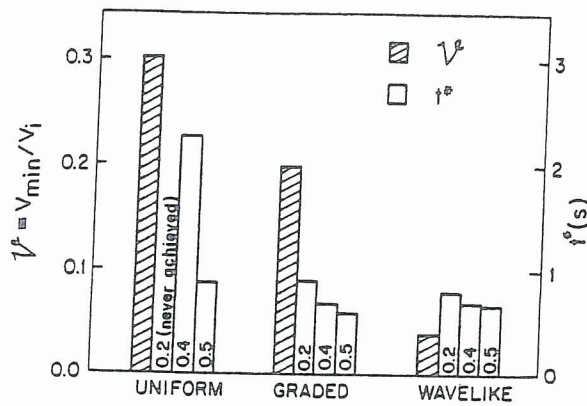


Fig. 11 Overall comparison of the "optimal" cycles for each compression mode (see Table 1) in terms of the ratio V_{min}/V_i and time t^* required to reach values of $V(t)/V_i$ of 0.5, 0.4 and 0.2 where $V(t)$ is the blood volume contained in the calf at time t

the flow limiting throat), the graded and wavelike modes are clearly superior over the rest of the calf. In appearance, the most striking difference between uniform compression on one hand, and graded and wavelike compressions on the other, lies in the uniformity of augmentation in the latter. Wavelike compression appears to have some advantage over either of the other two modes in all categories.

Since the broad hemodynamic objectives of external compression are to eliminate the greatest possible amount of venous blood from the calf as rapidly as possible, we show in Fig. 11 two additional measures of comparison: (i) the ratio of the minimum blood volume to initial blood volume in the region below the knee (V_{min}/V_i), and (ii) the times (t^*) required to reach values of $V(t)/V_i$ of 0.5, 0.4 and 0.2, where $V(t)$ is the blood volume contained below the knee at time t .

Wavelike compression is most effective in emptying the veins, followed by graded and then uniform compression. Uniform compression expels only about 70 percent of the blood volume contained in the large veins, a figure which is relatively independent of the rate of compression or pressure magnitude. We attribute this to the area minimum at the knee which produces a high frictional pressure drop locally and thus prevents the remaining vessels from emptying more completely.

The differences between cycles are even more striking when viewed in terms of the time required to produce a certain amount of vessel emptying. Graded and wavelike compressions are about equally effective as judged by this comparison but both are clearly superior to uniform compression.

In general, graded and wavelike compressions provide greater and more uniform, velocity and shear augmentation than uniform compression. (In all instances, the greatest benefits are achieved when pressures are applied rapidly or, for wavelike compression, when the pressurization wave moves most rapidly.) Although there appears to be some advantage in using the greatest tolerable pressure, the benefits of increasing mean calf pressure above about 4 kPa are relatively small.

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