

Hemodynamic alterations in venous blood flow produced by external pneumatic compression

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Venous stasis associated with prolonged bed rest can enhance the risk of deep venous thrombosis (DVT). Pneumatic compression of the lower extremities can reduce this risk by preventing venous stasis. When selecting a method of leg compression for their patients, physicians must choose between two distinctly different types of compression devices. One device applies pressure with a single-chambered sleeve to the below knee region while the other applies pressure in a sequential gradient fashion from the ankle to the thigh. The current prospective study was designed to evaluate the ability of two such devices to increase blood flow in the profunda femoral vein. Venous blood flow velocity, compression time, and vein diameter were measured in nine normal experimental subjects using an Accuson duplex-Doppler before, during and after leg compression. Compression with the single-chambered device produced a significant rise in venous blood flow velocity; however, this could not be maintained and our results indicate a higher average velocity was achieved with the sequential gradient device. The sequential gradient device also moved a greater volume of blood and achieved a higher average blood flow rate. The time between deflation of the sleeve and return of a phasic respiratory signal was greater after compression with the sequential gradient device. These results suggest that sequential gradient compression produces the type of hemodynamic alterations needed to reduce the risk of DVT by achieving a sustained increase in venous blood flow and more completely emptying of the veins in the leg.

KEY WORDS: Thrombophlebitis, deep - Thromboembolism - Pneumatic compression - Venous blood flow - Duplex-Doppler.

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It has been reported that death from pulmonary emboli is the most common preventable cause of death in our hospitals today.¹ The NIH Consensus Development Conference suggested that deep venous thrombosis occurs in 300,000 to 600,000 patients each year.² In this group, mortality occurs in as many as 50,000 individuals each year as a result of pulmonary emboli.² In addition to human suffering, the cost of treating individuals who have developed a thromboembolic complication adds a significant monetary stress on our medical community. Previous cost analysis studies have indicated that the use of preventive measures for patients who are at risk can greatly decrease the incidence of thromboembolic disease and the cost to our health care facilities.³

The available techniques that can be used to reduce the risk of deep venous thrombosis include both pharmacological and mechanical approaches. Pharmacological approaches include a wide variety of drugs. Unfortunately, most, if not all, of the pharmacological agents produce side effects that are unacceptable in many patient groups.⁴ Mechanical methods have been shown to reduce the risk of deep venous thrombosis without producing side effects. These mechanical methods include both pneumatic and elastic compression of the lower extremities.

The need to provide safe and effective DVT prophylaxis for hospital patients has resulted in a search for new methods of accomplishing this goal.

External pneumatic compression provides an attractive alternative when used alone or in combination with pharmacological agents.

Most investigators agree that the beneficial effects produced by external pneumatic compression can be attributed to the prevention of blood stasis in the deep veins of the lower extremities.⁵ Various devices to accomplish this goal have been introduced during the last ten years. Single chambered devices typically apply pressure to the below knee region of the leg in a cyclical fashion. Sequential gradient pneumatic sleeves also apply pressure in a cyclical fashion; however, the pressure is applied first to the ankle and then to the more proximal regions of the leg extending up to the thigh.^{6,7} During the compression cycle, the pressure applied to the ankle is greater than the pressure applied to the more proximal regions of the leg. The current study was undertaken to evaluate the hemodynamic alterations in venous blood flow produced by these two different types of external pneumatic compression devices.

Materials and methods

Four male and 5 female subjects who reported to be in good health and were free of any detectable arterial or venous disease were included in the study. The subjects represented a wide variation of physiques, ranging from 0.29 to 0.48 kg of body weight per cm of height. All subjects were used in the evaluation of both compression devices. After signing an approved informed agreement, the subjects were asked to loose fitting gym shorts and lie in a supine position on a semi-soft exam table. Compression sleeves from one of the units were placed around the subject's legs. The right leg was then rotated outward to expose the inner surface of the thigh. Ultrasound gel was applied to the mid-thigh region over the profunda femoral vein. A licensed sonographer identified the profunda femoral vein in cross section using an Acuson duplex-Doppler (model #128) equipped with a 5 MHz probe. After the vessel was viewed in cross section for one full compression cycle, the probe was turned 90 degrees to display a longitudinal view of the vein. The Doppler component of the probe was then employed to measure blood flow velocity in the vein before, during, and after three consecutive cycles.

The length of the compression period and decompression period is similar for both devices. The compression occurs over a relatively short portion of the

cycle followed by a longer decompression period before the cycle repeats. The initiation of the compression phase was identified using an external timing system so that the initial blood flow alterations would not go unrealized. Immediately before the onset of compression, the subjects were asked to stop breathing at mid-inspiration. This measure was taken to avoid any artifact that would occur from the influence of respiration on venous flow. Immediately upon deflation of the sleeve, the subject was asked to breathe normally throughout the remainder of the cycle until the next compression segment of the cycle was repeated.

After one unit had been evaluated through three complete cycles, the compression sleeves were removed from the subject's legs and those of the other unit were applied. The order in which the devices were evaluated on each subject was alternated to reduce the risk of experimental bias.

The units were adjusted so that the maximum pressure applied was 50 mmHg. The single chambered unit (Venodyne model EPS - 310, Lyne-Nicholson, Inc., Needham Heights, Massachusetts, USA) applies this pressure to the area of the leg extending from the ankle to the upper calf. The sequential compression unit (SCO model 5320, Kendall Healthcare Products, Co., Mansfield, Massachusetts, USA) applies the 50 mmHg only to the ankle and less pressure to the more proximal regions of the leg.

The visual and auditory signals received by the Acuson duplex-Doppler were recorded on VHS video tape for later analysis. Evaluation of the data stored on the video tapes was accomplished as time permitted. Individual segments of each compression cycle were reentered into the Acuson's computer. Each segment of the compression cycle was selected from the tape and displayed on the Acuson monitor. The segments were identified as illustrated in Figure 1. The sequential gradient compression device produced three separate increases in blood flow velocity. These correspond to compression of the ankle, ankle + calf, and ankle + calf + thigh. Demarcation between these segments was chosen by the technician and represents the lowest discernable point between the flow peaks. The first arrow located below the sequential gradient tracing shows the onset of compression induced blood flow. The next two arrows indicate the onset of flow augmentation produced by compression of the ankle + calf and the ankle + calf + thigh, respectively. The last arrow demarcates the point between

the final major flow augmentation and the lower flow that lasted until decompression of the sleeve. The single chamber device produced one increase in blood flow velocity that corresponds to compression of the ankle and calf simultaneously. The first arrow below this tracing corresponds to the initial blood flow increase while the second arrow identifies the point between the major flow augmentation and the lower flow rate that continues until decompression of the sleeve.

Changes in blood flow velocity and elapsed time were determined from the Doppler tracing. The cross-sectional area of the vein was determined for each subject. These data were recorded manually and also on film using a Matrix 1000 which converts a video image into a photographic image. Measurements were taken from the three compression cycles applied with each sleeve to each of the nine subjects. These data were then transferred to an IBM PC equipped with LOTUS 123. Using this spreadsheet, the data from the three compressions recorded for each device was averaged and recorded. Calculations were then performed on the data collected from both devices to determine the time averaged blood flow velocity, the volume of blood moved by each compression, and the average blood flow rate produced by the compression sleeve. The equations shown below were used to perform these calculations. The equation given for the time averaged velocity was used with the data collected from the sequential compression device. A similar equation was used for the single chambered device; however, it only had to consider one major flow peak and therefore had less factors.

Time Averaged Velocity:

$$TAV_{AVG} = \frac{[(TAV_A \times AT_A) + (TAV_C \times AT_C) + (TAV_T \times AT_T)]}{AT_A + AT_C + AT_T}$$

where:

TAV_{AVG} = Time averaged velocity across the entire compression cycle (m/sec); TAV_{A-r} = Time averaged velocity for each segment of the compression cycle (m/sec); AT_{A-r} = Time elapsed during each segment of the compression cycle (sec).

Blood flow volume:

$$Q = \text{Vein Area} \times TAV \times AT$$

where-

Q = Volume of Blood Moved (ml); Vein Area = Cross sectional area of the vein measured (mm^2); TAV = Time Averaged Ve-

locity of blood in vein (m/sec); AT = Time Elapsed during measurement period (sec).

Blood flow rate:

$$Q = Q \times 60/AT$$

where:

Q = Blood Flow Rate (ml/min); Q = Volume of Blood Moved (ml); AT = Time Elapsed During Compression Period (sec).

Statistical analysis of the data was performed using analysis of variance when the evaluation included multiple comparisons of similar data (e.g. velocity of blood flow during each segment of the compression cycle). The two-tailed paired Student's "t"-test was used to compare differences when only one value existed for each compression device (e.g. total volume of blood moved by the compression cycle). Significance was accepted at $p < 0.05$.

Results

The single chambered unit applies pressure in a uniform fashion to the below knee area of the leg. This uniform compression produced a single increase in blood flow velocity. The sequential gradient sleeve applies pressure first to the ankle, then to the ankle and calf, and finally to the entire leg (ankle, calf and thigh). The sequential compression produced three separate peaks in blood flow velocity. Figure 1 shows reconstructed tracings for both compression devices on the same subject. Although variations occurred between subjects, this basic pattern was observed in all tracings. The time and velocity scales are shown in the graph. The time scale has been reduced and the velocity scale expanded to more clearly demonstrate the changes in blood flow produced by the compression.

The peak blood flow velocity obtained during the various phases of the compression cycle is shown for both the sequential gradient compression device and the single chambered compression device. The results of this comparison are shown in Figure 2. The greatest velocity was achieved by compression of the ankle + calf region with the single chambered device and this was found to be statistically greater than that obtained by the sequential compression device ($p < 0.05$).

The average velocity of blood flow produced by the compression cycle of both devices is shown in

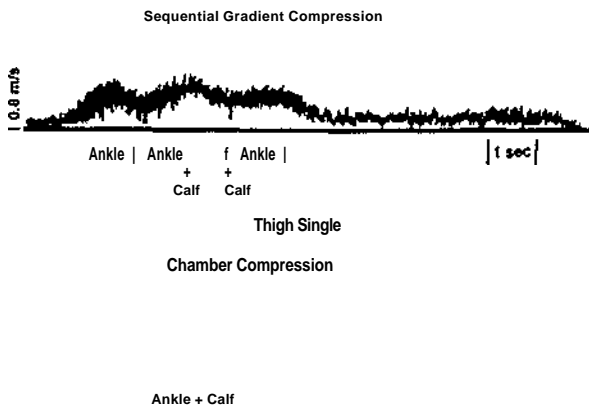


Fig. 1.—This figure illustrates the venous blood flow velocity tracings taken with the Acuson duplex-Doppler in the profunda femoral vein following compression with the sequential gradient device and the single-chambered device. Three distinctive peaks in blood flow velocity are produced by the sequential gradient device (ankle, ankle + calf, and ankle, calf + thigh). One major peak in blood flow velocity is produced by compression with the single chambered devices (ankle + calf). The time scale has been reduced and the velocity scale expanded to more clearly demonstrate the changes produced by the compression cycles.

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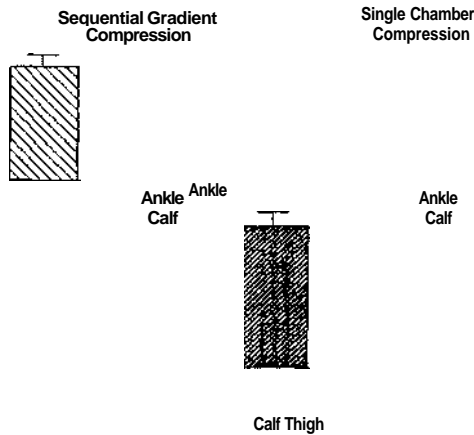


Fig. 2.—The peak velocity obtained with both devices is shown (mean±SEM). The peak velocity obtained with the single chambered device is statistically greater than that obtained with any segment of the sequential gradient device.

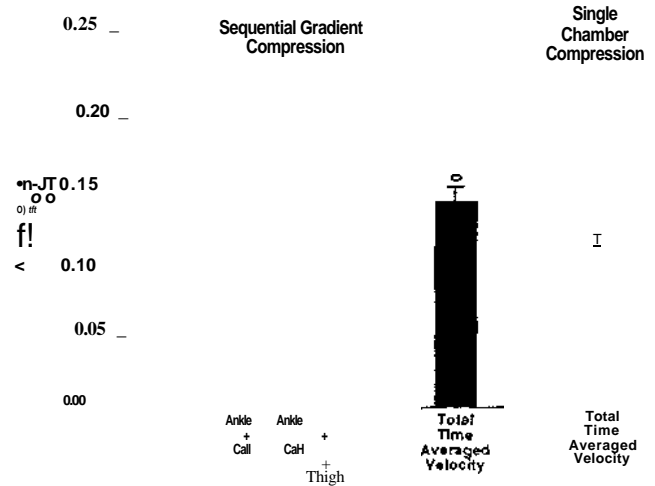


Fig. 3.—The time averaged velocity maintained throughout each of the three segments of the sequential compression cycle is shown. The total time averaged velocity produced by the sequential gradient device was calculated and compared to the total time averaged velocity produced by the single chambered device. Statistical analysis demonstrated that the total time averaged velocity produced by the sequential gradient device is significantly greater than produced by the single chambered device.

Figure 3. The average velocity produced by each segment of the three chambers of the sequential gradient sleeve is shown. The total time averaged velocity is shown for the sequential gradient device and for the single chamber unit. Analysis of the total time averaged velocity data with the two-tailed paired Student's "t"-test demonstrated that the sequential gradient compression technique was able to maintain a greater average velocity than the single chambered compression device ($p < 0.05$).

The average blood flow rate produced by the two compression devices can be seen in Figure 4. Analysis of the data with the two-tailed paired Student's "t"-test demonstrated that the average blood flow rate was statistically greater for the sequential gradient compression unit than the single chambered compression device ($p < 0.05$).

Figure 5 illustrates the volume of venous blood moved by the compression cycle of the sequential gradient device and the single chambered device. Analysis of the data with the two-tailed paired Student's "t"-test demonstrated that the sequential gradient compression cycle moved significantly more

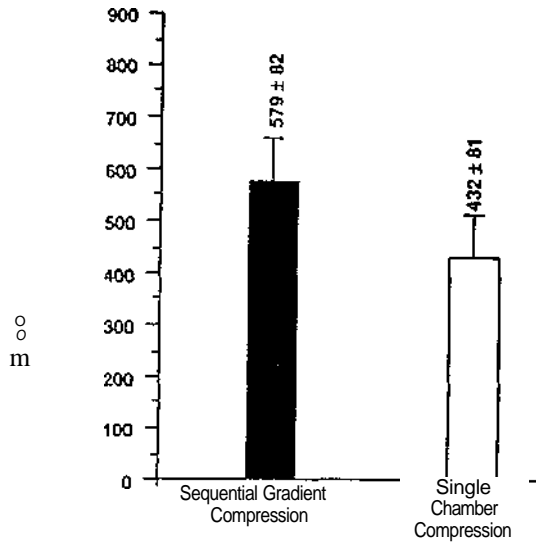


Fig. 4.—The average blood flow rate produced by the sequential gradient device is statistically greater than that produced by the single chambered device. The data are shown as the mean±SEM.

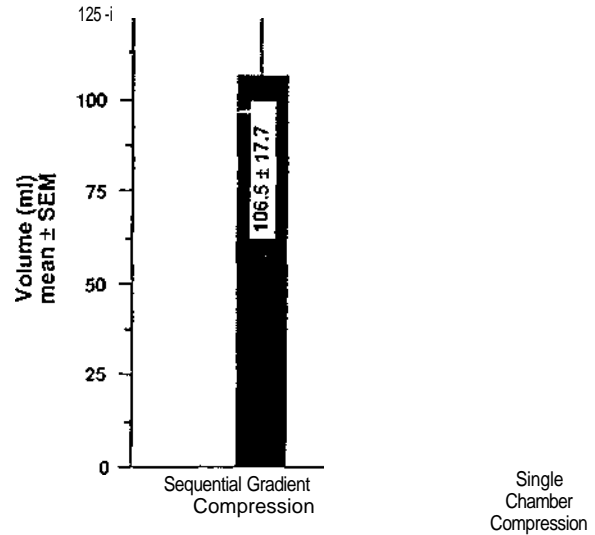


Fig. 5.—The volume of blood moved by the compression cycles is shown (mean±SEM). Statistical analysis demonstrated that the volume of blood moved by the sequential gradient device is greater than that moved by the single chambered device.

blood per compression than did the single chambered unit ($p < 0.05$).

Normally, venous blood flow in the lower extremities occurs in a phasic pattern. This phasic pattern is induced by a person's respiratory rhythm. In most individuals, inspiration is associated with a decrease in lower limb blood flow velocity. Conversely, during expiration, venous blood flow velocity in the lower extremities is elevated. In the current study, each subject was asked to hold his or her breath at a mid-inspiratory level beginning immediately before the compression and continuing during inflation of the sleeve. Immediately upon deflation of the sleeve, the subject was asked to start breathing normally. The time between deflation of the compression sleeve and the first detectable venous flow signal was measured. Additionally, the time required for the return of a normal phasic venous flow pattern was also measured. The results of this comparison can be seen in Figure 6. Analysis of the data with the two-tailed paired Student's "t"-test indicated that the time required for return of the first detectable venous flow as well as the normal flow pattern was greater with the sequential gradient unit than for the single chambered compression device ($p < 0.05$).

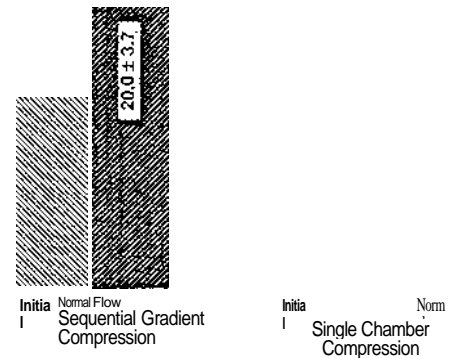


Fig. 6.—The time that elapsed between the end of the compression cycle and the return of any venous flow and the return of normal venous flow is shown (mean ± SEM). Statistical analysis found that the time of both measurements is greater with the sequential gradient device.

Discussion

Over 100 years ago Virchow introduced the concept of blood coagulation we now know as Virchow's Triad. Despite many advances in our understanding of the blood coagulation process, the basic principle described by Virchow remains unchanged. In practical application, Virchow's Triad tells us that two of the three contributing factors must be present before a clot will form. These include: (1) Blood stasis. (2) Vascular damage. (3) Increased clotting factors in the blood. After surgery, the clots that need to form at the incision site do so because of vascular damage and increased clotting factors. Unfortunately, many of these same patients require extended bed rest following operation. During the bed rest, sluggish blood flow in the deep veins of the legs coupled with the increased clotting factors in the blood can result in the formation of deep vein thrombi.⁸ Prevention of the DVT's can be accomplished by removing the hypercoagulable state using pharmacological methods; however, this also removes one of the two factors responsible for the formation of clots at the incision site. Successful use of the pharmacological approach in these patients requires careful monitoring of the patient to prevent unwanted side effects which may manifest themselves as bruising or prolonged wound bleeding.⁹ As our awareness of these problems increased, the need to develop safe and effective methods of prophylaxis became evident. An understanding of Virchow's Triad led clinicians to propose methods that would reduce venous stasis, thus reducing the risk of DVT formation without increasing the risk of bleeding complications. Prevention of venous stasis has been encouraged using leg elevation,¹⁰ early ambulation,¹¹ elastic compression,¹² and external pneumatic compression techniques.¹³ Each of these methods used alone or in combination with pharmacological agents appears to be effective.^{14, 15} External pneumatic compression appears to offer several distinct advantages over the other mechanical methods of preventing venous stasis. First, it can be applied intraoperatively and in the patient incapable of ambulation to reduce venous stasis. Second, it is reported to be free of side effects. Third, external pneumatic compression is considered to be cost effective when compared to the use of no prophylaxis or to the use of pharmacological means of DVT prophylaxis.

Several methods of applying external pneumatic compression have been introduced during the last two decades. The most notable alterations in the approach include the rate at which the compression is applied and the area of the leg to be compressed. The current study was designed to compare two of the most widely used compression techniques. The single chambered device consists of a plastic sleeve which is placed around the lower leg. During the compression phase of the cycle, air pressure is applied to the sleeve which covers the region of the leg from the ankle to the upper calf. The second device employs a more elaborate method which compresses first the ankle, then the ankle and calf and finally the ankle, calf and thigh. During all phases of this compression, the pressure applied to the more distal regions exceeds that being applied proximally. When combined, these characteristics give the unit the sequential gradient profile used to describe the unit.

The results obtained in the current study indicate that both units are capable of increasing venous blood flow. The peak velocity achieved with the single chambered unit exceeded that of the multi-chambered sequential compression device (Fig. 2); however, this greater velocity could not be maintained throughout the compression phase. This most likely occurs because the sequential gradient sleeve compresses a larger volume of muscle mass in a gradient fashion and is therefore able to maintain the average flow rate at a significantly higher level (Fig. 3). This increased average velocity also allows the sequential gradient technique to maintain a higher average blood flow rate (Fig. 4) and to move a greater volume of blood with each compression cycle (Fig. 5).

Venous blood flow normally occurs in a phasic pattern which corresponds to the respiratory rhythm.¹⁶ All nine subjects included in the current study demonstrated this normal venous flow pattern. In an attempt to prevent this venous blood flow pattern from interfering with the blood flow alterations produced by the compression unit, the subjects were asked to stop breathing immediately prior to initiation of the leg compression. Upon deflation of the sleeve, the individual was asked to begin breathing normally. Despite normal respiratory efforts, no venous blood flow in the profunda femoral was noted immediately after deflation, presumably because the blood removed by the compression of the legs had not been replaced. Once the veins had been refilled, the respira-

tory cycle was again seen with the duplex-Doppler. Although not proven, it appears logical to assume that the length of time between deflation of the sleeve and return of the respiratory cycle corresponds to the time required to replenish the blood removed by the compression cycle. Based on this logic, it appears that the sequential gradient compression technique removes more blood from the lower extremities than does the single chambered device (Fig. 6). This logic is reinforced by the observation that compression with the sequential gradient sleeve moved a larger volume of blood than compression with the single chambered device (Fig. 5).

Direct clinical comparison of the two compression devices have been reported in only a few studies.^{17 18} These results suggest that sequential gradient compression may be more effective at preventing deep venous thrombosis. Although additional studies are needed to confirm these data, the results of the current study support the previous work by Nicolaides *et al.*, which concluded that sequential gradient compression is capable of significantly elevating venous blood flow above baseline values.⁵ If, as assumed by most investigators, external pneumatic compression achieves its beneficial results by preventing the venous stasis component of Virchow's Triad, it would appear that sequential gradient compression encompassing the region of the leg from the ankle to the thigh is well equipped to accomplish this task.

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