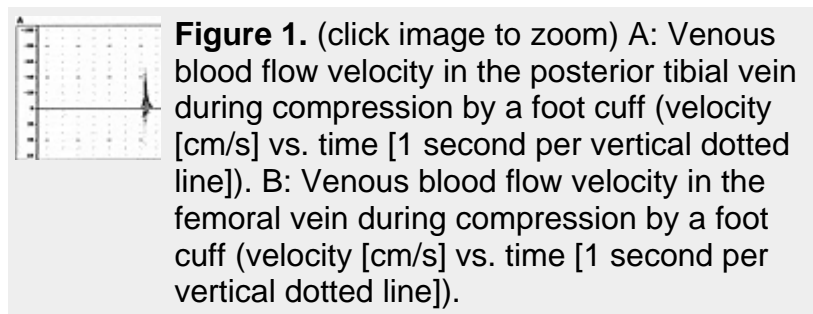


What Effect Do Intermittent Compression Systems Have on Venous Blood Flow Velocity?

Intermittent compression systems augment blood flow in proximal veins for a short time, while they compress. The size, duration, and profile of that augmentation will be dependent on the particular compression system that is used. Changes have been observed in the femoral vein, as a result of calf and thigh compression,^[10-17] and of foot compression;^[14-19] in the popliteal vein due to calf compression,^[13,15,16] and foot compression;^[13,15,16,18,19] and in the posterior tibial vein after foot compression.^[13,19] It is, of course, difficult to measure changes in the popliteal vein with most thigh-length cuffs, just as measurements in the posterior tibial vein would not describe outflow effects when thigh or calf-length garments are used. Examples of velocity measurements in the femoral and posterior tibial veins are given in Figure 1, in this case due to foot compression. In the posterior tibial vein, there is a sharp augmentation, against a background of resting flow too slow to be detected, whereas the femoral augmentation is smoother, and greater in duration, with resting flow easily detectable.



The site of velocity measurement is important since the blood flow velocity in a vein is dependent on the diameter of that vein.^[20] Under normal circumstances, the greatest diameter of the common femoral vein is approximately 16 mm,^[21] the popliteal vein is 8 mm,^[21] and the posterior tibial vein 4 mm.^[22] Therefore, for a given amount of blood being ejected from, for instance, the foot, the velocities achieved would be expected to be higher in the posterior tibial vein than the femoral. However, the velocity must also depend on the part of the limb compressed, since the plantar venous plexus within the foot holds a smaller volume of blood than the calf and thigh. Different volumes of blood accelerated through the same blood vessel would be expected to have different velocity properties.

Reports have consistently shown that all intermittent compression systems produce changes in femoral vein velocity. At pressures around 40 mm Hg, the typical maximum velocities achieved with calf and/or thigh compression would be 35-60 cm/s^[11-13,17] with augmentations (maximum velocity during compression compared with maximum velocity resting) at around 50-250%.^[10,12,14,17] Corresponding popliteal velocities are around 55 cm/s.^[13] Pressures of 120 mm Hg have produced peak velocities of >100 cm/s in both popliteal and femoral

veins,^[16] as has a system that inflates rapidly to 80 mm Hg before reducing to "normal" levels.^[17] Foot compression has produced more modest results, typically 20-40 cm/s in the femoral vein,^[13,17-19] with figures for the popliteal vein slightly higher (30-55 cm/s), as expected. Posterior tibial vein velocity in one example was over twice that in the popliteal vein.^[19]

It should always be noted, however, that venous blood flow is *variable*. Not only will resting blood flow in the femoral vein change from person to person,^[23] but will change in a single subject over time, due to natural fluctuations in the inflow to the limb.^[24] The pattern of flow will change according to the particular physiology and body position at the time, with breathing and the cardiac cycle modulating the flow to differing extents.^[25] Moreover, venous blood pressure will change; therefore, the reproducibility of the velocity results from a particular pump in a particular individual over time will not be perfect.

Is Thigh Compression Important in DVT Prophylaxis?

Lower limb compression cuffs for DVT prophylaxis come in at least five varieties, foot compression, foot and calf compression, calf compression, calf and thigh compression, and whole limb compression, irrespective of how the compression is applied (ie, uniform/graded sequential). The choice of cuff is sometimes dictated by the circumstance - whole leg compression would not be appropriate during or after knee surgery - however, in other cases, the choice might not be obvious and would be left to the preference of the surgeon.

There have been few studies that have included the velocity effects of thigh and calf versus calf compression.^[11,12,17] Comparisons have been made between the pumps of different manufacturers, but the differences between the systems were greater than simply the garment length; therefore, the data are of questionable use to assess the thigh contribution. In a direct comparison of the thigh and calf garment of a single manufacturer, one study appeared to show higher peak velocities and augmentation for the thigh length garment, although there was no direct statistical evaluation of the difference.^[17] Assuming that graded sequential devices were not designed to produce higher peak velocities than uniform systems (and are therefore comparable for this measure, if not any other), then in 2 studies where uniform calf compression was compared with graded sequential thigh-length compression, 1 found no statistically significant difference in peak velocities,^[11] and the other showed calf compression to be preferable (peak 39.5 cm/s vs. 34.2 cm/s, augmentation 107.0% vs. 77.3%, $P < 0.002$).^[12]

Clearly, sufficient direct evidence for a difference is lacking. Although it might seem logical that the more of the limb that you compress, the greater the effect, since the major deep veins of the thigh are supplied by the calf, it could be argued that calf compression is all that is necessary, as it will prevent stasis in the thigh. The DVT outcome studies comparing thigh and calf-length systems are similarly scarce. The research comparing calf-length uniform compression with

thigh-length graded sequential compression reported no significant difference in the calf DVT outcomes, but a significant difference in the number of proximal DVT (7.2% calf-length, 2.4% thigh-length, $P < 0.05$).^[10] Again, due to the difference in the systems, it would be impossible to know which property of the particular system produced the difference, particularly since the uniform system inflated very slowly, and compressed in a 1 minute 'on,' 1 minute 'off' cycle, and that DVT was only detected some time after intermittent compression has ceased. Another study by Fedullo et al has been quoted by Vanek,^[26] which showed no significant difference, again between uniform calf compression, and graded sequential thigh-length compression.

If there is a difference in performance between calf, and thigh and calf compression, it is not yet clear, but it is clear that both types are effective.

Is Foot Compression as Effective as Calf Compression?

Foot compression has become a popular alternative to calf compression in recent years, especially during surgery on the lower limbs where calf compression might restrict access. Indeed, the "out of the way" nature of the cuffs has encouraged their use in all types of surgery. Foot compression, however, needs significantly higher pressures than calf compression, typically 130 mm Hg or more, compared with 40 mm Hg in the calf, there being a small amount of blood in the plantar venous plexus: about 20-30 mL,^[27] compared with 100-150 mL in the calf,^[28] and the muscles are less readily compressible. This inevitably means that patient compliance can be more of a problem with foot compression,^[29] although the proper use of intermittent compression in a hospital situation will depend on many other factors, such as staff training.^[30,31]

There is good recent evidence that foot compression is hemodynamically effective,^[13-19,32-34] typically showing doubling of peak velocities on compression compared with resting, with some small differences between systems.^[13] Comparison with calf and/or thigh compression depends, as previously discussed, on the definition of a "good" response. In at least 2 such comparative studies, the performance of the foot compression devices was poorer than for other systems, and indeed worse than in noncomparative studies of foot compression.^[14,17] It would certainly appear, from limited information, that foot compression is less *hemodynamically* effective than calf compression (peak velocity, duration, etc.).^[16] The venous volume ejected by foot compression will always be lower^[16]; therefore, even when systems are set to reduce high peak velocities, the augmentation would not be expected to last as long as from other compression systems.

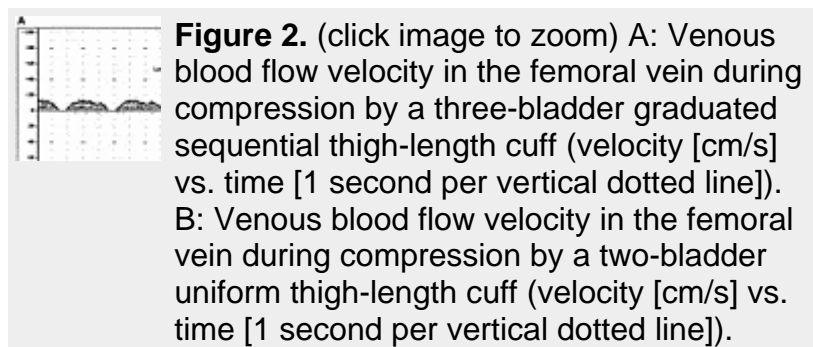
DVT outcome studies on foot compression have also been generally positive, and it would appear from one study to be as effective as graded-sequential calf compression.^[35] Other investigations have compared foot compression to the use of heparin, aspirin, and compression stockings. The outcomes of those trials

cannot be used to compare with those from calf compression, as there would be so many confounding factors, but in general it would appear that foot compression is more effective than certain types of heparin and aspirin,^[36,37] and stockings, but perhaps not as effective,^[38] or at least no more effective,^[29] than low molecular weight heparin. The combination of stockings and foot compression has proved more effective than stockings alone in both DVT and pulmonary embolism incidence.^[39,40]

Is Graded Sequential Compression "Better" Than Uniform Compression?

Graduated or graded sequential compression uses multiple bladders to compress the limb in a "milking" action. The cuffs are sequential because the most distal bladder inflates first and the most proximal bladder last and are graded because the most distal bladder will inflate to the highest pressure, and the most proximal to the lowest. The cuffs were devised after rigorous laboratory work on fluid flow,^[41-43] which indicated that they would be more efficient at emptying a limb.

A typical velocity profile from such a system is shown in Figure 2a, where it can be seen that the individual bladders (their inflations labeled in the figure) produce individual peaks in the augmentation, effectively spreading out the augmentation over a long period. The peak velocities produced by such systems are however generally no higher than simpler uniform compression, an example of which is the response in Figure 2b.



Whether graded sequential is "better" than uniform depends on how you define the success of intermittent compression. If the aim is to extend the augmentation period by a second or 2 over that produced otherwise, then they are "better." However, intermittent compression for DVT prophylaxis aims to prevent thrombosis. In that regard, there is no evidence that they are significantly better, as concluded early on in a paper by Salzman et al,^[44] among whose authors were Kamm and Shapiro who were instrumental in designing a graded sequential system. The conclusion has been confirmed by others more recently.^[45] To quote Salzman et al: "These results suggest either that uniform compression offers all that can be expected of external pneumatic calf compression in prevention of venous thrombosis, or that even if a study with greater statistical power showed

graded-sequential filling to be superior, the benefit/cost ratio of the more complex latter system is not likely to be large." Fifteen years later, complexity in an intermittent compression system has still not been shown to equate with efficacy.

Is "Distal Venous Trapping" Important?

Graduated compression was devised, partly due to the concerns about the phenomenon termed "distal venous trapping." The idea was first documented by Kamm and Shapiro in 1976,^[46] and was promoted again by Nicolaides et al in 1980.^[10] Simply expressed, distal venous trapping is when a cuff system compresses both the calf and thigh simultaneously, and the blood ejected from the calf is prevented from returning to the heart by the compressed thigh. The other manifestation would be a single bladder where a proximal section of vein is caused to collapse before the rest, trapping blood in the distal segment. Kamm and Shapiro used models of veins to show that collapse during compression could occur in only a very small proximal part of the vein, producing outflow characteristics that they had measured from their hydraulic models.

The implication of that research was that trapping was a property of uniform compression systems and would prevent proper emptying of the deep veins by the cuffs. However, if this were true, there would surely be evidence either that uniform systems had poorer velocity properties, or worse DVT incidence, and as has been noted, DVT incidence has never been shown to be poorer with uniform systems.

Nicolaides et al^[10] produced illustrations of apparent distal venous trapping with uniform compression. When a cuff inflates, it empties the deep veins; when it deflates, those deep veins must refill. When observations are made on deflation, for instance in the femoral vein, the flow velocity will decline, sometimes to zero, as the inflow is taken up refilling the deep veins (a notable reduction can be seen in Fig. 2b from a uniform compression system). Nicolaides et al showed examples where there was no reduction in velocity on deflation, and assumed that there was no emptying, and therefore, distal venous trapping. However, if there had been no emptying, there would have been no augmentation of flow, which there clearly was in the illustration. Indeed, experimentally, with the variability of venous flow, it is quite easy to select examples where there is comparably little reduction postcompression, with whatever system. Figure 3 is an example from a type of *graded sequential* system where there is not only no decrease but a notable increase in flow on deflation, indicating blood trapped in the knee and/or foot region.

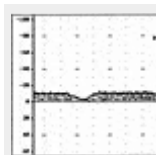


Figure 3. (click image to zoom) Venous blood flow velocity in the femoral vein during compression by a two-bladder graduated sequential thigh-length cuff (velocity [cm/s] vs. time [1 second per vertical dotted line]).

Distal venous trapping happens, but there is no evidence that it happens consistently, or with a particular system. Indeed, if it does happen sporadically, it is probably of little consequence as the time the blood is "trapped" is only short. A variety of perfectly natural activities, such as yawning, laughing, and coughing, will restrict outflow for short times. Some blood will have been emptied from the veins beneath the cuff if flow is augmented proximally, and that should be enough to prevent stasis. Until there is firm evidence of distal venous trapping reducing the effectiveness of DVT prophylaxis, it cannot be considered an important feature of intermittent compression generally, and only when uniform compression is shown to have worse DVT outcomes than graded sequential compression can distal venous trapping be considered a negative aspect of uniform compression in particular.

Is "Asymmetric" Compression Different to Circumferential Compression?

Aside from the site of compression and the graded sequential/uniform difference, there is another way to differentiate compression systems, and that is in the extent of the air bladders. Some particularly older systems have bladders that extend over the whole limb (circumferential), either as boots that zip up or wrap-around garments rather like extended sphygmomanometer cuffs. The total volume of the bladder is then quite large, and powerful pumps are required for inflation unless extremely long inflation times are used. The noncircumferential ("asymmetric")-type garments typically have a smaller bladder in the part of the garment that is placed at the back of the limb. The bladder will extend along the length of the garment, but not to its entire circumference. The idea is that the inflation of the bladder will act against the nonstretching material around the rest of the limb, and compression will be applied along the whole surface.

There remains little research into the relative physiological and medical merits of these different cuff formats, except to say that both circumferential (boot or cylinder type,^[47,48] and wrap-around^[49,50]) and noncircumferential^[51,52] have been used with success in DVT prophylaxis, and both have been shown to prevent stasis.^[12,14,17] One study^[53] has used finite-element analysis to model the deformation of a limb under those different compression cuffs. It concluded that so-called "asymmetric" (ie, noncircumferential) calf compression had advantages in emptying veins over circumferential calf compression. However, it should be noted that their model was quite simple and assumed compression at points at the front and back of the limb. In a real cuff, the bladder is only at the back, although it is assumed that the material over the rest of the limb has an effect. Foot compression can also be "asymmetric" (compressing the sole of the foot) or "circumferential" (compressing the whole foot), but there is no specific comparative research in this area.

Is Intermittent Compression Effective in the Upper Limb?

Intermittent compression of the arms for prevention of DVT at that site is a relatively new area of interest, but upper limb DVT is being reported, particularly associated with central venous catheters.^[54] There are patents for upper-limb cuffs for possible prophylactic devices, but not published experimental data. Some experimentation has looked at systemic effects of intermittent compression (on fibrinolysis) by compressing the arms, and measuring lower limb DVT outcomes.^[55] Most upper limb intermittent compression is to treat lymphedema.^[56]

What Effect Do Compression Stockings Have on Venous Blood Flow Velocity?

Compression stockings are cheaper and simpler than intermittent compression devices and, for that reason, remain the most popular physical method of DVT prophylaxis. Their method of action, however, remains unclear. There is growing consensus that they are effective DVT prophylaxis,^[57-60] although perhaps not as effective as anticoagulants or intermittent compression.^[26] There has been suggestion that they are not as useful in certain types of orthopedic surgery as in other procedures^[61,62] but may, in combination with other prophylactic methods, be more effective than it or the other method alone.^[60]

Much of the initial enthusiasm for compression stockings was supported by physiological evidence from radiopharmaceutical clearance,^[63-65] invasive electromagnetic flowmeters,^[7] and early Doppler ultrasound,^[66,67] that intermittent compression increased resting venous blood flow velocities. The method of action that is often quoted, and has been suggested for some time,^[68] is that the stockings compress the veins and reduce their diameter. The velocity of a given amount of blood flowing through a vessel is dependent on its cross-sectional diameter, as previously stated; therefore, the stockings would be expected to increase the velocity in the vein.

Some later studies using modern duplex ultrasound techniques have found no increases in resting flow velocity when stockings are worn.^[11,21,69] The diameter of veins under stockings has been found to reduce,^[70] and there have been measurements of changes in indices such as venous volume, and ejection fraction after tiptoe exercise,^[71,72] and venous capacitance after cuff compression.^[73] The evidence, when grouped together, suggests that a significant effect of stockings may be to reduce pooling of blood in deep veins by mechanically preventing distension of the vessels. Operative venodilatation has been recorded,^[74] and it would be logical for the risk of stasis to be higher during surgery where there is excessive venous distension. Improvements in venous pump function would perhaps be of more relevance in preventing travel DVT, and to aid those with chronic venous insufficiency, than those immobile during surgery.

The major drawback with stockings is their fitting. Thigh-length stockings, in particular, appear to be difficult to apply and wear in some circumstances, and

some have preferred calf-length stockings for that reason.^[75-77] More worrying are studies of thigh-length,^[78] and calf-length^[79] stockings in clinical settings where the large majority of the stockings did not produce the pressure profile intended by the manufacturers (98% for calf-length), and the majority (70% for thigh-length, 54% for calf-length) produced "reverse gradients," where the pressure was higher at the proximal end of the cuff. The danger is that poorly fitted stockings, or those of an incorrect shape and size, could produce "tourniquets" at the proximal end, causing ischemia,^[80] and an increased risk of thrombosis.^[79]

The hemodynamic effects of stockings remain uncertain, although prevention of pooling is a plausible mechanism for their undoubted efficacy in preventing DVT. While not necessarily as effective as other prophylactic methods, their ready availability would recommend their use in the absence of other options, or in combination with other methods. However, it is vitally important that stockings are correctly fitted, and do not wrinkle, slip, or otherwise produce a compressive band at the proximal end.

Should Compression Stockings Be Used in Combination With Intermittent Compression?

Some manufacturers of intermittent compression systems, particularly those who also produce stockings, recommend that the two types of compression should be worn together: the stockings underneath the cuff. If the proposed mechanisms of action are true (stockings preventing distension, intermittent compression emptying veins), then there is no reason why both should not be worn together, as they are separate effects. However, there is relatively little research into either the hemodynamic effects (whether stockings improve the velocity augmentation of intermittent compression) or into the DVT outcomes. The first major study, which is often quoted, found that there was a reduction in rates of DVT in general surgical patients when graduated compression stockings were worn with graded sequential intermittent compression, as opposed to the intermittent compression alone.^[81] Velocity studies, however, have not been as positive, with the combination of the same stockings and the same intermittent compression device producing augmentation equal to intermittent compression alone,^[11] and stockings in combination with foot compression even appear to have reduced the expected velocities.^[82]

There is not enough research into this area of combined treatments to come to definite conclusions. Although the potential for intermittent compression and compression stockings for DVT prophylaxis emerged at around the same time, compression stockings have gained acceptance more rapidly, despite slightly inferior levels of scientific evidence. Therefore, it is not surprising that in comparisons of efficacy so few have used stockings as the variable against a background of intermittent compression. If combined use could provide even greater protection, then it would be necessary to research the fitting of the

stockings, and the potential of intermittent compression to exacerbate the wrinkling of stockings beneath.

What Effect Do Exercise Devices Have on Venous Blood Flow Velocity?

While physical methods of DVT prophylaxis have been used in the surgical environment because the risk of bleeding is lessened, they would appear to be ideally suited to use in long-haul travel. Although the possible risk of DVT during flights has been suggested for more than 60 years,^[83] it has only recently occupied the public mind. Intermittent compression devices have not yet been developed into forms that would be used easily during long-haul travel. Exercise devices (air cushions, primarily) have therefore been recommended, along with compression stockings.^[84]

Most of the exercise devices encourage limb exercise by the user, who pushes air from the bladder under one foot to the bladder under their other foot, or alternatively to a second bladder under the same foot (front to back, and vice versa) in a similar action to the treddle devices, which are also available. The cushions do not provide any prophylaxis by themselves, they simply, at best, allow plantar and dorsiflexion, which is known to effectively empty the deep veins by activating the calf muscle pump^[14,17] and, therefore, is a perfectly good way of preventing stasis. "Stamping" on the cushion with no flexion would be unlikely to be as efficient, as the calf muscles are not as actively employed. The drawback of exercise devices is obvious; they are not effective when not used, especially not when sleeping on the plane.