# Compression-induced pulsatile blood flow changes in human legs

**H. N. Mayrovitz**

Miami Heart Research Institute, Miami Beach, Florida, USA
Received 10 May 1997; accepted 1 July 1997
Correspondence: Harvey N. Mayrovitz, PhD, Director of Cardiovascular Research, Miami Heart Research Institute, 801 Arthur Godfrey Road, Miami Beach, FL 33140, USA

## Summary

Initial and sustained (7-h) impacts of foot-to-knee compression bandaging on leg arterial pulsatile blood flow were assessed by nuclear magnetic resonance flowmetry in eight healthy supine subjects. A widely used bandaging method (zinc impregnated gauze + Coban) and a slight variant (Coban only) were applied one week apart to one leg. Blood flow was measured on each day of bandage application before and after bandaging and after 7 h of normal activity. Initial mean sub-bandage pressures (lateral gaiter) were between 28·4 and 28·9 mmHg but were significantly reduced after 7 h to 16·3–19·4 mmHg. Overall below-knee pulsatile blood perfusion was initially significantly increased by both methods mainly due to increased proximal blood flow. Bandaging was also associated with a decrease in blood perfusion of the nonbandaged control leg mainly due to a decrease in distal blood flow. Neither of these effects were sustained after 7 h. The fact that neither sub-bandage pressure nor blood flow was sustained may indicate a causal linkage, a concept consistent with the finding of a linear relationship between afternoon blood flow and sub-bandage pressure reductions. The implications of the present findings for venous ulcer therapy are speculative and based on the concept that arterial pulsatile flow augmentation is a positive feature. If so, more frequent bandage changes to provide transient flow stimulation or use of bandages to better maintain sub-bandage pressure to sustain flow increases may be useful.

*Keywords*: leg blood flow, nuclear magnetic resonance, pulsatile blood flow, venous disease.

## Introduction

Compression of the lower extremities via compression bandaging is the mainstay of effective treatment of venous ulcers (Blair *et al*., 1988) and is used for a number of other vascular conditions both as therapy and for prophylaxis (Aba-Own *et al*., 1994). Usual sub-bandage pressures associated with compression range between 20 and 40 mmHg (Moffatt & Dickson, 1993) and vascularly related effects had previously been thought to be primarily due to changes in venous haemodynamics (Meyerowitz & Nelson, 1964). Recently, however, ankle-to-knee compression to a level of about 40 mmHg was shown also to have a significant impact on leg arterial pulsatile blood flow resulting in an acute blood flow augmentation (Mayrovitz & Larsen, 1997). Because the compression system used had four layers, the outer two of which were specifically designed to produce pressures at the high end of the therapeutic level, it was not possible to evaluate the impact of lower sub-bandage pressures. Further, although the previous work showed initial pulsatile blood flow increases, no studies have been done to determine if such compression-induced flow increases are sustained over time. To address these two issues, nuclear magnetic resonance flowmetry (NMRF) was used to measure pulsatile blood flow bilaterally at five below-knee

 

sites before and after application of a widely used compression bandaging technique and repeated one week later using a slight variant of the initial bandage. In each of the eight healthy volunteer subjects studied, blood flow was measured soon after bandage application and subsequently after 7 h of normal activities.

## Methods

### Subjects and preliminary evaluations

Healthy female volunteer subjects ($n = 8$, age $46 \pm 5{\cdot}8$ years) were studied after they had read and signed an Institutional Review Board approved informed consent. No subject had diabetes, had any history of venous or arterial disease or was taking any vasoactive medication. Absence of lower extremity arterial disease was confirmed in each participant based on screening with bilateral NMRF and ankle-brachial systolic pressure indices (ABI) obtained using standard Doppler ultrasound at the posterior tibia and dorsal pedis arteries. All subjects tested normal with mean blood perfusion at the knee and ankle of $1{\cdot}74 \pm 0{\cdot}28$ and $1{\cdot}89 \pm 0{\cdot}16$ ml min$^{-1}$ 100 cc$^{-1}$, respectively, and an average ankle systolic pressure and ABI of $130{\cdot}8 \pm 5{\cdot}5$ and $1{\cdot}02 \pm 0{\cdot}02$, respectively. Systemic blood pressures measured with standard blood pressure cuffs also verified that the group was normotensive (systolic $124 \pm 5{\cdot}9$, diastolic $81{\cdot}4 \pm 3{\cdot}0$ mmHg).

### Leg pulsatile blood flow methodology

Pulsatile blood flow was evaluated under resting supine conditions by nuclear magnetic resonance flowmetry (NMRF). Details of this method have been given previously (Mayrovitz & Larsen, 1997). Briefly, the subject is placed on a moveable table which is advanced by an operator to position a specific leg site within the centre of a tubular measurement section of the NMRF system (Metriflow AFM100, Milwaukee, USA). Within the section a fixed magnet (0·1 Tesla) causes hydrogen nuclei of fluids within the leg to precess and an NMR sensor detects the amount of precession. The main NMR signal detected and processed is due to precession of hydrogen nuclei associated with intravascular water and is proportional to the number of precessing hydrogen nuclei and thus to the amount of vascular water flowing into and out of the measurement section. Nonpulsatile flow (e.g. tissue water, venous flow) produces small contributions which are filtered out. The flow signal arises from a flow-induced adiabatic tipping of the nuclear magnetization in all of the flows simultaneously in a cross-section, whether in major or minor arteries or collateral pathways. The NMR system's radio frequency (RF) transmitter and RF receiver are both 'on' continuously, so all pulsatile flows in the cross-section contribute to the magnitude of the real-time, continuous pulsatile flow signal induced in the receiver coil. This signal is detected in sidebands of the RF transmitter frequency, which are produced due to the presence of a continuous modulating field applied along the direction of the 0·1 Tesla main field. Calibration to obtain absolute pulsatile blood flow is done with a pulsatile flow pump which drives water doped with a paramagnetic solute to simulate the NMR characteristics of blood through a phantom limb. The pump pulsatile flow is registered using an electromagnetic sensor and a range of calibration flows are used to obtain a calibration curve each day prior to patient use. Among the advantages of the used NMRF method is that measurements can be done without removing the bandages or without making any holes in the bandages. Further technical details regarding NMRF and applications may be found in the literature (Battocletti, 1986; Kerr *et al.*, 1991; Kofler *et al.*, 1991; Rice, 1994; Salles-Cunha & Beebe, 1994; Mayrovitz & Larsen, 1996a, b).

### Leg external compression

Leg compression was produced by wrapping one leg from fore-foot to knee with a widely used bandaging method as follows. On experimental day 1, a Tegapore dressing was applied to the lateral supramalleolar region over which was placed a rolled $4 \times 4$ cotton gauze 'bolster'. A zinc oxide-coated gauze bandage was then wrapped around the limb, from fore-foot to knee using a spiral wrap at 50% extension. The final layer, which was the main pressure-inducing component, was Coban, wrapped at mid-stretch, again from fore-foot to knee. On day 2 (7 days later) a variant bandage was used which differed only in the elimination of the zinc gauze wrap

component. Bandaging was done by the same wound care nurse who had extensive experience with the use of these bandage methods.

### Sequence

At ≈ 08·00 h (a.m. measurements) the subject assumed a supine position on the NMRF table. Following necessary leg measurements and markings, a baseline bilateral flow study was done after 15 min of supine rest. These flow assessments consisted of measuring pulsatile blood flow at five standardized below-knee sites on each leg. Immediately after this bilateral procedure, one leg was bandaged and the contralateral leg was similarly manipulated with a Kling noncompressive bandage used as a sham control. Prior to the bandaging procedure an interface pressure sensor (Talley Oxford Pressure Monitor, MKII), previously calibrated, was placed in contact with the skin at the lateral supra-malleolar region under the Tegapore. This sensor was used to measure sub-bandage pressures. Fifteen minutes after completing the bandaging a second bilateral NMRF flow assessment was started; the nonbandaged leg was evaluated first followed by measurements on the bandaged leg. Sub-bandage sensor pressures were recorded in triplicate before and after the flow measurements. The measuring connector attached to the pressure sensor was removed from the system control box and carefully secured to the subject with the sensor remaining in its initial position at the lateral supra-malleolar site. The subject was then temporarily discharged to carry on with normal activities. These activities included those normally encountered in the daily routine of nurses ($n = 4$) and clerical and data processing activities ($n = 4$). In the former there was a substantial component of ambulatory activity and in the latter a significant component of seated activity. At ≈ 16·00 h (p.m. measurements) of the same day, the subject was re-evaluated with a bilateral NMRF flow assessment commencing after 15 min of supine rest. Sub-bandage pressures were measured and recorded before and after the p.m. flow evaluations. At the conclusion of this measurement the bandage was removed and a final bilateral flow measurement taken. One week later, the above procedure was repeated on seven of the eight original subjects using the variant bandaging technique.

### Blood flow procedure and parameters

All tests were done in a room temperature controlled to 23·1 ± 1·4°C. Pulsatile leg blood flow ($Q$, ml min$^{-1}$) at each of the five below-knee sites was determined by integrating each pulse waveform over a cardiac cycle and then ensemble-averaging for 15–20 beats. The sites were standardized for all subjects by measuring the distance ($L$) between the lateral malleolus and the tibial tubercle and marking five sites located at 10%, 25%, 50%, 75% and 90% of the malleolus-tubercle distance with the zero reference point at the malleolus. Flow measured at the 90% site represents the approximate pulsatile flow perfusing the lower limb. The measurement includes the sum of all pulsatile arterial flow passing peripherally through the leg cross-section within an axial segment 5 cm in length. The blood perfusion at each site (ml min$^{-1}$ 100 cc$^{-1}$) was calculated by dividing the corresponding measured $Q$ by the leg volume distal to the measurement site. An estimate of leg volume between knee and ankle was made by first calculating the volume of each of the four leg segments between the 90% and 10% sites using a truncated frustrum model with the measured proximal and distal circumferences being the upper and lower boundaries for the calculation. The knee-ankle volume was taken as the sum of these volume segments. This method of below-knee volume determination has been shown to be essentially equivalent to water displacement volumetric methods. Total volume was estimated by adding the below-ankle (foot) volume determined by an algorithm in the NMRF instrumentation which is based on shoe size. The total below-knee blood perfusion (ml min$^{-1}$ 100 cc$^{-1}$) was determined by averaging the calculated blood perfusion values obtained at each measured site.

### Flow comparisons

Flow parameters were compared with respect to differences between before and after bandaging (with compression in place) for the bandaged leg and the control uncompressed leg separately. Also, paired-leg differences and parameter ratios (bandaged leg/control leg) were compared with respect to before and after bandaging differences. Nonparametric statistical tests (Wilcoxon) were used with a level of $<0·05$ taken as statistically significant.

## Results

### Sub-bandage interface pressures (lateral gaiter)

All results as reported in the text are expressed as mean ± SEM.

On experimental day 1 using the full bandage ($n = 8$), intial a.m. sub-bandage interface pressures after bandaging but prior to blood flow measurement were 28·4 ± 2·3 mmHg (Fig. 1). A small insignificant decrease to 26·3 ± 2·6 mmHg was noted after flow measurements were completed at about 30 min after the initial pressure measurement. Follow-up p.m. pressure measurements made on average 7 h later showed a significant ($P < 0·01$) decrease in sub-bandage pressure to 16·3 ± 2·7 mmHg as measured after the p.m. blood flow evaluations. On experimental day 2 using the variant bandage ($n = 7$), initial a.m. sub-bandage interface pressures after bandaging but prior to blood flow measurement were 28·9 ± 3·3 mmHg. A small insignificant decrease to 27·1 ± 2·8 mmHg was noted after flow measurements were completed. These values did not significantly differ from those obtained on day 1. Follow-up p.m. pressure measurements showed a significant ($P<0·01$) decrease in sub-bandage pressure to 19·4 ± 3·0 mmHg after the p.m. blood flow evaluations. These values did not significantly differ from those obtained on day 1. These results show that both bandage methods are similar with respect to initial sub-bandage pressures and their inability to maintain this pressure over time.

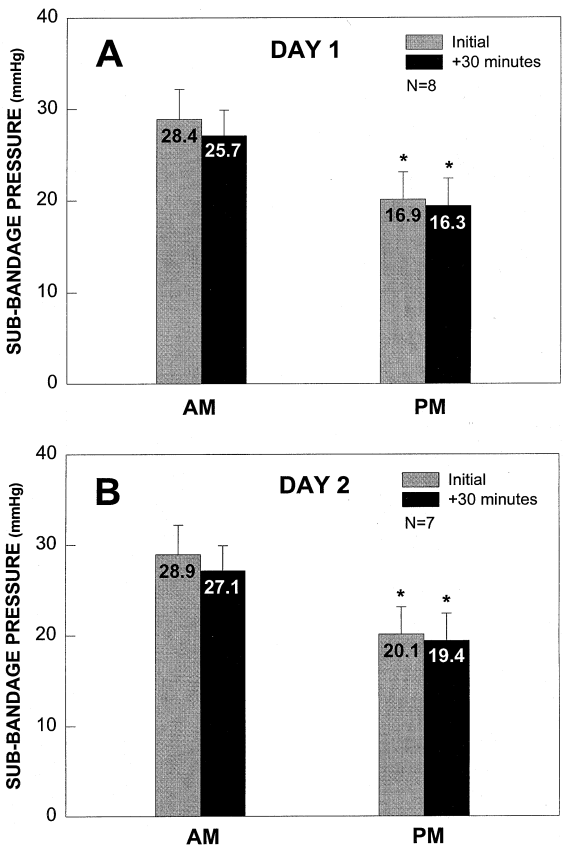


**Figure 1** Sub-bandage pressures. Morning (a.m.) pressures achieved with full bandage (day 1) and variant bandage (without zinc gauze, day 2, 7 days later) were similar. With both, afternoon (p.m.) pressures fell significantly.

### Leg pulsatile blood flow and perfusion

*Overall leg perfusion.* On day 1, prior to bandaging in the morning, below-knee average blood perfusions (ml $min^{-1}$ 100 $cc^{-1}$) of the control leg (right) and experimental leg (left) were insignificantly different (1·76 ± 0·09 vs. 1·80 ± 0·09, Fig. 2). Paired-leg perfusion ratios (left leg/right leg) were near unity (0·98 ± 0·04, Fig. 3) Bandaging was associated with a significant increase in left leg perfusion to 2·17 ± 0·19 ($P = 0·017$) and a significant decrease in right leg perfusion to 1·51 ± 0·07 ($P = 0·001$). Differences in absolute perfusion between bandaged (left) and control legs were significant at the $P<0·01$ level. Bandaging was associated with a perfusion ratio increase to 1·43 ± 0·11 ($P = 0·01$). Follow-up p.m. blood flow measurements showed a tendency for blood perfusion of the bandaged leg to decrease from its a.m. bandaged-induced increased value and the control leg perfusion to increase from its initial reduced value. These oppositely directed tendencies resulted in a nonsignificant difference in perfusion between bandaged and control legs at the p.m. assessment (1·92 ± 0·20 vs. 1·79 ± 0·16 ml $min^{-1}$ 100 $cc^{-1}$). Perfusion ratios based on p.m. flow measurements were near a.m. prebandaged levels. Day 2 results (not shown) were similar.

*Blood flow changes by leg site (a.m.).* Prior to bandaging both legs showed a normal pulsatile blood flow decrease from proximal (90%) to distal (10%) sites (Fig. 4). After bandaging blood flow tended to be higher at all five leg sites in the bandaged leg, but only the more proximal sites (90, 75 and 50%) could be shown as statistically greater (Fig. 4a). By contrast,

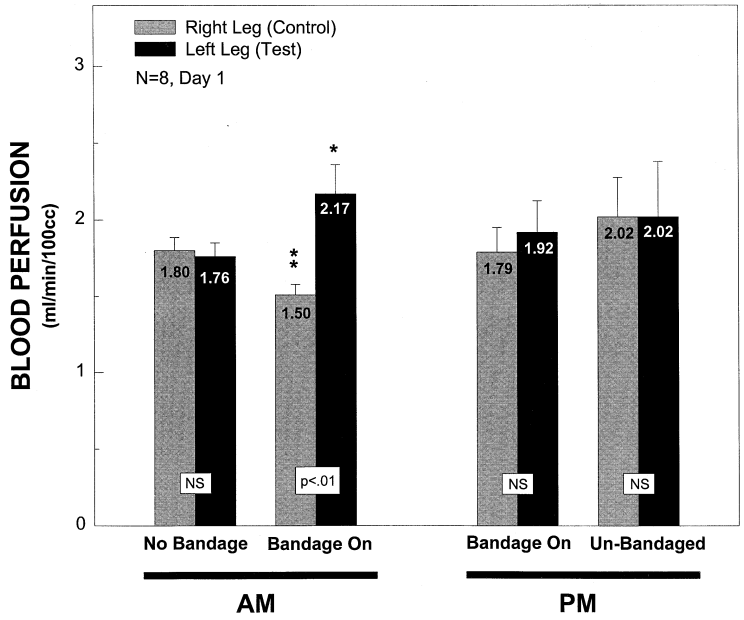


**Figure 2** Compression effects on below-knee pulsatile blood perfusion. Paired-leg perfusions did not differ prior to bandaging. After bandaging the test leg perfusion significantly increased (*) whereas the contralateral control leg perfusion significantly decreased (**). These effects were not sustained through the p.m. on average 7 h later.

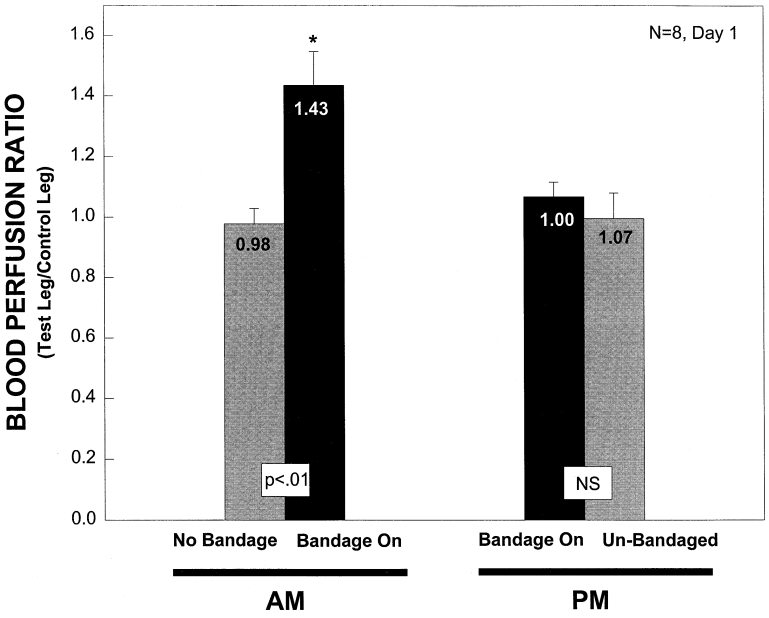


**Figure 3** Effect of compression on blood perfusion ratios (bandaged leg/control leg). In the morning (a.m.) prior to compression, paired-leg perfusion ratios were near unity but significantly (*, $P = 0{\cdot}017$) increased after bandaging the test leg. Ratios normalized after 7 h of normal activities.

bandaging was associated with significant decreases in distal flows of the control leg (Fig. 4b). Flow ratios (bandaged leg/control leg) prior to bandaging were in the normal range for paired legs, ranging from $1{\cdot}16 \pm 0{\cdot}14$ to $0{\cdot}88 \pm 0{\cdot}08$. After bandaging ratios at corresponding anatomical sites were all significantly greater in the bandaged leg, ranging from $1{\cdot}65 \pm 0{\cdot}15$ to $1{\cdot}32 \pm 0{\cdot}12$ (Fig. 5).

### Relationship of flow changes to sub-bandage pressure

In the top part of Fig. 6 the relationship between sub-bandage pressure (lateral supra-malleolar) and the day 1, morning (a.m.) blood flow increase recorded at the most proximal (90%) leg site is shown for each of the eight subjects. It is noted that all flows increased as compared with baseline prebandaged levels. The

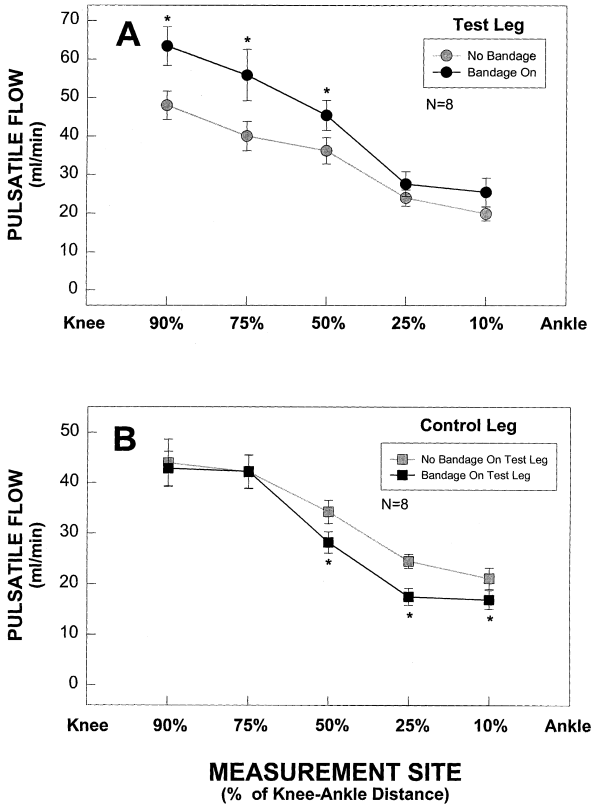


**Figure 4** Blood flow changes by leg site. (a) B andaging of the test leg produces significant increases in pulsatile flow at proximal sites and (b) decreases in contralateral leg flow at distal sites.

percentage increase in blood flow is well fitted by the linear regression equation shown in the figure. The sub-bandage pressures used are those measured directly after the bandaged leg flow measurements. In the bottom part of this figure the relationship between the change in sub-bandage pressure as measured in the afternoon (p.m.) and the change in blood flow from its a.m. bandaged value is shown. It may be seen that all flows decreased with the smaller pressure changes tending to be associated with smaller decrements in blood flow. This relationship is well fitted by the regression equation shown in the figure.

## Discussion

The present findings show an initially significant increase in leg pulsatile blood flow due to fore-foot-to-knee compression bandaging to a sub-bandage pressure of about 28 mmHg. Flow augmentation occurs preferentially at more proximal leg sites and is associated with an overall increase in below-knee blood perfusion of the bandaged leg. Flow-pulse waveform morphology, spatial patterns and magnitude of increase in the bandaged leg are similar to those previously obtained with a different bandaging system that produced a sub-bandage pressure of about 40 mmHg (Mayrovitz & Larsen, 1997). Thus the flow augmentation process appears to be fairly robust

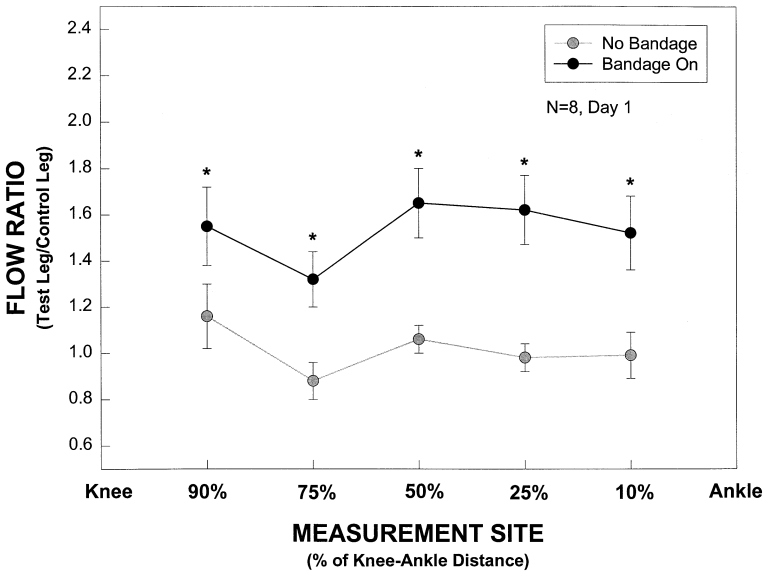


**Figure 5** Paired-leg flow ratios. Flow ratios at corresponding anatomical sites are all significantly increased by compression bandaging.

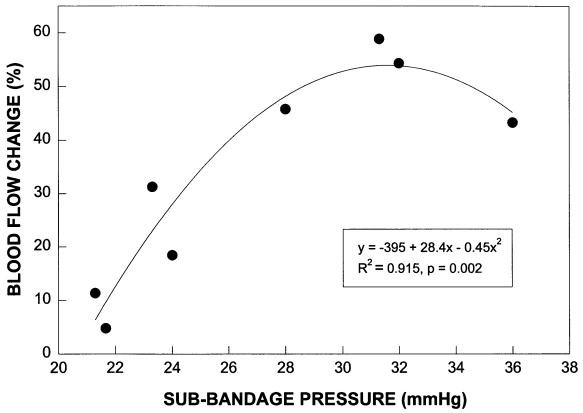


**Figure 6** Relationship of flow changes to sub-bandage pressure. Top: Morning (a.m.) percentage increases in blood flow due to bandaging as a function of sub-bandage pressure measured directly after a.m. flow measurement. Bottom: Afternoon (p.m.) percentage reductions in blood flow as a function of the p.m. percentage reduction in sub-bandage pressure. Flows are those measured at the most proximal leg site (90%) and sub-bandage pressures as measured on the lateral supra-malleolar region. Solid lines are for linear regressions (equations shown in boxes) and dashed lines are 95% confidence intervals.

over this pressure range yielding absolute flow increases at the most proximal leg site of 30–40% and paired-leg perfusion ratios of 1·35–1·45. However, the present data indicate that at lower sub-bandage pressures, the initial flow increase is pressure dependent, a fact that may explain the absence of initial flow increases being sustained through 7 h of normal activities. Thus, sub-bandage pressure was found to decrease in all subjects studied, and this reduction occurred independently of the type of bandaging used. This pressure reduction is probably due to a decrease in elasticity of the compression component of the bandage over time. As a consequence either of the pressure reduction or of an as yet unknown mechanism, paired-leg blood flows as measured after 7 h of normal activity were insignificantly different from one another or from their corresponding unbandaged levels. The mechanism(s) responsible for the initial pulsatile blood flow increase in the bandaged leg remains unclarified but the phenomenon is consistent with earlier published results wherein several potential mechanisms were described (Mayrovitz & Larsen, 1997). In view of the consistency of the present results with previous experimental findings using different bandage methods and at different sub-bandage pressures, future studies need to be directed to sorting out and testing these hypotheses.

The paradoxical blood flow decrease in the non-bandaged control leg when the test leg is bandaged is at present unexplained. This phenomenon occurred in all tested subjects but, as with the flow increase in the bandaged leg, was not present after 7 h of normal activity on either test day. Any explanation for the initial tendency for a decrease in pulsatile perfusion of the contralateral control leg concomitant with compression of the test leg is at this point speculative. The response may be reflexly triggered, perhaps by test leg venous distension, but neither the sensing mechanism nor communication pathways to the contralateral limb are known. The fact that flow decreases are most prominent at distal leg segments (mid-calf to ankle) suggests that operant mechanisms might be clarified if these regions were monitored during application of contralateral limb compression.

### Potential impact on venous ulcers

The question as to the role, if any, of arterial pulsatile blood flow increase in the venous ulcer healing process is unknown. One theory to explain how venous pathology and chronic venous hypertension leads to skin ulceration is based on microvascular compromise in part secondary to capillary flow disturbances associated with leucocyte effects in skin capillaries and venules (Smith *et al.*, 1988; Thomas *et al.*, 1988). However it is unclear if such leucocyte involvement is related to plugging or cell activation following entrapment within the microvasculature (Wilkinson *et al.*, 1993; Pappas *et al.*, 1995). These events would need to occur in the presence of an elevated arterial pulsatile flow in the vicinity of the venous ulcer (Mayrovitz & Larsen, 1994a) and an elevated peri-ulcer skin blood perfusion (Mayrovitz & Larsen, 1994b). Since leucocyte adherence within the microvasculature is dependent on local haemodynamic forces it may be that the combined effect of compression-related arteriolar vasodilation and increased pulsatile blood flow might tend to minimize, partially clear, or reverse such white blood cell capillary plugging effects thereby partially off-setting negative impacts on venous ulcer healing. However, based on the present results which show an inability

of a widely used bandaging method to sustain the flow augmentation, such beneficial effects would likely occur over a limited time-frame with the greatest effects probably in the first hours of bandage application. The frequency of compression bandaging changing in patients, which is widely variable ranging from weekly to daily, may thus impact on the venous ulcer healing process. By contrast, if a bandaging system were used in which both sub-bandage pressures and thereby flow augmentation were maintained for longer times, one would speculate on a more favourable effect for similar bandage application durations. Clearly further experimental work will be required to test these concepts.

### Acknowledgements

The author wishes to thank Marie Delgado, R.N. and Joshua Smith, M.S. for superlative technical assistance and to gratefully acknowledge the research support of Organogenesis Inc., the Hugoton Foundation and the Walter G. Ross Foundation.

### References

Aba-Own A., Shami K. S., Chittenden S. J., Farrah J., Scurr J. H. & Coleridge-Smith P. D. (1994) Microangiopathy of the skin and the effect of leg compression in patients with chronic venous insufficiency. *J Vasc Surg*, **19**, 1074–1083.

Battocletti J. H. (1986) Blood Flow Measurement by NMR. *CRC Critical Rev in Biochemical Engineering*, **4**, 311–367.

Blair S. D., Wright D. D. I., Backhouse C. M., Riddle E. & McCollum C. N. (1988) Sustained compression and healing of chronic venous ulcers. *Br Med J*, **297**, 1159–1161.

Kerr T. M., Cranley J. J., Johnson R., Lutter K. S., Duldner J. E. & Sampson M. G. (1991) Measurement of blood flow rates in the lower extremities with use of a nuclear magnetic resonance based instrument. *J Vasc Surg*, **14**, 649–657.

Kofler J. M., Morin R. L. & Johnson C. M. (1991) Performance testing of a dedicated magnetic resonance peripheral blood flow scanner. *Med Phys*, **18**, 1057–1062.

Mayrovitz H. N. & Larsen P. B. (1994a) Leg blood flow in patients with venous ulcers: relationship to site and ulcer area. *Wounds*, **6**, 195–200.

Mayrovitz H. N. & Larsen P. B. (1994b) Periwound skin microcirculation of venous leg ulcers. *Microvasc Res*, **48**, 114–123.

Mayrovitz H. N. & Larsen P. B. (1996a) Pulsatile blood flow indices in lower extremity arterial disease: leg only compared with leg and cardiac parameters. *Vascular Surg*, **30**, 337–344.

Mayrovitz H. N. & Larsen P. B. (1996b) Pulsatile blood flow asymmetry in paired human legs. *Clin Physiol*, **16**, 495–505.

Mayrovitz H. N. & Larsen P. B. (1997) Effects of compression bandaging on leg pulsatile blood flow. *Clin Physiol*, **17**, 105–117.

Meyerowitz B. R. & Nelson R. (1964) Measurement of the velocity of blood in lower limb veins with and without compression. *Surg*, **56**, 481–486.

Moffatt C. J. & Dickson D. (1993) The charing cross high compression four-layer bandage system. *J Wound Care*, **2**, 91–94.

Pappas P. J., Fallek S. R., Garcia A., Araki C. T., Black T. L., Duran W. N. & Hobson R. W. (1995) Role of leukocyte activation in patients with venous stasis ulcers. *J Surg Res*, **59**, 553–559.

Rice K. I. (1994) Magnetic resonance flowmetry: Clinical applications. *J Vasc Tech*, **18**, 277–285.

Salles-Cunha S. X. & Beebe H. G. (1994) Magnetic resonance blood flowmetry: A review. *J Vasc Tech*, **18**, 141–147.

Smith P. D. C., Thomas P., Scurr T. & Dormandy J. A. (1988) Causes of venous ulceration: A new hypothesis. *Br Med J*, **296**, 1726–1727.

Thomas S., Nash G. B. & Dormandy J. A. (1988) White cell accumulation in dependent legs of patients with venous hypertension: A possible mechanism for trophic changes in the skin. *Br Med J*, **296**, 1693–1695.

Wilkinson L. S., Bunker C., Edwards J. C. W., Scurr J. H. & Coleridge-Smith P. D. (1993) Leukocytes: Their role in the etiopathogenesis of skin damage in venous disease. *J Vasc Surg*, **17**, 669–675.