Medical Compression: Effects on Pulsatile Leg Blood Flow

H. N. Mayrovitz[1] and J.M Macdonald[2]
[1]Nova Southeastern University, College of Medical Sciences, Ft Lauderdale, FL, USA
[2]Miller School of Medicine, University of Miami, Miami, FL, USA

The paper is based on a presentation given at a meeting of the International Compression Club (ICC) in Lucca, Sept. 2008. This congress was dedicated to the problem of the assessment of effects of compression therapy on the human extremities and all presenters were invited to submit their articles to International Angiology.

Short Title: Compression effects on pulsatile blood flow

Correspondence and Proofs to:
Harvey N. Mayrovitz, PhD
College of Medical Sciences
Nova Southeastern University
3200 S. University Drive
Ft. Lauderdale, Florida 33328
954-262-1313
mayrovit@nova.edu

ABSTRACT

Background: Leg compression bandaging is the mainstay of venous ulcer treatment, yet little is known about the impact of therapeutic compression levels on arterial haemodynamics. In this study, the effect of foot-to-knee, four-layer compression bandaging on below-knee arterial pulsatile blood flow was assessed by nuclear magnetic resonance flowmetry.

Methods: In 14 healthy supine subjects, bilateral pulsatile blood flow measured at five below-knee sites without compression; and during compression of one leg to an average malleolar sub-bandage pressure of 40·7±4·0 mmHg.

Results: The forefoot-to-knee compression bandaging caused a highly significant ($P<0.001$) increase in the bandaged leg pulsatile blood flow due to increases in both peak flow and pulse width.

Conclusions: It is hypothesized that arteriolar vasodilatation, induced either myogenically by reduced transmural pressure or by vasodilatory substance release triggered by increased venous shear stress and veno-arterial interactions, possibly combined with altered vascular compliance, produce the observed compression-related phenomenon. Whatever the mechanism(s), the finding of a compression-associated pulsatile flow increase suggests an arterial linkage, which may play a role in the well-documented beneficial effects of compression bandaging in venous ulcer and lymphedema treatment. Possible beneficial effects of the arterial flow-pulse increase on venous ulcer outcome may be related to a decrease in leukocyte effects in the distal microvasculature.

Key words: blood flow, venous ulcer, lymphedema, hemodynamics,

INTRODUCTION

As a therapeutic modality external compression of the limbs is used on an intermittent basis for edema and lymphedema reduction and sustained compression bandaging is the mainstay of effective treatment of venous conditions and the treatment of venous ulcers. In conjunction with the latter there has been interest and experimental work regarding the effect of compression therapy on venous hemodynamics. However, there is very little known with regard its effect on arterial hemodynamics, especially leg pulsatile blood flow. Since the magnitude of pressures routinely used are about 40 mmHg, and in some cases higher, it was reasoned that even though these pressures are less than arterial diastolic pressure there might be an impact on leg pulsatile blood flow. Because the magnitude and pattern of leg flow pulses depend on arterial compliance, peripheral vascular impedance and complex reflected wave phenomena that might be influenced by external compression, this study was done to provide data on the type and nature of alterations in leg pulsatile blood flow features that might be associated with medical compression bandaging. For this purpose nuclear magnetic resonance flowmetry (NMRF) was used to measure pulsatile blood flow bilaterally at five below-knee sites before and during application of a four-layer compression bandage to one of the legs.

METHODS

Subjects and Preliminary Evaluations

Healthy volunteer subjects (N=14, seven female, age 42 ± 5.3 years) were studied after signing an Institutional Review Board approved informed consent. Subjects were free of diabetes and lower extremity venous or arterial disease. Measured systemic blood pressures showed that the group was normotensive (systolic 126 ± 4.7, diastolic 84 ± 3.2 mmHg).

Leg Pulsatile Blood Flow Methodology

Pulsatile blood flow (PBF) was measured under resting supine conditions by nuclear magnetic resonance flowmetry (NMRF) in which a subject is placed on a moveable table that is advanced so as to position a specific leg site within the center of a tubular measurement section of the NMRF system Within this section a 0.1 Tesla fixed magnet causes hydrogen nuclei of fluids within the leg to precess with an NMR sensor detecting the amount of precession. The main NMR signal detected and processed is due to precession of hydrogen nuclei of intravascular water. This signal is proportional to the number of precessing hydrogen nuclei and is thus proportional to the amount of vascular water flowing into and out-of the measurement section. Non-pulsatile flow produces small contributions which are filtered out by the system. The measured PBF depends on a flow-induced adiabatic tipping of the nuclear magnetization in all flows within the limb cross section. Blood perfusion information is generated by dividing cross-sectional flow rate by the volume of tissue distal to the cross section. Calibration to obtain absolute PBF 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 phantom has simulated vessels which are positioned within the NMRF measurement region. Further technical details and theoretical aspects regarding this method may be found in the literature (1-4).

Leg External Compression

Leg compression was produced by wrapping one leg from fore-foot to knee with a four-layer bandaging system designed and used therapeutically for treatment of venous ulcers. In all subjects, bandaging was done by the same person who had extensive experience. Prior to bandaging a pressure sensor was placed on the medial aspect of the leg 4-5 cm. proximal to the malleolus to record sub-bandage pressures. The sub-bandage pressure recorded for the group was 40.7 ± 4.0 mmHg which is near the target level recommended for therapeutic use (40 mmHg).

Blood Flow Procedure and Parameters

PBF (ml/min) was measured at five below knee sites located 10%, 25%, 50%, 75% and 90% of the measured length between the lateral malleolus and the tibia tubercle with the malleolus as the 0% reference. Each pulse waveform was integrated over a cardiac cycle and ensemble averaged for 15-20 beats. PBF at each site includes the sum of all pulsatile arterial flow passing peripherally through the leg cross section within an axial segment five cm in length. Pulsatile perfusion (ml/min/100cc) was calculated by dividing PBF by the leg volume distal to the measurement site. An estimate of the relative broadness (width) of the flow pulse at each site was determined by measuring its width at one-half of the flow pulse maximum amplitude. Flow parameters were compared with respect to differences before compression bandaging and with compression in place. Also, paired-leg parameter ratios (compressed 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

A typical response to compression bandaging is illustrated in **figure 1**.

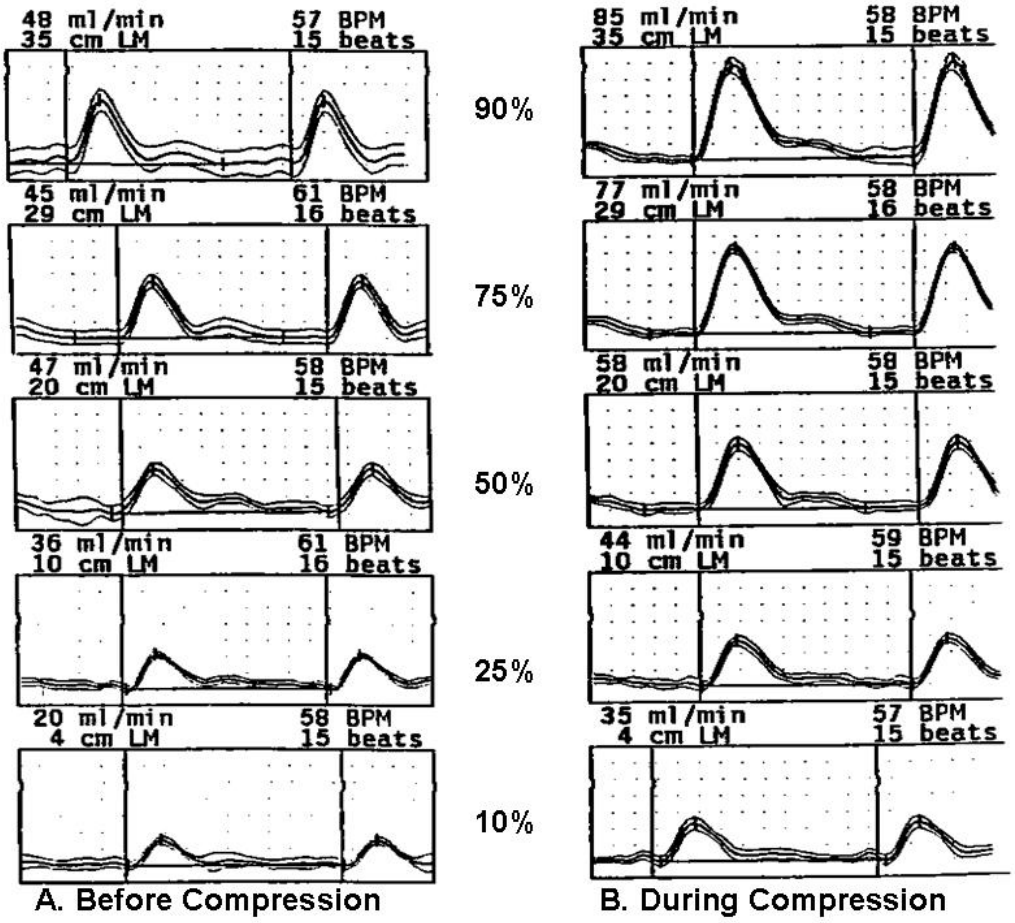


Figure 1 Pulsatile blood flow (PBF) before and during leg compression bandaging Flow waveforms at five below knee sites in a subject before compression (A) and during compression (B) show an increase in flow-pulse amplitude and width at all sites. The 90% site is closest to the knee and the 10% site closest to the ankle. PBF values (ml/min) are shown at the top left for each site. Heart rate (BPM) are shown at the top left during recording for each site. PBF values are the ensemble average of 15 consecutive beats.

PBF waveforms before compression are shown in A and during compression in B. There was a generalized increase in flow during compression with the flow-pulse peak and width showing an increase at every measured site. Flows increased without an appreciable change in average heart rate which for this subject was 59 bpm before and 58 bpm during compression.

The composite group data, shown in **figure 2**, indicates that PBF during compression was significantly greater ($p<0.001$) at all sites save the 10% site, with a tendency for a greater flow differential at the more proximal leg sites. Considering total below-knee arterial PBF perfusion, compression bandaging caused a highly significant ($p<0.001$) increase, with PBF perfusion increasing from 1.64 ± 0.11 to 2.11 ± 0.14 ml/min/100cc. Contrastingly, during compression of one leg, the contralateral unbandaged leg showed a slight ($p<0.05$) decrease from 1.69 ± 0.11 to 1.55 ± 0.08 ml/min/100cc. Separate analyses of the flow-pulse peak amplitude show that the compressed leg / control leg ratio was significantly increased at all sites and the flow-pulse width was significantly increased at the more proximal sites.

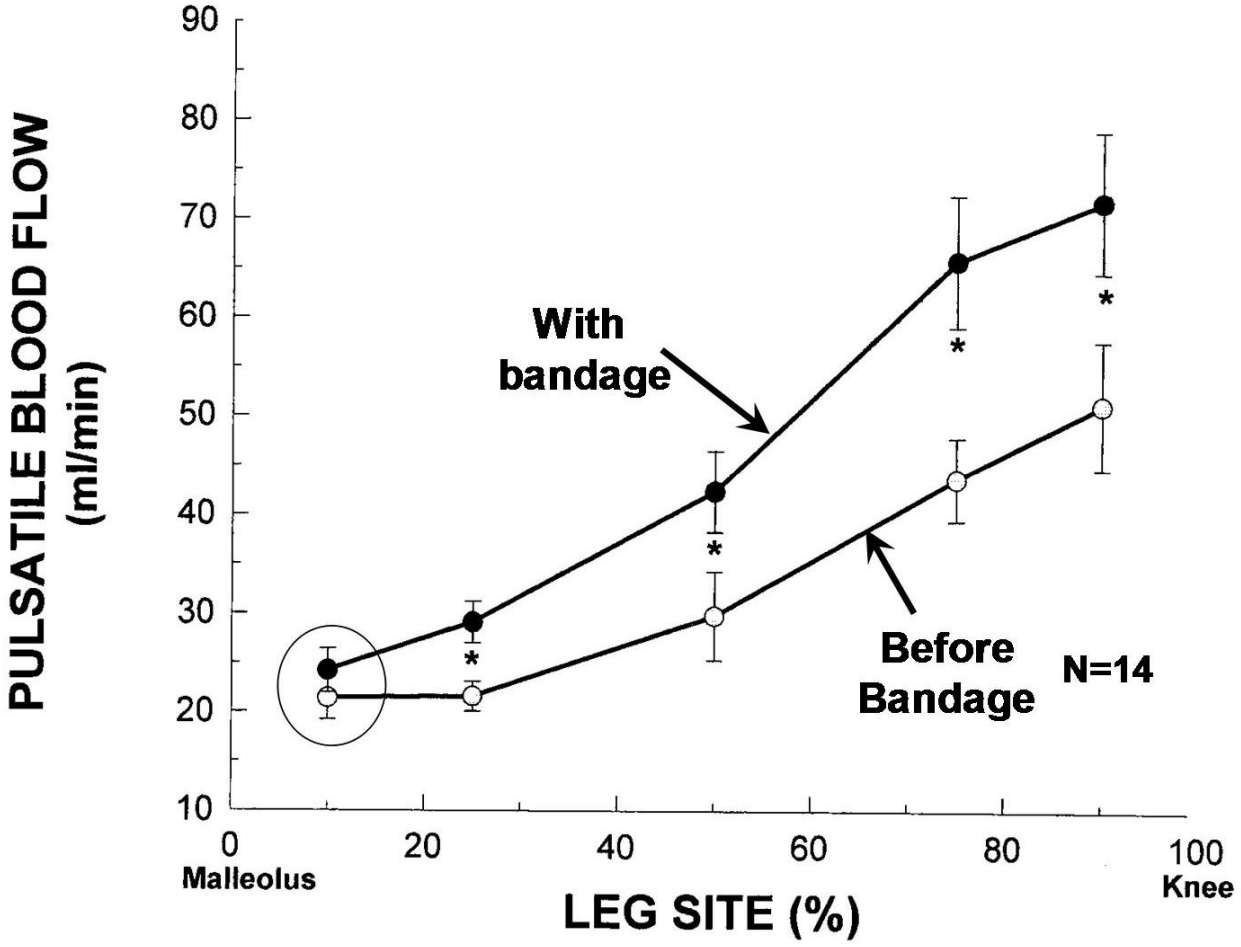


Figure 2: Compression effect on pulsatile blood flow at each below-knee site. Leg sites are shown as percentages of the distance between the lateral malleolus and the tibia tubercle with the malleolus as the zero reference. Except for the most distal site (10%), compression produced a significant increase in all measured sites *$p<0.001$. Error bars are ± 1 SD.

Figure 3 shows a posterior tibia artery duplex Doppler ultrasound recording made in one subject illustrating the peak blood velocity increase associated with bandaging.

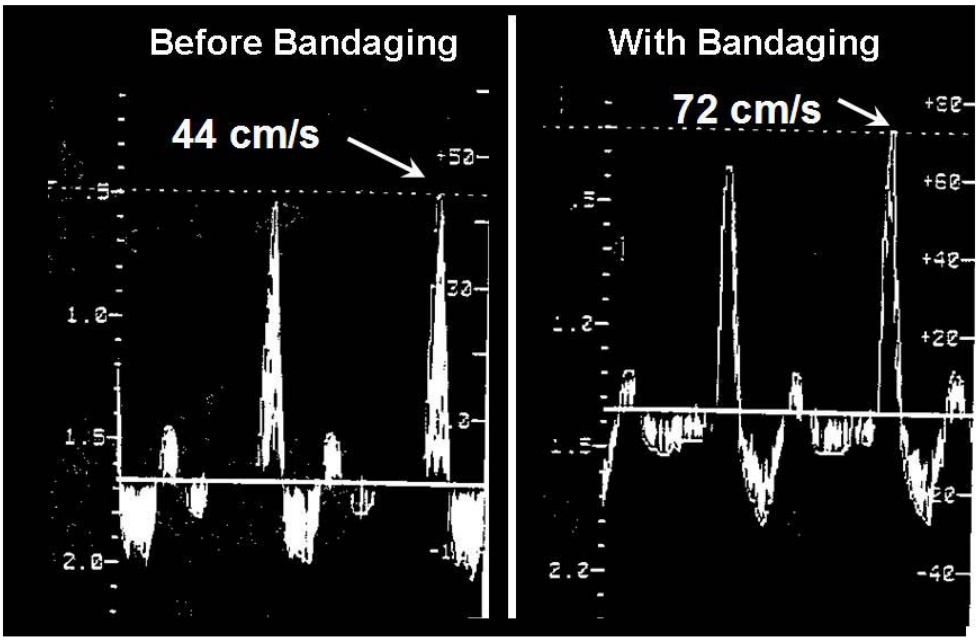


Figure 3: Posterior tibia artery blood velocity without and with leg bandaging
Doppler ultrasound recording (one subject) made prior to compression bandaging (A) and with bandaging in place (B) shows a blood velocity increase consistent with the overall findings using the nuclear magnetic resonance flowmetry method. In the illustrative case shown, when the bandage was removed the blood velocity returned to its pre-bandage levels within two minutes.

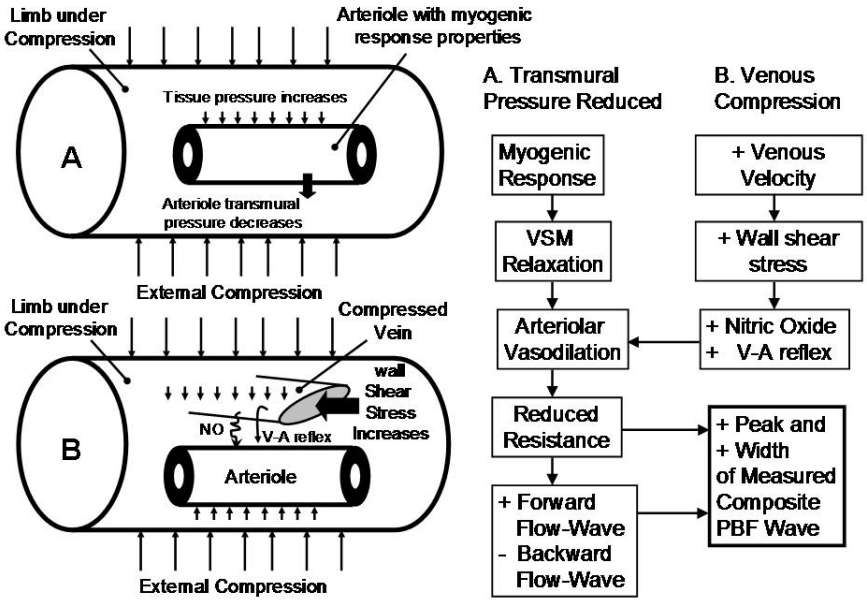
DISCUSSION

The findings demonstrate a significant increase in arterial PBF produced by fore-foot to knee compression bandaging at pressure values routinely used therapeutically. Analysis of flow-pulse waveform morphology shows the flow increase is due to increased peak flow and flow-pulse broadening. These findings raise several physiological and clinically related questions. From the physiological side there is the question of operative mechanisms and a prime clinical question is if and how such pulsatile flow augmentation impacts treatment outcomes.

Because the PBF waveform is dependent on various interactive factors not intrinsically studied, the underlying mechanisms responsible for the flow increase are speculative. It is the author's view that the observed compression-related alteration in the PBF waveform is consistent with changes in arterial pulse-wave phenomena caused by compression-related changes in arteriolar resistance and arterial compliance. PBF waveforms at any leg cross-section depend on the summed forward and reflected flow waves within the set of arterial vessels at the cross-section. Normally, the leg distal vasculature presents a resistance to the forward moving wave that is high compared to the characteristic impedance of the artery (5-7). The impedance mismatch produces reflected flow-waves nearly 180^{o} out-of-phase with incident waves, which destructively

interferes with forward waves. When the arteriolar vasculature dilates reflected flow-waves are thus reduced in magnitude and altered in phase causing the measured composite PBF wave pattern to increase in peak and demonstrate pulse widening. Since this pattern is observed due to compression bandaging in every subject who was tested, it is plausible that an arteriolar vasodilation is involved, for which two broad possibilities may be offered. One relates to a reduced arteriolar resistance subsequent to a compression-related reduction in arteriolar transmural pressure and one relates to arteriolar vasodilation induced by compression-related effects on the venous system.

Possible Myogenic Effects Triggered by Compression: Because of the small diameter and thick-walled structure of arterioles, compression pressure values as used in this study would not mechanically reduce arteriolar diameters as would occur for veins or lymphatic vessels. But, whereas limb exposure to sub-atmospheric pressures causes increased transmural pressure (8), increased extravascular tissue pressure due to external compression reduces arteriolar transmural pressure and sets the stage for an adaptive myogenic vasodilatory response (9-12). Experimental evidence for this in humans at external pressures between 10-30 mmHg has been reported (13, 14) and increases in skin blood perfusion produced by regional leg compression has also been documented (15). **Figure 4A** schematizes the way this possible mechanism might work.



Possible Venous Effects triggered by Compression: Increased blood flow velocity in veins of the lower extremity has been demonstrated with external compression between 30-50 mmHg (16-18). Increased endothelial shear stress due to such velocity increases may elicit release of vasodilatory substances (19) which subsequently impact the arteriolar vasculature (20). Evidence for such venous-arteriolar linkages has been described (21, 22) and may play a role in the well documented effects of static (23, 24) and possibly intermittent (25-28) compression therapy. **Figure 4B** schematizes possible ways in which this venous-arteriolar process might work.

The impact of such arteriolar dilation, whether due to myogenic, venous or other factors, on the measured flow-pulse wave would be expected to cause an increase in peak flow associated primarily with the forwardly transmitted flow-pulse into a distal region of lowered vascular resistance and to reduce the reflected wave thereby resulting in a broadened flow-pulse. An additional factor that probably contributes to the augmentation of the PBF wave is a change in artery dynamic compliance associated with a compression-related reduction in arterial

transmural pressure. Such compliance changes would alter the pulse-wave velocity which is an important determinant of PBF features. Though indeed speculative, the concepts presented provide self consistent and testable explanations. Clearly further experimental work will be required to test these concepts and further clarify the mechanism of the observed compression-related pulsatile blood flow augmentation.

In summary, lower extremity forefoot-to-knee compression bandaging of the type and level herein used results in an increase in leg pulsatile blood flow as a consequence of increases in both peak flow and pulse-width. The mechanism for this is hypothesized to be arteriolar vasodilation due to either or both a myogenic arteriolar response and a shear dependent venous effect with possible additional effects on arterial pulse-wave speed. Whatever the mechanism(s), the finding of a compression-associated pulsatile flow increase suggests an arterial linkage, which may play a role in the well-documented beneficial effects of compression bandaging in venous ulcer and lymphedema treatment. A possible impact of the arterial flow-pulse increase is speculated to effect venous ulcer outcome via a decrease in leukocyte effects in the distal microvasculature due to the more vigorous arterial haemodynamic state.

REFERENCES

1. Battocletti JH. Blood flow measurement by NMR. Crit Rev Biomed Eng. 1986: 13(4): 311-67.
2. Kerr TM, Cranley JJ, Johnson JR, Lutter KS, Duldner JE, Sampson MG. Measurement of blood flow rates in the lower extremities with use of a nuclear magnetic resonance based instrument. J Vasc Surg. 1991: 14(5): 649-57.
3. Kofler JM, Jr., Morin RL, Johnson CM. Performance testing of a dedicated magnetic resonance peripheral blood flow scanner. Med Phys. 1991: 18(5): 1057-62.
4. Mayrovitz HN, Larsen PB. Pulsatile blood flow asymmetry in paired human legs. Clin Physiol. 1996: 16(5): 495-505.
5. McDonald D. The relation of pulsatile pressure to flow in arteries. J Physiol. 1955: 127(3): 533-52.
6. Nichols WW, Denardo SJ, Wilkinson IB, McEniery CM, Cockcroft J, O'Rourke MF. Effects of arterial stiffness, pulse wave velocity, and wave reflections on the central aortic pressure waveform. J Clin Hypertens (Greenwich). 2008: 10(4): 295-303.
7. O'Rourke MF, Yaginuma T. Wave reflections and the arterial pulse. Arch Intern Med. 1984: 144(2): 366-71.
8. Coles DR, Kidd BS, Patterson GC. The reactions of the blood vessels of the human calf to increases in transmural pressure. J Physiol. 1956: 134(3): 665-74.
9. Bayliss WM. On the local reactions of the arterial wall to changes of internal pressure. J Physiol. 1902: 28(3): 220-31.
10. Folkow B. Transmural pressure and vascular tone--some aspects of an old controversy. Arch Int Pharmacodyn Ther. 1962: 139: 455-69.
11. Mellander S, Oberg B, Odelram H. Vascular Adjustments to Increased Transmural Pressure in Cat and Man with Special Reference to Shifts in Capillary Fluid Transfer. Acta Physiol Scand. 1964: 61: 34-48.

12. Nielsen HV. External pressure--blood flow relations during limb compression in man. Acta Physiol Scand. 1983: 119(3): 253-60.
13. Caro CG, Foley TH, Sudlow MF. Forearm vasodilatation following release of venous congestion. J Physiol. 1970: 207(2): 257-69.
14. Holloway GA, Daly CH, Kennedy D, Chimoskey J. Effects of external pressure loading on human skin blood flow measured by 133Xe clearance. J Appl Physiol. 1976: 40(4): 597-600.
15. Abu-Own A, Shami SK, Chittenden SJ, Farrah J, Scurr JH, Smith PD. Microangiopathy of the skin and the effect of leg compression in patients with chronic venous insufficiency. J Vasc Surg. 1994: 19(6): 1074-83.
16. Lawrence D, Kakkar VV. Graduated, static, external compression of the lower limb: a physiological assessment. Br J Surg. 1980: 67(2): 119-21.
17. Meyerowitz BR, Nelson R. Measurement of the Velocity of Blood in Lower Limb Veins with and without Compression. Surgery. 1964: 56: 481-6.
18. Stanton JR, Freis ED, Wilkins RW. The acceleration of linear flow in the deep veins of the lower extremity of man by local compression. J Clin Invest. 1949: 28(3): 553-8.
19. Falcone JC, Bohlen HG. EDRF from rat intestine and skeletal muscle venules causes dilation of arterioles. Am J Physiol. 1990: 258(5 Pt 2): H1515-23.
20. Boegehold MA. Shear-dependent release of venular nitric oxide: effect on arteriolar tone in rat striated muscle. Am J Physiol. 1996: 271(2 Pt 2): H387-95.
21. Saito Y, Eraslan A, Hester RL. Importance of venular flow in control of arteriolar diameter in hamster cremaster muscle. Am J Physiol. 1993: 265(4 Pt 2): H1294-300.
22. Saito Y, Eraslan A, Lockard V, Hester RL. Role of venular endothelium in control of arteriolar diameter during functional hyperemia. Am J Physiol. 1994: 267(3 Pt 2): H1227-31.
23. Belcaro G, Christopoulos A, Nicolaides AN. Diabetic microangiopathy treated with elastic compression--a microcirculatory evaluation using laser-Doppler flowmetry, transcutaneous PO2/PCO2 and capillary permeability measurements. Vasa. 1990: 19(3): 247-51.
24. Belcaro G, Grigg M, Vasdekis S, Rulo A, Christopoulos D, Nicolaides A. Evaluation of the effects of elastic compression in patients with postphlebitic limbs by laser-Doppler flowmetry. Phlebologie. 1988: 41(4): 797-802.
25. Delis KT, Husmann MJ, Cheshire NJ, Nicolaides AN. Effects of intermittent pneumatic compression of the calf and thigh on arterial calf inflow: a study of normals, claudicants, and grafted arteriopaths. Surgery. 2001: 129(2): 188-95.
26. Delis KT, Nicolaides AN, Wolfe JH. Peripheral sympathetic autoregulation in arterial calf inflow enhancement with intermittent pneumatic compression. Eur J Vasc Endovasc Surg. 2001: 22(4): 317-25.
27. Griffin M, Kakkos SK, Geroulakos G, Nicolaides AN. Comparison of three intermittent pneumatic compression systems in patients with varicose veins: a hemodynamic study. Int Angiol. 2007: 26(2): 158-64.
28. Nicolaides AN, Fernandes e Fernandes J, Pollock AV. Intermittent sequential pneumatic compression of the legs in the prevention of venous stasis and postoperative deep venous thrombosis. Surgery. 1980: 87(1): 69-76.