Chapter 7.

Hemodynamic effect of different types of compression (pressure and stiffness) on venous haemodynamics and the microcirculation

**Pathophysiology of venous hemodynamic impairment**

Venous pressure in the leg is different in the different body positions: in the supine position it is lower than 20 mm Hg while in the standing position it corresponds to the weight of the blood column between the right heart and the measuring point. In a dorsal foot vein the venous pressure in the standing position is about 80-100 mm Hg in both healthy subjects and in patients with venous insufficiency (1,2).

In the healthy subject, the peripheral muscle pump is able to reduce the venous standing pressure from approximately 80-100 mm Hg to less than 30 mm Hg within a few steps (1,2). In patients with venous disease due to chronic obstruction or valvular incompetence venous return is impaired and a failure to reduce venous pressure with exercise occurs: the intravenous pressure in the distal leg remains at about 50 mm Hg or higher. This condition, termed ambulatory venous hypertension (3,4), results in a reduction of the ejection fraction from the lower leg (5,6).

Another important cause for ambulatory venous hypertension is a dysfunction of the venous calf pump due to muscle weakness or joint dysfunction.

As CVD progresses, the valvular function deterioration produces an increase of venous reflux, venous volume and calf muscle pump impairment resulting in a further increase of ambulatory venous hypertension (7). When deep venous obstruction is the main pathophysiological mechanism of CVD the valvular insufficiency and the calf muscle pump dysfunction are even more severe, and the ambulatory venous hypertension higher than in patients without evidence of obstruction (7). It has been shown that ambulatory venous hypertension correlates with the severity of resulting clinical symptoms of chronic venous disease (CVD).

**Compression materials, Pressure and Stiffness**

Compression stockings, different types of bandages, adjustable velcro-band-devices and pumps may be used. Essential differences between these devices concerning their hemodynamic implications are the pressure and the elastic property of the materials.

Compression Pressure

The pressure exerted by a device on the extremity corresponds to the dosage of compression therapy.

The pressure produced by a stocking is determined by the compression class of the hosiery in relation to the individual leg size which is measured by the prescriber and will rarely exceed a resting pressure over 40 mmHg (8). The pressure exerted by a bandage depends mainly on the strength of application. Inelastic bandages and Velcro band devices with short extension are usually applied under full stretch and produce initial pressures of 60 mmHg and more. These high initial pressures will drop immediately, mainly due to edema reduction (9). In contrast to inelastic bandages which should be applied by trained staff, requiring some skill and experience, Velcro band devices can be put on and re-adjusted by the patients themselves.

Pumps (see Chapter 8) consisting of several circumferential cuffs which are intermittently inflated with air at variable sequence and pressure will be considered in this chapter only as models in comparison with conventional compression systems.

Stiffness

Stiffness of a compression device is defined as the pressure increase induced by an increase in leg circumference of 1 cm (8) and represents the relationship between its resting and working pressures. Based on stiffness compression materials are differentiated in “elastic” and “inelastic”. Elastic or long-stretch material is extensible to more than 100%. Inelastic material may be “no-stretch” (e.g. zinc-paste) or short stretch with a maximal extensibility of less than 100%,. By combining several materials over each other the elastic property of the final bandage will change in an unpredictable manner. For instance, multi-component bandages consisting of different elastic components (the so-called “Four layer bandages”) present a stiffness comparable to that of inelastic material due to the friction between the different layers (10 ). It is therefore a misconception to call such bandages “elastic” (11). For this reason the terms of “elastic” and “inelastic” may appropriately be used for single bandages while, the elastic property of a multi-component bandage should rather be characterized by stiffness for which in vivo assessment has been proposed (12-14).

Stiffness in vivo can be assessed by measuring the pressure under a compression product at the B1 point and by calculating a “Static Stiffness Index (SSI)”, subtracting the supine from the standing pressure, (13,14). The B1 point is defined by the transition of the muscular into the tendinous part of the part of the medial gastrocnemius muscle, showing the biggest increase of the leg circumference by dorsiflexion. As a cut-off between elastic and inelastic material a value of 10 was proposed (12). Elastic material is characterized by values lower than 10; inelastic by values higher than 10. Other parameters of stiffness correlating with SSI are the maximal pressure achieved during exercise, pressure peaks, and pressure amplitudes during walking (the difference between systolic and diastolic pressure) (15).

Stiffness plays an important role in the performance of compression devices during standing and walking. With muscle contraction, elastic material gives way to the muscle volume increase exerting a sub-bandage pressure which will be only slightly higher than the lying pressure. Inelastic, stiff material doesn’t give way to the muscle expansion and the exerted pressure will rise significantly to the range able to overcome the intravenous pressure thereby producing a significant vein narrowing or occlusion. These important differences concerning the pressures of inelastic and elastic materials are shown in Fig. 1.



Fig. 1: Sub-bandage pressure tracings: a) elastic bandage (top), b) elastic bandage strongly applied (middle) and c) inelastic bandage (bottom). The resting pressure of a) and c) are around 40 mmHg. The pressure increase by standing up (=SSI) for a) is 4,5 , for c) 20,8. During walking the pressure amplitudes (“massaging effect”) are much higher under the inelastic than under the elastic bandages.

According to the law of Pascal there is an equal increase of pressure at any point inside the system in a closed, non-yielding container when pressure increases by muscle activity. The energy created by functional activity is maintained so that already minimal muscle movement will create great variations in pressure (16).

Due to its elastic properties, elastic material would need to be applied with very strong pressure at rest to achieve a similar high standing and working pressure and consequently would be painful and intolerable. (17)

**Impact of Pressure and Stiffness on disturbed Venous Haemodynamics**

Different imaging procedures like phlebography, Duplex ultrasound or magnetic resonance imaging (MRI) were able to demonstrate a narrowing of venous diameter by external compression, which is a prerequisite for its hemodynamic efficacy. The degree of narrowing depends on the body position and the amount of compression pressure.

In the supine position a pressure of about 20 mm Hg is enough to narrow the veins (18-22) which causes a shift of blood volume towards the heart (23) . The resulting increase of the preload of the heart needs to be taken into consideration in patients with cardiac disease. At the same time the reduction of venous calibre leads to an increase of venous blood flow velocity, demonstrable by measuring the mean transit time to the groin after injection of radio-tracers into a dorsal foot vein (24,25) and by Doppler and Duplex investigations (26-29).

In the upright position, pressures of 70-80 mm Hg are necessary to counteract the standing intravenous pressure and to achieve a reduction of the venous diameter, clearly shown by phlebography (30), Duplex (21,31) and, recently, by MRI (32-34). To compress the femoral vein at thigh level in upright position a minimal pressure of 60 mmHg is required (20). Surprisingly it could be shown that in the prone and in the standing position compression may lead to a more pronounced narrowing of deep than of superficial veins, probably due to a shift of the muscle compartments (32-34).

While walking the external compression created by inelastic material produces pressure peaks with every muscle systole, which overcome the intravenous pressure and lead to an intermittent narrowing of the veins, demonstrated by Duplex (21). Measuring the pressure in a dorsal foot vein in patients with avalvulia it could be shown that a thigh cuff inflated to 70 mmHg was able to cut down the elevated intravenous pressure peaks during walking reflecting venous reflux, which led to a reduction of mean ambulatory venous hypertension (35). Based on Duplex-investigations in patients with superficial reflux it has been speculated that a coaptation of valvular cuffs to restore valvular competence may be the mechanism of action of compression therapy in venous disease. (36)

However, the important hemodynamic improvement of the impaired pumping mechanism even in avalvulia can certainly not be explained by a kind of re-approaching of damaged valves by external compression, but is rather the result of intermittent venous narrowing during walking, creating a kind of artificial valve mechanism which blocks reflux with every muscle contraction (35). Measuring venous pressure in a dorsal foot vein while walking on a treadmill in patients with severe venous insufficiency revealed similar results: by cutting down the systolic peaks of the intravenous pressure curve using inelastic compression bandages exceeding a resting pressure over 50 mmHg the values of mean ambulatory hypertension could significantly be reduced, while this could not be achieved using elastic stockings with much lower pressure (37).

However, O’Donnell et al. were able to demonstrate in patients with post-thrombotic syndrome a significant reduction of the maximal pressure peaks under strong compression stockings. (38)

Abolishment of venous reflux by strong and stiff compression can also be shown in experiments in which global venous reflux was quantified in patients with postthrombotic syndrome and deep venous reflux by air-plethysmography. Venous filling index (VFI), as the parameter quantifying reflux, was reduced by increasing external pressures and inelastic compression was more effective at each pressure range. With a pressure of more than 60 mmHg inelastic bandages could achieve even normal VFI-values corresponding to a complete reflux abolition. (39).

In patients presenting with superficial axial reflux similar results could be obtained by using Duplex ultrasound: increasing leg compression led to a progressive reduction of reflux and sub-bandage pressures of more than 80 mmHg achieved by a non-elastic bandage in the standing position was able to abolish reflux completely (40).

Improvement of venous pumping function in patients with venous insufficiency has also been demonstrated by different plethysmographic techniques, like foot volumetry (41-43), air plethysmography (39,44-46) or strain gauge plethysmography measuring volume changes of the leg proximal to the compressed area (47,48). Using this latter methodology it could be demonstrated that the ejection fraction of the calf pump measured which is reduced in patients with chronic venous insufficiency, can be improved by external compression under standardized exercise (48). There was a significant correlation between ejection fraction and sub-bandage pressure during standing and walking and between ejection fraction and static stiffness index, demonstrating again the hemodynamic superiority of inelastic material (48). This improvement of the pumping function by inelastic compression is mainly based on two hemodynamic mechanisms: one is the abolishment of venous reflux, the other is based on the fact that effective compression will strengthen the venous calf pump by distributing the pressure peaks during each muscle contraction inside the closed system which is covered by a stiff bandage following the law or Pascal (49).

High compression pressures over the calf were shown to be more effective than the conventional pressure gradient of compression devices in increasing the ejection fraction (50,51 ).

**Impact of Pressure and Stiffness on the arterial flow, on microcirculation and edema**

Arterial flow

Measuring the ankle pressure by using a sphygmomanometer on the distal leg and a CW-Doppler instrument gives important information on the local perfusion pressure. Values under 50 mmHg define critical ischemia (52) and are a clear contraindication for a sustained external compression exceeding this value. However, it was demonstrated that especially designed intermittent pneumatic compression pumps providing pressures of more than 100 mmHg for a very short time period, followed by prolonged periods of pressure release can be quite beneficial in such patients (53).

Using magnetic resonance flowmetry Mayrovitz and Macdonald reported in a group of healthy persons an increase of pulsatile arterial flow under stiff, multi-component ankle to knee bandages applied with a pressure around 40 mmHg (54). Only few data are available concerning the influence of sustained compression on the arterial flow in patients with arterial occlusive disease. Top et al showed that inelastic compression bandages did not reduce toe pressure (55). This is in accordance with findings from Mosti et al. who demonstrated that in patients with mixed arterial ulcers and an ABPI between 0,5 and 0,8 there was no reduction but even an increase of Laser Doppler flux under the bandage as long as the exerted resting pressure of inelastic bandages did not exceed 40 mmHg. At the same time the authors could also demonstrate a significant improvement of the venous pumping function in these mixed ulcer patients (56).

Microcirculation

As a consequence of ambulatory venous hypertension various changes of the microcirculation have been described (57,58).

Experimental work has shown beneficial effects of compression on such changes.

In patients with chronic venous insufficiency capillary microscopy revealed an increase in capillary density associated with a decrease in capillary diameter and pericapillary halo diameter after 2 weeks of compression (59).

Limb oxygenation measured by HbO2 concentration during walking exercise, could be shown to increase with stronger compression stockings reaching significance with class III stockings only (60). Abu Own et al. showed increasing Laser Doppler flux values in normal and lipodermatosclerotic skin areas of the lower leg under a compression up to a pressure of 60 mmHg in the sitting position (61).

The influence of compression on the physiologic vasoconstrictor response induced by leg dependency demonstrated by 133 Xenon clearance (62) and laser Doppler fluxmetry (63, 64) has been discussed. Patients with arterial occlusive disease show a reduced vasoconstrictor response which is augmented under intermittent pneumatic compression (64).

Impressive biochemical changes were reported with intermittent compression pumps which may be taken as a model for the intermittent compression under inelastic bandages during walking (65). Due to intermittent compressive strain and shear on endothelial cells several anti-coagulatory, anti-inflammatory and vasodilating mediators are released from the endothelial cells. Inflammatory cytokine levels in leg ulcer tissue were demonstrated to be reduced 4 weeks after compression therapy (66). Compression therapy results in a reduction of the pro-inflammatory environment characterizing chronic venous ulcers by decreasing elevated matrix metalloproteinases (MMP) levels (67).

Edema

Following the law of Starling, edema develops because of a complex interaction that involves the permeability of the capillary wall and the hydrostatic and oncotic pressure gradients that exist between the blood vessels and the tissues. Edema will form when net capillary filtration in the affected site exceeds lymphatic drainage. (68,69). The lymphatic drainage is always a major key-factor since in peripheral tissues, practically 100% of liquid is removed by the lymphatic circulation(69).

Studies using micro-lymphangiography and indirect lymphography have demonstrated that micro-lymphangiopathy is a typical feature of chronic venous insufficiency (57, 70). In spite of these overlaps the problem of lymphedema and its treatment by compression is outside the scope of this chapter and will therefore not further discussed.

Compression counteracts edema formation especially by increasing the tissue pressure (71) and is also able to normalize the pathological pattern of damaged initial lymphatics in patients with skin changes due to chronic venous insufficiency (72).

Edema reduction by compression is clinically so evident that only relative few studies were interested to investigate a dose-response relationship, measuring compression pressure and stiffness in relation to the amount of volume reduction. It could be demonstrated that low pressure stockings (less than 20 mmHg) are able to prevent occupational edema in people with standing profession (73,74) and that also for reducing chronic edema lower pressures are effective compared to those which are needed to compress a vein (75,76).

**Indications for compression devices based on hemodynamic evidence**

Based on the experimentally demonstrated effects different compression devices have gained rational support for several clinical indications. Table I summarizes levels of evidence concerning some hemodynamic effects that have been demonstrated in several trials.

|  |  |  |  |
| --- | --- | --- | --- |
| **Statements concerning**  **hemodynamic effects of compression** | **Level of**  **Evidence**  **A. High quality**  **B. Moderate**  **quality**  **C. Low or very**  **low quality** | **Methodolgy** | **References** |
| **Compression stockings < 20mmHg** |  | | |
| narrow superficial and deep veins in horizontal position | A | MRI | 32,33 |
| increase venous flow velocity | B | Radio-tracers, Doppler-Duplex | 24-29 |
| prevent leg swelling after long sitting/swelling | A | Volumetry | 73,74 |
| reduce leg edema | B | Volumetry | 75,76 |
| **Compression stockings 20-40mmHg** |  | | |
| May narrow deep but not superficial veins in standing position | B | MRI | 34 |
| reduce leg edema | A | Volumetry | 75,76 |
| reduce reflux | A | APG, Duplex | 39,40 |
| improve venous pumping function | A | APG, foot volumetry, plethysmography | 36,37, 41-46 |
| reduce ambulatory venous hypertension | A | Venous pressure measurement | 38 |
| **Stiff bandages 20-40 mmHg** |  | | |
| reduce leg edema | A | volumetry | 75,76 |
| reduce reflux more than stockings | A | APG, Duplex | 39,40,45 |
| improve venous pumping function more than stockings | A | APG, foot volumetry, plethysmography | 17, 37, 39,45 |
| increase arterial flow | A | Nuclear magnetic flowmetry, Laser Doppler, | 54,56 |
| **Stiff bandages 40-80 mmHg** |  | | |
| Narrow superficial and deep veins in standing position | A | MRI | 22 |
| intermittently narrow leg veins during muscle systole | B | Duplex | 21 |
| reduce leg edema | A | volumetry | 76,83 |
| reduce reflux more than stockings | A | APG, Duplex | 39,40, 45 |
| improve venous pumping function more than stockings | A | APG, foot volumetry, plethysmography | 17, 39,45 |
| reduce ambulatory venous hypertension more than stockings | A | Venous pressure measurement | 37 |

Table I: Hemodynamic effects of compression therapy in chronic venous insufficiency and level of evidence.

Compression hosiery

Elastic stockings are very effective in reducing vein diameter in the supine position thereby increasing venous flow velocity (Grade A). This is the basis for the recommendation to use elastic stockings exerting 18 mm Hg for the prevention venous thromboembolism (77).

The main role of compression stockings is to prevent and to reduce swelling which is a major challenge in the long-term management of chronic venous disease.

Compression stockings with a pressure of less than 20 mmHg are able to prevent edema after long sitting, as e.g. during long haul flights and after long standing (occupational edema) (Grade A).

Elastic stockings with higher pressure are effective also in the upright position to reduce reflux and increase venous pumping function (Grade A). To achieve higher compression pressures which are still manageable for the patients two stockings may be donned over each other, which cause also an increase of stiffness (78). The basic stocking may stay over night while the second stocking is applied over the first during daily activities when higher external pressure will be needed to counteract gravity.

Compression bandages with high stiffness

Inelastic materials are hemodynamically more effective than stockings, both in reducing reflux and in increasing venous pumping function (Grade A).

Due to the higher standing pressure inelastic devices with high stiffness can achieve this greater effect also starting from relatively low supine pressure of 20 mmHg (79). Inelastic materials are blamed to lose effectiveness overtime due to their pressure loss while elastic materials should maintain their performance as they loose pressure only slightly. It could be demonstrated that this is not the case and that inelastic bandages applied for one week still show an improvement of the venous pumping function after 7 days, despite of a significant pressure loss (Grade B) (80).

The stronger hemodynamic effect of stiff bandages is the reason why they are especially indicated in severe forms of chronic venous insufficiency like in venous leg ulcers.

After interventions on varicose veins compression of the venous lumen (“empty vein”) needs high pressure (82). Compression stockings are too weak to significantly reduce superficial venous diameters in the upright position (21, 31). As demonstrated by MRI in the standing position pressures of more than 60 mmHg are necessary to compress superficial veins on the thigh and lower leg (Grade A). If we want to achieve an “empty vein” after sclerotherapy or after a catheter procedure this can be realized only by very strong bandaging (33,34) or by applying pressure pads over the treated veins in addition to conventional compression. It could be demonstrated that special pads applied under a compression stocking may exert a local pressure of 60 mmHg and consequently a closure of the underlying thigh vein (33, 34, and 82).

Adjustable Velcro band devices

These compression devices consisting of short stretch textiles may be assumed to produce hemodynamic effects comparable to those of inelastic bandages. The main advantage is the fact that, after a short demonstration, they can be applied and re-adjusted by the patients themselves (83).

**Conclusions**

As can be demonstrated in many experimental studies, most of them corresponding to level 1 evidence (Grade A), compression has positive effects on the impaired venous hemodynamic in patients with chronic venous disease causing:

* narrowing of superficial and deep veins, depending on body position and exerted pressure
* an increase of venous blood velocity
* a reduction/abolition of venous reflux
* an improvement/normalization of the venous pumping function and, consequently,
* a reduction/ normalization of ambulatory venous hypertension and an improvement of microcirculation.

Compression is able to counteract the hemodynamic impairment of CVD if the exerted interface pressure is higher than the intravenous pressure. The ideal compression device should therefore exert a low resting pressure (well tolerated at rest and during night time) combined with high standing and working pressure.

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