Physics of Compression

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Abstract

Background:

The deciding parameters concerning hemodynamic efficacy of compression devices are the interface pressure and the stiffness of the compression material.

Aim:

To discuss the relationship between the exerted pressure of different compression devices on venous diameter and intravenous pressure in different body positions.

Methods:

The diameter of leg veins in different body positions has been measured by Duplex under increasing pressure produced by pneumatic cuffs containing ultrasound- permeable windows. The difference of the interface pressure between standing and supine measured proximal to the inner ankle is a parameter for stiffness.

Results:

In the upright position a pressure of about 50-70 mmHg is necessary to narrow and to occlude veins of the lower leg. Intermittent pressure peaks of this magnitude may be obtained during walking under compression material of high stiffness.

Conclusion:

To obtain hemodynamic improvement in patients with severe venous insufficiency the pressure peaks of a compression device should intermittently exceed the local intravenous pressure on the leg during walking. This can preferably be achieved by compression devices with high stiffness resulting in a tolerable resting pressure in the supine position and a high working pressure.

Compression pressure and stiffness

Compression is defined by a force exerted to an area on the body surface. The compression pressure, expressed in Pascal (Pa) is the force of 1 Newton per square meter. In the medical field mainly mm Hg is used as the unit of pressure. (1 mm Hg= 133,3 Pascal).

According to the law of Laplace the pressure will be zero over completely flat areas, while it will be high over sharp edges. The compression pressure P is directly proportional to the tension of the textile (T) but inversely proportional to the radius of the curvature to which it is applied. (P ~T/R).

The pressure developed beneath a bandage is also governed by the width and number of layers applied.

Stiffness is defined as the increase in sub-bandage pressure per centimetre increase in the circumference of the leg (1). This parameter characterizes the elastic property of a compression device and defines the relationship between resting and working pressure. When the muscle contracts, inelastic material will produce a higher increase of interface pressure than elastic, yielding material. To achieve the same pressure peaks elastic material would need to be applied with a much higher pressure which would not be tolerated in the resting position (Fig. 1) .Stiffness may be measured in the laboratory where it corresponds to the slope of the hysteresis curve. The fact that it can also be assessed by in- vivo measurements on the individual leg will certainly be of increasing practical importance in future trials (2).

Compression material

The compression devices most commonly used are summarized in Table I.

Table I: Overview on low and high stiffness compression materials

Low stiffness	**High stiffness**
Compression stockings (single layer)	Rigid bandages (e.g. zinc paste), Velcro-band devices, pumps
Single component elastic bandages	Short stretch bandages, adhesive, cohesive material
	multi-layer bandages

Several layers of bandages or stockings applied over each other make bandages stiffer.

As shown in Fig. 1 inelastic material produces a much higher pressure increase in the upright position than elastic material. When several layers of elastic material are applied over each other stiffness of the final bandage will increase. This is also true for elastic stockings applied over each other (3). Adhesive and cohesive materials increase stiffness.

How can we assess interface pressure and stiffness in vivo?

Several devices to measure interface pressure of compression devices are commercially available. The prerequisites of a good sensor and the ideal measuring sites on the leg have been described in an international consensus paper (2).

The classification of compression stockings varies widely between different countries. The pressure ranges given by the producers are entirely based on vitro-testing. Therefore it was proposed not to use the terminology of compression classes but rather indicate the pressure exerted to the distal lower leg in mmHg. It could be shown that for high quality stockings there is a satisfactory agreement between the pressure data measured in vitro and in vivo(3). For compression bandages in vivo measurements are the only possibility to assess the interface pressure. In a recent consensus meeting it was proposed to classify bandages with a pressure on the distal lower leg of less than 20 mm Hg as mild, 20-40 mm Hg as moderate, 40-60 mm Hg as strong and >60 mmHg as very strong (4).

In order to obtain valuable information on the elastic property of a compression device which may be quite complex when several materials are combined, the so called “static stiffness index (SSI)” may be a useful parameter: A calibrated pressure sensor is fixed to the medial aspect of the leg about 12 cm above the inner ankle. This is the area where the muscular part of the gastrocnemius muscle changes into the tendinous part showing the most extensive changes in local curvature and leg-circumference by changing the body position between supine and standing. The difference between the interface pressure in the standing and in the lying position (mmHg), called SSI, is a valuable parameter for the stiffness of the compression system (2).

The pressure peaks and the pressure amplitudes during walking are also parameters for stiffness and correlate well with SSI. However, these parameters depend on the walking ability of the patient and require measuring systems that allow dynamic pressure readings.

It is important to note that different stiffness indices may be obtained with differently sized sensors .Therefore reliable comparisons will only be possible testing different compression devices by using the same sensor on the same site (2).

Therapeutic aim

The main target of any effective treatment of severe venous disease is to lower ambulatory venous hypertension.   This can be achieved by abolishment of venous refluxes by venous surgery, sclerotherapy or by compression treatment.

One of the main intentions of adequate compression therapy of the lower extremities is to counteract gravity.

Compression is able to affect venous hemodynamics if the interface pressure is high enough to overcome intravenous pressure, always adjusted to the body position. The ideal compression device would exert a low sub-bandage resting pressure in the supine position that is well tolerated during night-time and would show a pressure increase when the patient stands up in order to counteract the increasing intravenous pressure. While walking the external compression should reduce venous refluxes by intermittent narrowing of the veins and should increase the amount of blood pumped up towards the heart with every single step.

Table II summarizes the most important treatment goals.

Clinical indication	**Intended effect**	**Pressure required**
Oedema	Prevention (long sitting)	10-20 mmHg
	Therapy	20-60 mmHg *
Thromboprophylaxis	Acceleration of venous flow (lying position)	10-15 mm Hg
Venous occlusion after surgery, endovenous therapy	Occlusion of dissected branches, „empty vein“ Standing:	Lower leg >70 mm Hg, Thigh 30-60 mmHg
Chronic venous insufficiency (refluxes)	Intermittent narrowing of veins during walking	50-80 mmHg **

*) adjusted to the severity of oedema, limb circumference, consistency of tissue, mobility.

**) adjusted to the degree of ambulatory venous hypertension

Which compression pressure do we need?

In order to prevent leg swelling after prolonged sitting compression stockings exerting a pressure between 10 and 20 mmHg are sufficient (5). Existing oedema can be reduced in a shorter period of time using higher pressures (Table II).

In order to narrow superficial and deep leg veins the external compression pressure should be higher than the intravenous pressure. This can be shown by observing the venous diameter with a Duplex probe through a fenestrated, pneumatic cuff that is gradually inflated (6).The pressures needed to narrow and then to occlude a vein depend on the body position. They correspond to the physiological values; this is about 20 mm Hg in the supine and 50-70 mmHg in the upright position at lower leg level. So called thromboprophylactic stockings are able to accelerate venous blood flow velocity in the supine but not in the upright position.

How to achieve a compression pressure in the range of 50-70 mmHg?

Such high compression pressures may mainly be achieved with strongly applied compression bandages. Ideally these high values should be exerted only during standing and walking and should fall immediately when the patient lies down. The superposition of compression stockings may come close to these pressure ranges.

What are the hemodynamic consequences of higher stiffness?

The effects of compression do not depend only on the interface pressure.

With the same resting pressure inelastic compression material reduces venous refluxes more effectively than elastic bandages (7). In contrast to compression stockings exerting a pressure of around 30 mmHg inelastic bandages applied with a pressure of more than 50 mmHg are able to reduce ambulatory venous hypertension, even in patients with deep vein incompetence (8).

What is the hemodynamic mechanism of high stiffness material?

As it can be demonstrated by Duplex measurement of the venous diameter on the lower leg using a fenestrated inflatable cuff, stiff material can lead to an intermittent occlusion of the lower leg veins with each muscle contraction during walking. For a short moment the sub-bandage pressure peaks during muscle systole will overcome the intravenous pressure and will thereby occlude the vein. Stiff bandages may therefore act like an artificial valve suppressing refluxes during each muscle systole (9). At the same time the muscle veins will be squeezed out and the blood volume expelled towards the heart during walking will be increased. As we know from several experiments using pneumatic compression pumps intermittent pressure waves also have marked effects on the release of vasodilating, anticoagulatory and anti-inflammatory mediators from the endothelial cells (10).

Disadvantages of high stiffness bandages

The application of stiff bandages exerting high pressure is not easy and should be trained. Usually these bandages are applied to the lower leg in the sitting patient whose ankle is in maximal dorsiflexion. In general such bandages should be applied using several layers with a considerably higher resting pressure compared to elastic material. Just by lying down and relaxing the ankle interface pressure will show an immediate pressure drop. This pressure drop will continue in the first minutes and hours when the patient is walking to values that are 30-40% lower compared to the initial pressure, mainly due to an immediate reduction of leg volume. For the next few days only a mild further pressure drop occurs. Depending on the amount of oedema removed the bandages will get loose and have to be renewed accordingly. Compression stockings show only a minor pressure loss.

High stiffness and arterial occlusive disease

Sustained external compression should never exceed the intra-arterial pressure which can be assessed by measuring the systolic ankle pressure using a Doppler probe. Up to now a systolic ankle pressure of 50-70 mmHg was a clear contraindication for any kind of compression therapy. However, some recent experiments using specially designed intermittent pneumatic compression devices have shown that short pressure pulses with peak values of more than 100mm Hg followed by long intervals without pressure may increase arterial blood flow and produce beneficial clinical effects even in severe stages of peripheral arterial occlusive disease (11).

Bandages with high stiffness, applied with intentionally low resting pressure which should be adjusted to the systolic ankle pressure, will produce intermittent pressure peaks in a similar way when the patient is walking or moving the ankles. Especially in patients with oedema and mixed, arterial and venous disease the resulting massage effect of inelastic compression material will reduce the swelling and increase the arterial blood flow.

Elastic bandages exerting a sustained external resting pressure should not been applied in any kind of peripheral arterial disease.

Some practical considerations concerning measurement of pressure and stiffness in vivo

In future trials comparing different compression devices it will be mandatory to measure the “dosage” of the exerted pressure on the individual leg. This is especially important when multi-component bandages are developed, for which the elastic property of the final bandage is unpredictable (4). The pressure that is exerted during standing and walking is more relevant than the resting pressure in the supine position. Measurement of interface pressure is also an ideal educational tool for teaching correct bandaging.

Experienced bandagers will adapt the strength of the applied bandage to the circumference of the leg, to the amount of oedema and to the walking ability of the patient. It is rather unrealistic to adjust the bandage pressure to the degree of ambulatory venous hypertension in an individual case. However, based on the relationship between external compression pressure and intravenous pressure explained above, it seems reasonable to use strong compression in cases with severe venous pathology while light or medium pressure may be enough to treat milder cases and to counteract oedema.

In conclusion there is a need to measure interface pressure and stiffness of the final bandage in future trials comparing the clinical outcome by using different compression products.

In vivo measurements of these parameters are also recommended when new compression devices are developed.

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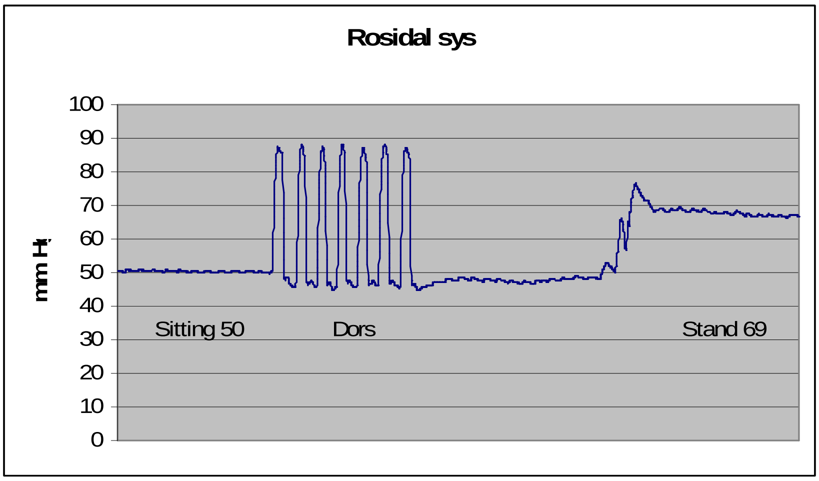
Figures:

Figure 1: Measurement of interface pressure in the medial gaiter area with an inelastic bandage system (Rosidal sys®) and with an elastic bandage applied in several layers (Perfekta®). In the sitting position both bandages exert a pressure of 50 mm Hg. The inelastic bandage system shows pressure peaks up to more than 80 mmHg during dorsiflexion and an increase of pressure to 69 mm Hg by standing up. The elastic bandage produces only very mild pressure increase during ankle movement and standing (below).



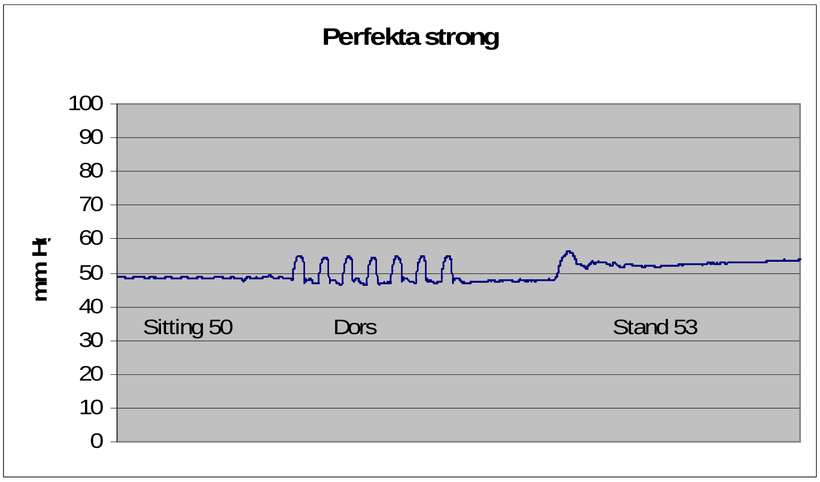
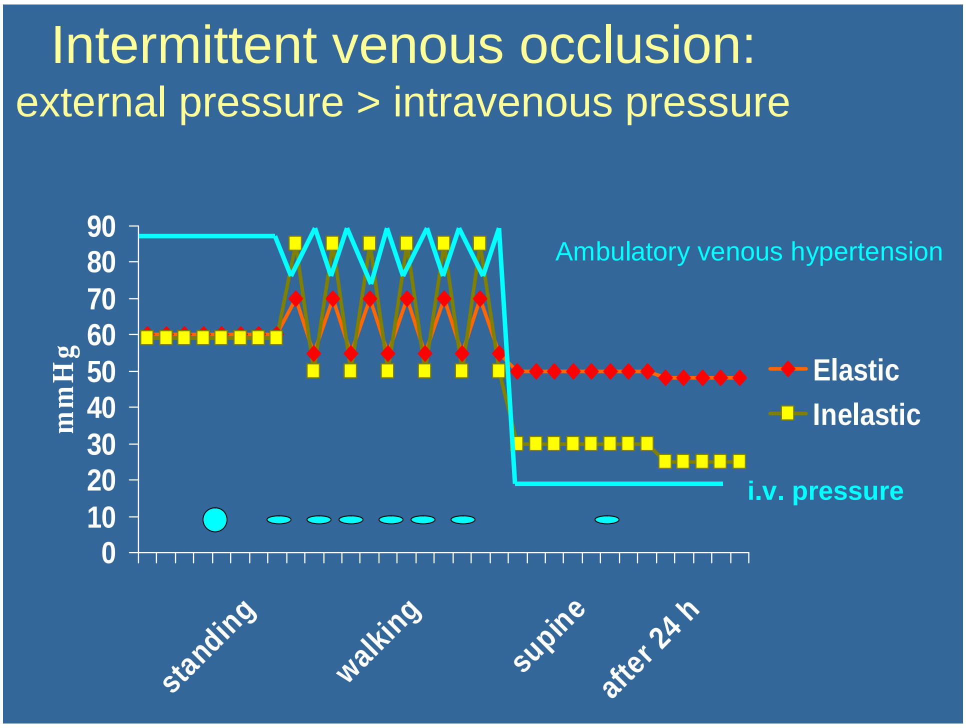


Fig. 2: Schematic drawing of the intravenous pressure in the distal leg in a patient with ambulatory venous hypertension (green) in comparison to the interface pressure under an elastic (red) and an inelastic bandage (yellow). The intravenous pressure is around 90mm Hg during standing, fluctuates between 75 and 90 mm Hg during walking (ambulatory venous hypertension) and falls down to 10-20 mmHg in the supine position. Short intermittent occlusions of the leg veins will occur when the external bandage pressure exceeds the intravenous pressure. This occurs during walking (muscle systole) with the inelastic bandage (yellow) but not with the elastic bandage (red). In the supine position the pressure of the elastic bandage will be too high to be tolerated.



Intermittent venous occlusion:

external pressure > intravenous pressure