Sub-bandage dynamics: stiffness unravelled

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Abstract

The static stiffness index (SSI) is mathematical equation that results in a simple number when the sub-bandage pressure in the supine position is subtracted from the sub-bandage pressure in the standing weight-bearing position. When SSI data are reported, often a wide range of values is observed for similar materials. The aim of this study was to explore the strength and weakness of the SSI and its measurement. Pressure was recorded with bandaging materials with different resting pressures and properties. Measurements in the upright position were performed under weight and non-weight bearing conditions for up to 12 min of motionless stance. The measurements reveal that the SSI reveals more about the muscle forces of the person included in the system, rather than providing accurate information on the applied system or how well this system is applied. In addition, venous filling has a major effect on the final SSI. When performed under similar conditions, the SSI is able to differentiate between elastic and inelastic materials. The SSI gives us a rough estimate of the effectiveness of an applied system but interpretation is influenced by the muscle forces of the person being bandaged as well as the measured effects of venous filling and, because of that, the timing of the measurements. Future guidelines on measuring the SSI should include that the final standing pressure value should be taken when a stable recording over a certain period is observed.

Introduction

There is a variety of methods to describe the properties of bandaging materials. Recently a consensus document was published, in which was stated that sub-bandage pressures and material stiffness characterize the elastic properties of the used materials and are the deciding parameters determining the dosage of compression treatment.[1] Therefore, it was recommended to measure and report these characteristics in future clinical trials. Proposals were made concerning methods for measuring the interface pressure and for assessing the stiffness of a compression device in an individual patient. However, stiffness is more than just a mathematical equation that results in a simple number. This article explores the strength and weakness of the static stiffness index (SSI).

The B1-position

In the European Committee for Standardization (CEN) Prestandard document,[2] an overview is provided on the anatomical locations to position pressure sensors on a leg. One of these locations is called cB1, the area at which the Achilles tendon changes into the calf muscles, approximately 10-15 cm proximal to the medial malleolus. Stolk *et al.*[3] performed static measurements and showed that the largest differences in the circumference between the maximal dorsiflexion and maximal plantar flexion positions of the foot occur at the level of the transition from the gastrocnemius muscle into its aponeurosis (the cB1 level or simplified: B1; Figure 1). The International Compression Club (ICC) consensus document proposes that location B1 should always be included in future pressure measurements, with the exact location of the sensor situated at the segment that shows the most extensive enlargement of the leg circumference during dorsiflexion or by standing up from the supine position.[1] Although B1 should always be included as a measurement location, other sites could be included in any measurement of pressures.[1] Figure 1 shows a screenshot of measurements with the PicoPress device (Microlab Elettronica SAS, Ponte S. Nicolò, Italy) and the sensor positioned at the B1 position. The measured pressure values are marked A, B, C.

Resting pressure, standing pressure, amplitudes

The resting pressure gives an indication of how much pressure is provided by a compression system when the subject is in a relaxed supine position with a slightly flexed knee and the foot resting on a flat surface. It is important that the calf muscles are not resting on a surface, as the result may be a too high resting pressure.[4] In Figure 1, the resting pressure (A) is around 40 mmHg.

The standing pressure gives an indication of the pressure when the subject is asked to stand up and put weight on the compressed leg.[5,6] In Figure 1, the standing pressure (B) is around 70 mmHg.

Resting and standing pressure are both values recorded in static situations. If a measuring device (like *e.g.* PicoPress) allows dynamic recording, it is advisable to measure also the amplitudes of a specified movement.

Possible movements include the following:[1] i) dorsal and plantar flexion of the ankle joint; ii) walking, for example on a treadmill; iii) adopting a *tip-toe* stance, or flexing of the knees; iv) passive ankle movement.

In Figure 1, the amplitudes are presented in the column exercise. The range of pressure values (C) is between 45 and 90 mmHg. The difference between these two pressure values results in a working pressure amplitude (WPA) The recording during the exercise in Figure 1 gives a WPA of 45.

The static stiffness index

The CEN European Prestandard document for medical compression hosiery defines stiffness as the increase in pressure per 1 cm increase of leg circumference.[2] For compression bandages, the extensibility of materials is often used to determine their characteristics. Partsch[5] identified the need for a simple tool to assess both pressure and stiffness on the individual leg. He describes the method to measure the pressure at a defined position of the lower leg at rest (B1), when its circumference is minimal, and to repeat the measurement on the same spot, when the circumference has maximally increased by the muscles actively engaged to stand in the upright position. For measuring stiffness, the pressure in the supine position is subtracted from the pressure in stance. The resulting index indicates the effectiveness of the applied system.[1] This index is referred to as SSI and, although it

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might be influenced by many variables, provides an indication of how well an applied compression system manages to keep forces produced by the muscle activity to stay in the upright position, inside the compressed area. In the measurement presented in Figure 1, a typical PicoPress recording is presented of the pressure under a 3M™ Coban™ 2 Layer application (3M™ HealthCare, St. Paul, MN, USA), with the sensor positioned at the B1 location. The resting pressure is presented in the column *supine* and is around 40 mmHg (A). The standing pressure can be taken from the column *stance* and is around 70 mmHg (B). This means that the SSI in this measurement is 30 (70-40).

Results and Discussion

Muscle forces

It is easy to imagine that both SSI and WPA are not only determined by the stiffness of the applied compression system but more by the muscle forces that are produced inside the bandaged area. Provided that the measurements are not performed on a leg with major disfigurations due to severe obesity or lymphoedema, the subject inside the system heavily *confounds* each measurement. As a consequence of measuring the muscle forces inside the compression system, both SSI and WPA tell more about the muscle forces of the person included in the system, rather than providing accurate information on the applied system or how well this system is applied. This can be easily demonstrated with the measurements presented in Figure 2. With the same system applied in the same way by the same experienced bandager on different subjects, the amplitudes are 23 on the left (C: 55-32) and 64 on the right pressure profile (C: 102-38).

These measurements are from a study on healthy volunteers, recorded with a Gaeltec strain gauge temperature-compensated (15-40°C) force transducer (Gaeltec Devices Ltd, Dunvegan, Isle of Skye, UK). The transducer was positioned at the B1 position and connected to a computer from which the data was recorded. The only difference in the two recordings is the volunteer. In both readings, a similar resting pressure was achieved. The SSI's (14 *versus* 46) as well as the WPA's during walking on a treadmill (23 *versus* 61) of the used system show big differences. This phenomenon can also be observed in studies in which actual SSI measurements are presented. A few studies present data on measurements on short-stretch bandages. Partsch (Derm Surg 2005) presents data of measurements on 12 volunteers. The reported SSI values vary between 10 and >40 for both Unna's boot and multilayer short-stretch bandages. Similar differences in reported SSI's are observed in publications by Mosti *et al.*[7,8] and Partsch *et al.*[9] In some of these measurements, there is even an overlap of individual values from the systems with the highest and lowest mean stiffness (*e.g.* 7).

The static stiffness index and venous filling

Another factor that might influence the accuracy of the SSI is the timing of the measurements. There are no clear guidelines on when recording of the standing pressure

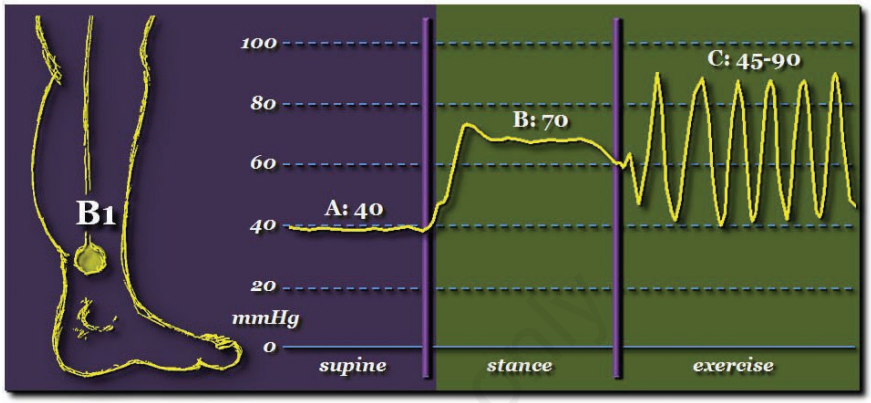

Figure 1. A typical PicoPress recording of a bandaged leg with the sensor positioned at the B1 location shown on the left. The measurements show the pressure in the supine position (A), in the standing position (B) and during functional activities (C).

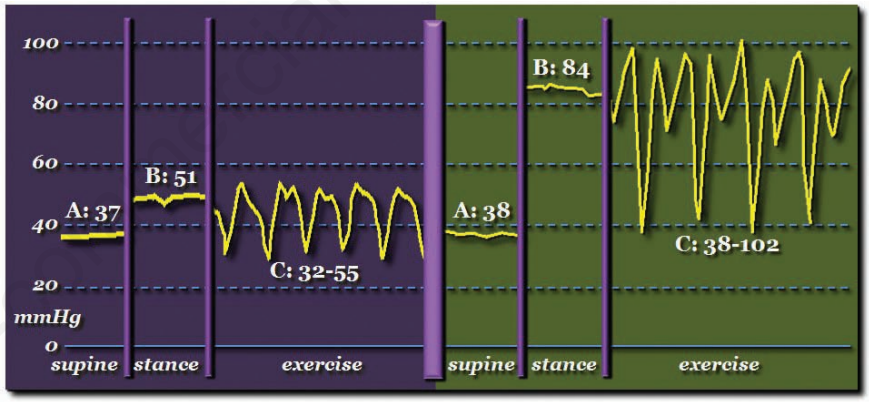

Figure 2. Sub-bandage pressure recordings from two different volunteers with the same compression system applied by the same experienced bandager.

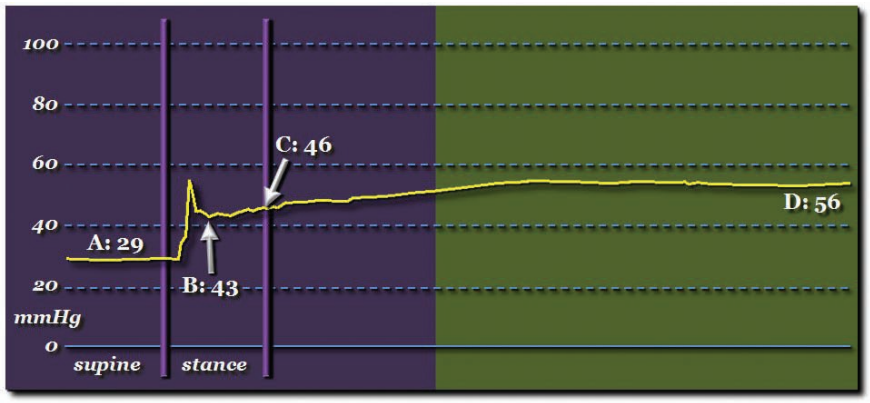

Figure 3. Recording of sub-bandage pressure of a normal limb in a Coban 2 Lite compression system, including the change from the supine to a weight bearing standing position.

should be performed. Similar to a normal unwrapped leg, the venous filling of a bandaged leg takes a certain period. Nicolaides *et al.*[10] recorded intravenous pressure of a normal limb in a vein on the dorsum of the foot. After ten tip-toe movements, it takes more than 30 s before the venous pressure returns to the pressure before the exercise. A similar refilling time can be observed after the application of a compression system, when the subject changes from a supine to an upright posture. Figure 3 provides an example of a healthy subject, compressed with Coban 2 Lite (3M™ HealthCare). Recording was performed immediately after the application. During the measurements in the upright position, the volunteer holds on to a frame to avoid balancing muscle activities in the leg. If the instructions of the used device (PicoPress) are followed, the pressure is taken from some of the values in the period located between the first two pink vertical lines. At the second line, the device gives a signal that the standing period is completed. Immediately after the position change, the standing pressure is 43 mmHg (B); the pressure at the end of this period is 46 mmHg (C). Looking at the resting pressure of 29, a reported SSI could be between 14 and 17. Venous filling of the lower limb however, takes much longer than the advised period. After the position change, it takes almost a minute before a stable pressure level of 56 mmHg (D) can be observed. If that recording would be used for the calculation, the SSI would be 27. The consequence of the above observations is that, depending on the time of measurement; the SSI can vary between 14 and 27.

Figure 4 shows another recording of the same leg in the same bandage. The resting pressure is 30 mmHg (A). Now the position change takes place without weight bearing. The volunteer steps on an elevation, bearing full weight on the contralateral leg. The bandaged leg is hanging free with a relaxed Achilles tendon. The initial pressure after this position change is 23 mmHg (B) and 28 mmHg after the signal (C) of the device. As in the previous recording, it takes a minute before a final stable pressure is established. This final pressure is 48 mmHg (D). During the change from the supine to the standing position, venous filling in isolation creates a pressure increase of 18 mmHg. In patients with chronic venous insufficiency, veins refill quickly and a stable recording can be observed much faster than in the provided example with a healthy volunteer.[11] In addition, it might be assumed, that in patients with significant venous dilatation, pressure increase due to venous refilling is more pronounced than in healthy volunteers. This could be explained by higher volume increase of dilated veins in the upright position, until an increasing venous wall tension prevents further venous filling. This means that in patients with chronic venous insufficiency the right time of standing pressure measurement is even more important.

Pannier *et al.*[12] measured the increase in leg volume increase after changing from a lying to a standing position and demonstrated that the position change initially leads to a rapid increase in volume. The main change is observed in the 1st min, followed by a further slower increase in the next 9 min. The authors state that the volume increase follows a bi-exponential function fitting to a rapid filling compartment (venous pooling) and a slow filling compartment-reflecting extravasation.

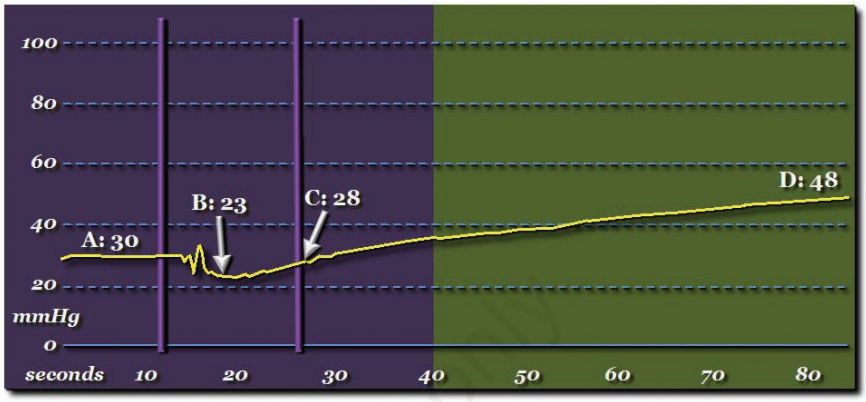

Figure 4. Recording of sub-bandage pressure of a normal limb under a Coban 2 Lite application including the change from a supine to a non-weight bearing standing position.

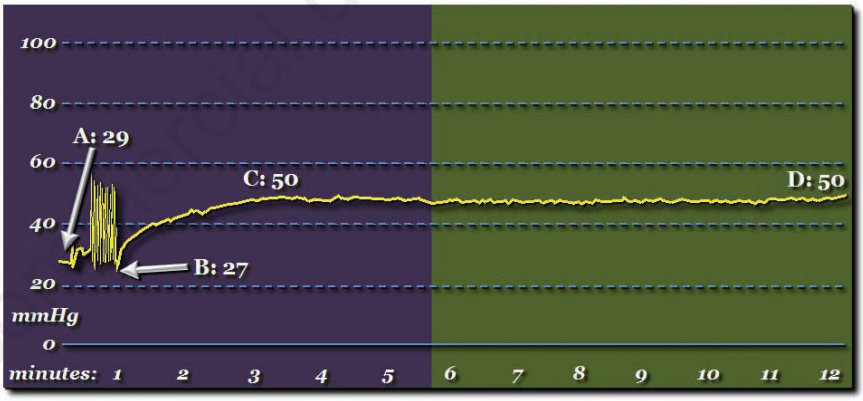

Figure 5. Recording of sub-bandage pressure of a normal limb compressed with Coban 2 Lite, including the change from the supine to non weight bearing standing position, which was maintained motionless during the entire recording time.

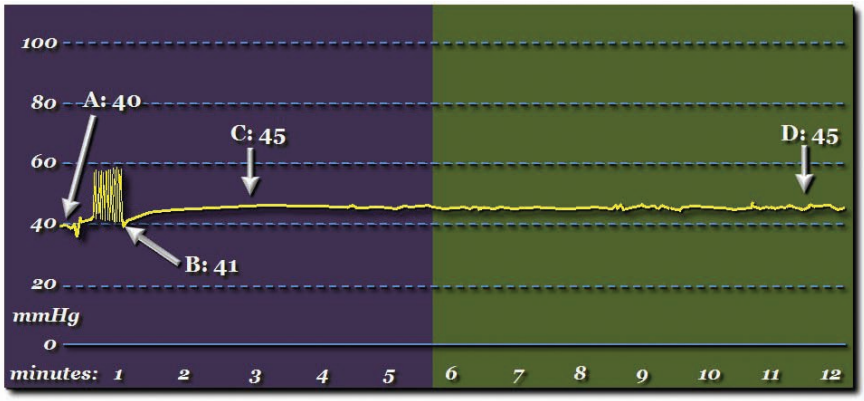

Figure 6. Recording of sub-bandage pressure of a normal limb compressed with a long-stretch bandage, including the change from the supine to non weight bearing standing position, which was maintained motionless during the entire recording time.

Stick *et al.*[13] used strain gauge plethysmography at calf and ankle level to document the volume changes, which occurred when a subject was tilted from the supine to the upright position. In both ankle and calf, the highest volume increase was observed in the first 2 min, after which the volume further increased at a less steep slope. The authors state that after the subject has been brought into the upright posture, an increased hydrostatic pressure in the arteries makes the blood flow via the arteriolar resistance vessels and via the capillaries into the venous capacitance vessels. Next, a further volume increase is observed in the following 10 min, which is due to an increased transcapillary filtration of fluid into the interstitial space. Mosti *et al.*[14] demonstrated that there is a significant correlation between the degree of improvement in venous hemodynamics of the ejection fraction (EF) examined by strain gauge plethysmography and both the SSI and the amplitudes of sub-bandage pressure during walking. The authors report that when elastic bandages are applied at high pressure and high stretch, only small pressure differences (SSI and WPA) occur by standing and walking resulting in low EF values. To evaluate the fluid shift into the interstitial space, we measured the effects of the position change on sub-bandage pressures during 12 min of standing with the leg under investigation in the non-weight bearing position. The subject is wearing the inelastic Coban 2 Lite compression system. As can be seen in Figure 5, the initial resting pressure is 29 mmHg (A). Next, the volunteer performed ten active maximal dorsal and plantar flexions. After the exercises, the pressure returned to 27 mmHg (B), a little lower that the initial resting pressure. Similar to what was observed in Figure 4; venous filling brings the pressure to 50 mmHg after 2.5 min (C). During the next 10 min of motionless stance, no change in pressure is observed (D: 50). This means that the bandage, which was applied at full stretch, manages to keep the forces that are generated by the dorsal and plantar flexions, inside the system, as well as the forces generated by the venous refilling. However, because the forces needed for the interstitial fluid shift into the lower leg (edema) are much lower than the gravitational forces responsible for venous refilling, it can be hypothesized that compression applied at full stretch also provides a sufficient counterforce for the forces responsible for the interstitial fluid shift, as they are not high enough to generate an additional increase of sub-bandage pressure (C=D).

This procedure was repeated after the application of the long-stretch compression bandage Biflex 16+ (Thuasne SA, Levallois Perret, France) with tension indicators for accuracy of application; the tension is correct when the printed markers are square-shaped. The bandage was applied in a spica manner according the included manufacturers instructions for use. The recording of this application is presented in Figure 6. The application provides a resting pressure of around 40 mmHg (A). After the exercises, the pressure is 41 mmHg (B). Venous filling brings the pressure to 45 mmHg after 2 min (C), a value that is still observed after 10 min of motionless stance (D). These observations, combined with the low amplitudes that are observed, demonstrate that the stretchability of the applied long stretch bandage absorbs a certain amount of the gravitational venous filling forces that are related to the position change and allows volume changes of the included leg. However, these measurements also reveal that the applied force is high enough to counteract the forces responsible for the fluid shift into the interstitial tissue. This means that also extensible materials can play a role in the prevention of edema.[15]

Conclusions

It can be concluded that the SSI gives us a rough estimate of the effectiveness of an applied system but interpretation is influenced by the muscle forces of the person being bandaged as well as the measured effects of venous filling and, because of that, the timing of the measurements. However, the well-established SSI in general is able to differentiate between elastic and inelastic materials[16] and the suggested cut-off point of 10 by the ICC,[17] represents a very simple quotient that may be taken as a rule of thumb and is measurable in patients without major disfigurations of the legs due to severe obesity or lymphoedema. Future guidelines on measuring the SSI should include that the final standing pressure value should be taken when a stable recording over a certain period is observed.

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