Pascal's law and the dynamics of compression therapy: a study on healthy volunteers

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***Aim*. The aim of this paper was to determine whether Pascal's law can be used to explain the dynamics of compression therapy.**
Methods. Sub-bandage pressures were recorded at three different levels to investigate the transmission of applied pressure on the legs of 12 healthy volunteers and 216 applications.
***Results*. The experimental model revealed that when pressure is increased at a certain area in a compressed leg, the pressure is transmitted within the compressed area.**
***Conclusion*. The dynamics of effective compression therapy are explained by Pascal's Law, which states that when pressure is applied on a fluid (a muscle or muscle group) in a closed container (fascia muscularis and compression bandage), there is an equal increase at every other point in the container.**
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Key words: **Stockings, compression – Bandages - Venous insufficiency.**

Compression is generally considered to be the standard treatment for venous leg ulcers. Many types of compression systems are available, some of which are just a single bandage, whilst others involve the application of several different bandages to the leg. Compression stockings are also used as an alternative to compression bandages.1 This article addresses the application and relevance of Pascal's Law to explain the dynamics of compression systems. Pascal's law is presented and its application is explained by measurement on healthy volunteers.

Pascal's Law

Blaise Pascal (1623-1662) was an influential French mathematician, physicist and philosopher. Pascal's work on hydrodynamics and hydrostatics was focused on the properties of fluids in hydraulic systems.[2] His inventions include the hydraulic press and the syringe. Pascal's law states that, when there is an increase in pressure at any point in a contained fluid, there is an equal increase at every other point in the container. Pascal's principle means that an incompressible fluid transmits applied pressure. It can be demonstrated by making a few similar openings in a closed toothpaste tube. If pressure is applied at any point on the tube, the toothpaste will come out evenly from all the holes. In orthopedics, this natural law is often used in the treatment of diaphyseal fractures such as of the tibia or humerus. When the muscle compartments around the fractured long bones are bound by a fracture brace, they will displace under load but only until all the gaps within the container are filled.[3] From then, the pressure created by functional activities will be transmitted to support and stabilise the fractured bone. Even when a brace that is made of a flexible but non-stretchable material is used, fractures can be supported similarly to treatment with a completely rigid brace.[4] Sarmiento and Latta [3] demonstrated that the compliance of a piece of beefsteak can be significantly improved by tightly wrapping it with a sleeve of paper. All of the above findings demonstrate that soft tissues in the human body act as incompressible fluids. As a consequence,

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Conflicts of interest.—Both authors are employed by the 3M Company in Germany and were involved in the development of the 3M™ Coban™ Two-layer Compression System.

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Pascal's law may be used to explain the principles and dynamics of compression therapy.

Material and methods

Test 1

To demonstrate the effects of transmission of pressure, three strain-gauge temperature-compensated (15-40 °C) force transducers, 13 mm in diameter and 3 mm thick (Gaeltec Ltd. Scotland) connected *via* amplifiers and filters to a computer, were positioned to the lower leg of a healthy volunteer. Two sensors were placed distally and proximally on the musculus tibialis anterior, the third on the B1 position. Posteriorly, a large pressure sensor (Kikuhime , TT Medi Trade, Denmark) was positioned. This sensor partially covered the lateral and medial head of the musculus gastrocnemius (Figure 1). Next a Coban 2 Layer compression system (3M Health Care, Neuss, Germany) was applied. After the application, the pressure on the Gaeltec transducers was zeroed so that only changes were recorded. The Kikuhime sensor was gradually inflated to 50, 100, 150, 200 and 250 mmHg and deflated. The pressure changes on the three sensors during inflation and deflation was recorded.

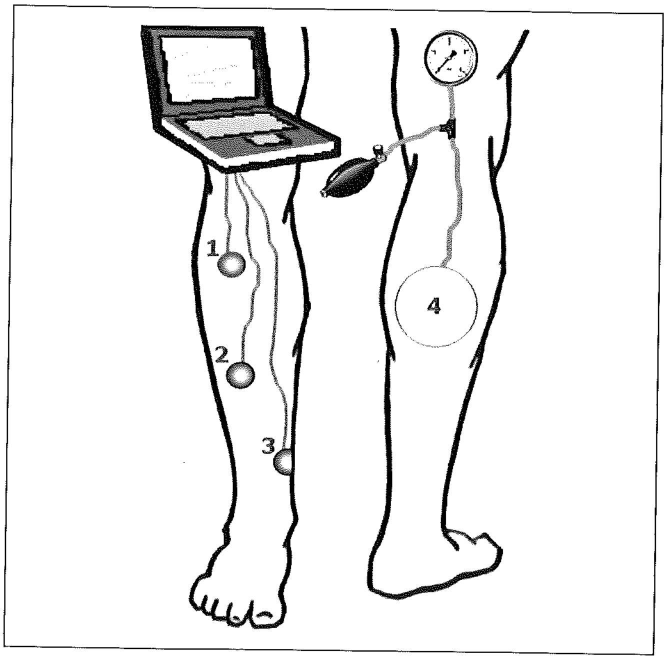

Figure 1.—The positioning of the pressure sensors (1, 2 and 3) and the inflatable transducer.[4]

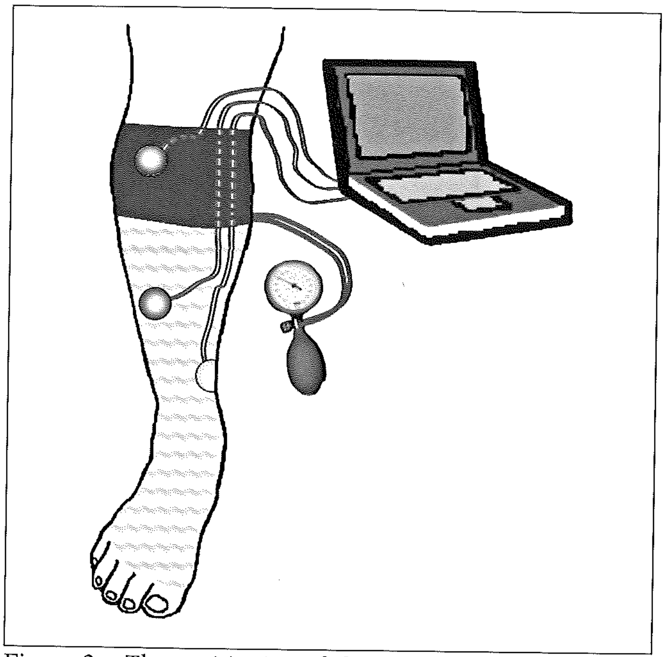

Figure 2.—The positioning of the pressure sensors and the blood pressure cuff.

Test 2

The effects of transmission of pressure in a compressed lower leg were examined in a controlled laboratory study [5] to evaluate 3M Coban 2-layer Compression System prototypes. The study was approved by the Ethics Commission of the Freiburger Ethik-Kommission GmbH, Germany and 3M's Institutional Review Board. Each participant signed an informed consent. Three Gaeltec pressure sensors were positioned on the lower legs of twelve healthy volunteers (6 females and 6 males). Two sensors were placed distally and proximally on the musculus tibialis anterior, the third on the B1 position. Nine prototypes were tested on both legs, in total 216 systems with a high stiffness (static stiffness index >10) were applied. After the application of each system, a blood pressure cuff was applied over the most proximal sensor (Figure 2). The two distal sensors were not covered (Figure 2). Next the blood pressure cuff was gradually inflated and pressure was recorded on the three sensors during 0, 20, 40, 60, 80 and 100 mmHg inflation.

Results

Test 1

The test with the inflatable transducer revealed that inflation of the transducer gives an increase

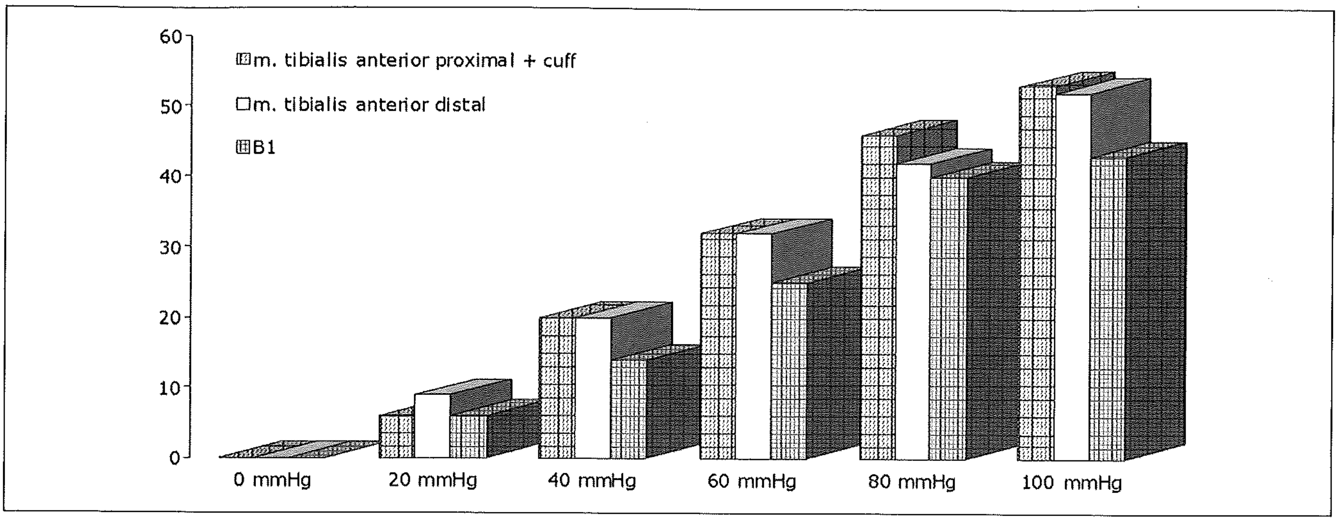

Figure 3.—Pressure recordings during gradual inflation of the inflatable transducer.

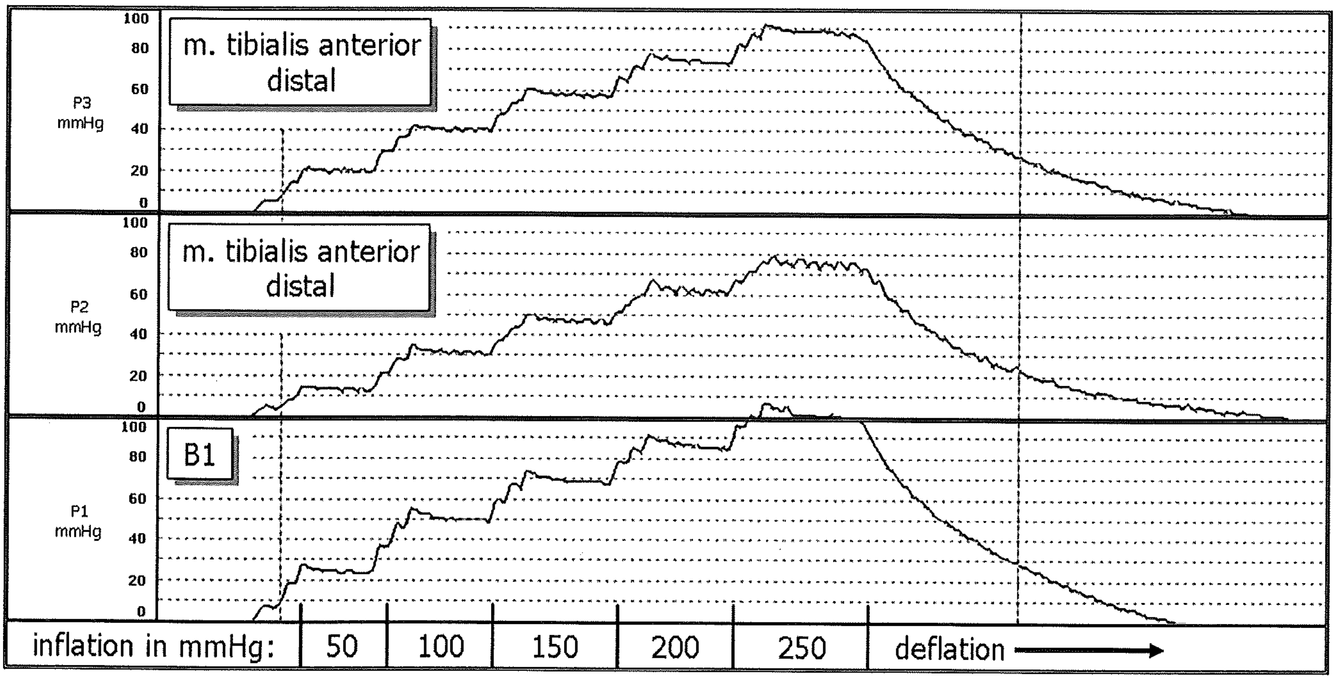

Figure 4.—Percentual pressure changes under the compression bandage with gradual inflation of the blood pressure cuff.

of pressure throughout the leg. The recording at the three sensors is presented in Figure 3.

Test 2

The results of the study on the effects of the inflated blood pressure cuff are presented graphically in Figure 4. Because a different starting value was measured on each sensor, the changes that were measured during the inflation of the cuff are not presented in mmHg, but as percental changes. It is clearly shown that the sensors that are not located under the blood pressure cuff (distally on the m. tibialis anterior and on B1), show pressure changes at each 20 mmHg increase of pressure, which are similar to the changes that are observed on the sensor under the cuff (proximal on the m. tibialis anterior).

Discussion

The human skin is made of a stretchable material. This can be easily demonstrated by comparing the circumference of the upper arm of a body-builder at rest and the same arm with the biceps muscles under tension. Because of this stretchability, human skin absorbs much of the forces produced by functional activity. To keep these forces inside the leg in the presence of venous insufficiency, the so-called muscle pump is often supported with additional compression around the leg to improve venous flow. Narrowing of veins is considered to be a basic objective of compression therapy.[6] Current concepts indicate that compression effectiveness for venous ulcers is partially linked to the amount of sub-bandage pressure exerted.[7] Clinical practice is based on achieving high enough compression to deliver the most favourable outcome in venous ulcer treatment.[8, 9] As a result, it is advocated that, to reverse venous hypertension in an ambulatory patient, an average pressure of 40 mmHg is required at the ankle, with a graduated decrease up the leg to approximately 20 mmHg at the calf.[10] This is now commonly referred to as "40-17". Much of the literature supports these 40-17 mmHg compression values as the ideal in healing venous leg ulcers.[11] Many practitioners take these values for granted and sub-bandage pressures are therefore rarely measured.[12-17] The widespread belief that correctly applied compression systems provide pressure values graduating from 40 mmHg at the ankle to 17 mmHg below the knee, is based solely on theoretical mathematical equations.[18] In this light, it is interesting to see how a giraffe, with probably the most challenging venous return in nature, avoids pooling of blood and edema in the extremities. Minimal movement, produced by only a small amount of calf muscles, creates great variations in pressure, which combined with a tight and non-stretchable skin layer, move fluid upward against gravity in a very effective way.[19, 20] Similar to human skin, the skin of the giraffe is not tight, which means the resting pressure underneath the skin is very low. The effective return of fluid against gravity is produced with a very low resting pressure that is provided by the giraffe's natural compression system: its leather-like skin. This system does not allow the circumference changes during functional activities, that can be observed in the human leg. Mosti and Mattaliano [21] showed that the control of leg circumference changes by bandages of different elasticity, during functional activities is related to the stiffness of the bandage. The giraffe does not need resting pressures of 40 mmHg around the ankle joint to effectively move fluid to heights much greater than a human. Recently it was proposed that in the case of multilayer bandage systems, the terms "high or low stiffness" should be used to characterise the behavior of the final bandage.[22] Stiffness may be characterised by the increase of interface pressure measured in the gaiter area when standing up from the supine position. A pressure increase of more than 10 mmHg measured in the gaiter area is characteristic for a stiff bandage system.[23] Compression systems with high stiffness have the effect of a non-stretchable second skin. This means that within a stiff compression system, muscle movement creates pressure which is evenly distributed within the lower limb as if in as a closed cylinder. These pressures can be measured by positioning pressure transducers between the skin and the compression system. Compression systems with high stiffness will have a similar effect on an included leg, as a tube on the included toothpaste. The paste can only be pressed out, if the wall of the tube cannot be stretched. A compression system with a high stiffness index does not only form a cylinder around the leg but also manages to keep the forces that are produced by functional activities, inside the cylinder. In return, these forces effectively compress the veins similar to the toothpaste. The blood in compressed veins will flow to the area were it can escape. Because the functional activities in the leg are dynamic and cyclic, also the tissue pressures are dynamic, cyclic and changing with every muscle contraction.[24] Due to the positioning of the valves in the veins, an increase of pressure will result in venous backflow to the heart. Bandages with a high static stiffness index result in the effect of an inelastic second skin after application. This means that the pressure, built up by the muscles during functional activities, works against a rigid tube and increases the pressure in this closed cylinder. The effect can be compared with emptying a tube in which the only opening in the closed system is the nozzle. In the lower leg,

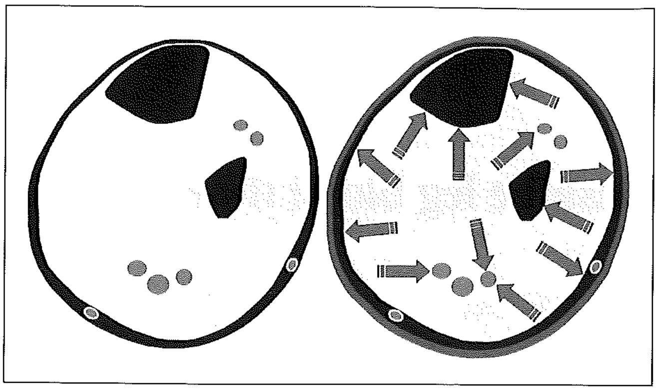

Figure 5.—Cross section of the lower leg (left); when muscle activity creates pressure within the compressed leg, then according to Pascal's law, the pressure will be transmitted evenly within the entire compressed area.

these are the blood vessels. The more the pressure in a tube is built up, the greater the force the fluid will be pressed out. If this force is built up within a compressed lower leg, the effects are equal and insufficient venous and lymphatic systems are optimally supported (Figure 5).

Conclusions

The dynamics of effective compression therapy are explained by Pascal's Law, which states that when pressure is applied (functional activity) on a fluid (a muscle or muscle group) in a closed container (fascia muscularis and compression bandage), there is an equal increase at every other point in the container.

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