The efficacy of Laplace's equation in calculating bandage pressure in venous leg ulcers

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Abstract

Background: Compression is generally considered to be the standard therapy for the treatment of venous leg ulcers. It controls oedema and supports venous blood flow to the heart. *Aims:* This article presents results from three studies comparing a new two-layer compression system with several other established systems in order to evaluate the efficacy of the compression forces exerted. *Methods:* Data from three studies, in which measurements were taken from 744 compression bandages applied to artificial legs equipped with pressure transducers are examined in this article. *Results:* The results are compared with theoretical compression forces calculated by a modified Laplace's law equation which predicts graduated compression ranging from 27–72mmHg at the ankle, tapering to 18–8mmHg below the knee. However, the results of the studies show that calculations using this equation do not reliably predict actual measured sub-bandage pressures. *Conclusions:* The widespread belief that compression bandages provide graduated pressure from 40mmHg at the ankle to 17mmHg below the knee is based solely on theoretical mathematical equations and is not supported by the results of experimental studies. *Conflict of interests:* Both authors are employed by the 3M Company in Germany and were involved in the development of the 3M™ Coban™ 2 Layer Compression System. All bandages that are not marketed by 3M, were applied by invited experts who routinely apply these bandages.

KEY WORDS

Compression therapy
Graduated compression
Laplace's law
Sub-bandage pressure
Venous leg ulcer

Compression is generally considered to be the standard therapy for the treatment of venous leg ulcers (Cullum et al, 2002). It controls oedema and supports venous blood flow to the heart. This article presents results from three studies that compared a new two-layer compression system (3M™ Coban™ 2 Layer Compression System, Neuss, Germany), with several other established systems. The aim of the these studies was to evaluate the compression forces provided by the various bandages.

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This article examines the results from these three studies, which challenge the widespread belief that Laplace's law is a useful tool in predicting and calculating sub-bandage pressures.

Laplace's law

In 1805, Pierre-Simon Laplace described a formula that defined the pressures exerted on curved surfaces (Pellicer et al, 2000). However, while Laplace's original formula provided a mechanistic view of the pressures exerted on curved surfaces, it did not take into account the adaptations that can occur in living organisms, for example, the human leg, which is neither solid nor has a constant curved structure (Basford, 2002). Therefore, the direct relationships that occur in solid objects may not apply to human bodies with deformable or irregular surfaces (Melhuish et al, 2000).

Thomas (2003) modified Laplace's law to include the importance of bandage width and the number of layers applied so that it can be used in clinical practice. The modified equation below, often referred to as Laplace's law, is frequently used to calculate the sub-bandage pressures of compression systems:

$$\text{Pressure (mmHg)} = \frac{\text{Tension (KgF)} \times \text{number of layers} \times 4620}{\text{Circumference (cm)} \times \text{bandage width (cm)}}$$

The use of this modified equation of Laplace's law to calculate or predict sub-bandage pressure remains controversial and the consistent formation of an ideal pressure gradient has been difficult to demonstrate practically.

It has been suggested that the failure to demonstrate graduated compression may reflect poor operator technique, poor measurement technique, or the practical problems of maintaining constant tension throughout the bandage during the application process (Clark, 2003).

Williams et al (1999) state that Laplace's equation must be interpreted with care with regard to the complex application of bandages to the leg. This is because the leg is neither cylindrical nor composed of fluid — therefore the tension around the limb is unlikely to be constant. In addition, the equation may not take into account all of the factors that can operate beneath a compression bandage (Melhuish et al, 2000).

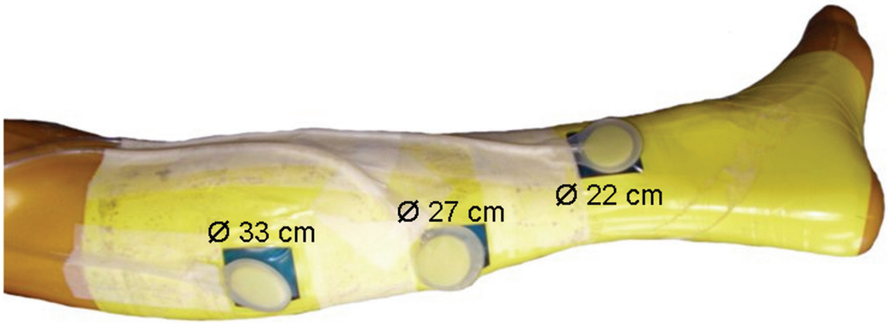

Figure 1. The artificial leg with the sensors positioned on gel cushions at different circumferences.

Methods

Theoretical pressure values on the three pressure sensors (positioned at 22cm, 27cm and 33cm leg circumference) were calculated using the modified Laplace's law equation. The physical properties of all the tested bandage materials were measured using a tensile tester (Hounsfield Test Equipment, Croydon) to record the force needed to stretch the included bandage materials to the elongation suggested by the manufacturer. If the manufacturer recommends a bandage to be applied at 50% stretch, the force needed to stretch this bandage to 50% was measured. This force value has been used for the calculation. The number of layers, as well as the amount of stretch at which individual layers were applied, were taken from manufacturers' recommendations.

Data from three studies (see below), in which measurements were taken from 744 compression bandages applied to artificial legs equipped with pressure transducers, are examined in this article. The studies were chosen as in all three of them, the same artificial leg and sensor positioning was used. Therefore, the collected data could be pooled to provide information on a large number of applications by experts in compression bandaging.

Study 1

Thirty-two experts in the application of compression bandages for the treatment of venous leg ulcers were invited to participate in this study, the details of which have been described elsewhere (Collier and Schuren, 2007).

Pressure transducers (Kikuhime small probe, MediTrade, Soro, Denmark) were used to monitor and record the forces operating under the compression bandages applied to artificial legs. Three transducers were positioned on fixed gel cushions on the artificial legs (*Figure 1*).

The first transducer was applied 10cm above the medial malleolus, where the leg circumference was 22cm. The second transducer was applied halfway between the first and third transducer at a leg circumference of 27cm. The third transducer was applied at the leg's widest circumference (33cm), which was approximately 15cm below the anticipated top of the bandage.

The study participants were asked to apply the compression bandage system they used most often to the artificial leg equipped with the transducers — they were asked to do this three times. Pressure forces at each of the three transducer locations were then recorded. Data were collected from four separate compression bandage systems:

- Profore™ multilayer compression bandage system (Smith & Nephew Medical Limited, Hull)
- Actico cohesive short-stretch bandage (Activa® Healthcare Limited, Staffordshire)
- Unna's Boot compression system (Medicopaste®, GF Health Products, Atlanta, USA); covered with a 3M™ Coban™ bandage roll (3M™, St Paul, USA)
- Rosidal® K short-stretch compression bandage (Lohmann & Rauscher International, Rengsdorf, Germany).

After the participants finished applying the compression bandage system they used most often, the technique for applying the Coban 2 Layer Compression System was demonstrated. The participants then applied this system to non-sensored artificial legs enough times to familiarise themselves with the application procedure. They were then asked to apply the Coban 2 Layer Compression System to the artificial leg equipped with the transducers — again, they were asked to do this three times. Before each application, the pressure transducers were calibrated to a force of zero mmHg — the pressure was then recorded again immediately after each application.

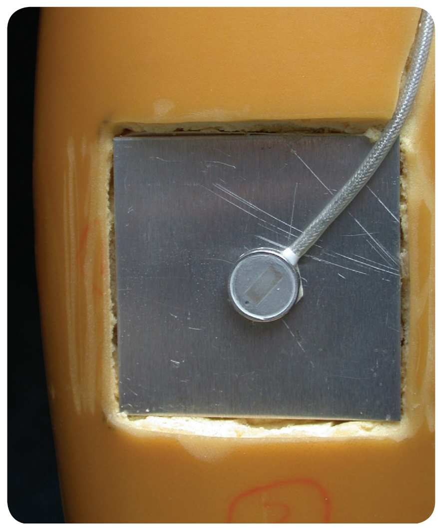

Figure 2. A pressure transducer positioned on a thin aluminium plate.

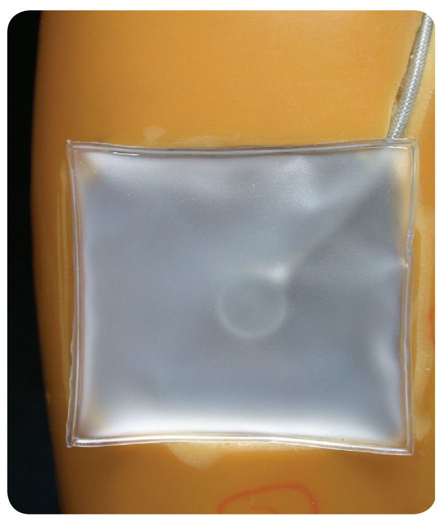

Figure 3. A pressure transducer fixed underneath a plastic ethylene glycol-filled pouch.

Table 1
Theoretical pressures of the materials under investigation as worked out using Laplace's law

Laplace equation	KgF from tensile tester	x4620	x layers	At 22cm ÷ 22x10	At 27cm ÷ 27x10	At 33cm ÷ 33x10
Profore						
Layer 1:0.075Kfg no stretch	0.075	346.50	693.00	3.15	2.57	2.10
Layer 2 0.502Kfg 50% stretch	0.502	2319.24	4638.48	21.08	17.18	14.06
layer 3: 0.382Kfg 50% stretch	0.382	1764.84	3529.68	16.04	13.07	10.70
Layer 4: 0.334 Kfg 50% stretch	0.334	1543.08	3086.16	14.03	11.43	9.35
Theoretical pressures using Laplace law				54.31	44.25	36.20
Unna's boot						
Layer 1 minimal stretch	0.100	462.00	2772.00	12.60	10.27	8.40
Layer 2 50% stretch	0.334	1543.08	3086.16	14.03	11.43	
Theoretical pressures using Laplace law				26.63	21.70	17.75
Short stretch - (Rosidal K)						
Layer 1 no stretch	0.075	346.50	693.00	3.15	2.57	2.10
Layer 2 full stretch	1.427	6592.74	13185.48	59.93	48.84	39.96
Theoretical pressures using Laplace law				63.08	51.40	42.06
Actico						
Layer 1 no stretch	0.075	346.50	693.00	3.15	2.57	2.10
Layer 2 full stretch	1.630	7530.60	15061.20	68.46	55.78	45.64
Theoretical pressures using Laplace law				71.61	58.35	47.74
Coban 2-layer compression system						
Layer 1 no stretch	0.075	346.50	346.50	1.58	1.28	1.05
Layer 2 full stretch	1.500	6930.00	13860.00	63.00	51.33	42.00
Theoretical pressures using Laplace law				64.58	52.62	43.05

Study 2

The second study (Schuren and Mohr, 2006) was designed as a controlled laboratory screening evaluation of early two-layer compression bandage prototypes. The prototypes tested in this study were similar in design and function to the currently marketed Coban 2 Layer Compression System, but with minor modifications.

Sub-bandage pressures were measured on an artificial leg using six strain-gauge temperature-compensated (15–40°C) force transducers (Gaeltec Ltd, Scotland). The transducers were 13mm in diameter and 3mm thick and were connected via amplifiers and filters to a computer from which the data was recorded.

Three 5 x 5cm holes were cut in the artificial leg, into which thin aluminium plates were fitted. The location of the aluminium plates corresponded with the location of the transducers described in Study 1 (*Figure 1*). On top of each plate, a sensor was fixed with double-sided adhesive tape (3M™ 410 Double-coated Tape, 3M, St Paul, USA). In this way, the aluminium plates provided sufficient counterforce to avoid sensor movement. A small gutter carved into the artificial leg allowed the cable to be positioned without interfering with the pressure measurements (*Figure 2*).

Three 5 x 5cm plastic bags filled with ethylene glycol were positioned to fill the holes in such a way that the surface of the bags was just above the surface of the leg (*Figure 3*). The bags were fixed at the borders with tape and a double stockinette (3M™ Synthetic Cast Stockinette, 3M, St Paul) was used to cover the leg.

Three orthopaedic technicians, experienced in the field of compression therapy, each applied 40 bandages to the artificial leg. Before each application, the pressure transducers were calibrated to a force of zero mmHg. Pressure values were immediately recorded after each application.

Study 3

The design of this study (Schuren and Mohr, 2006) was the same as Study 2, except that eight nurses experienced in the field of compression therapy each applied 54 Coban 2 Layer Compression System with minor modifications.
As in Study 2, pressure values were immediately recorded after each application.

Results

Theoretical pressure values according to Laplace's law

The sum of the individual layers determined the final theoretical pressure values provided at the different

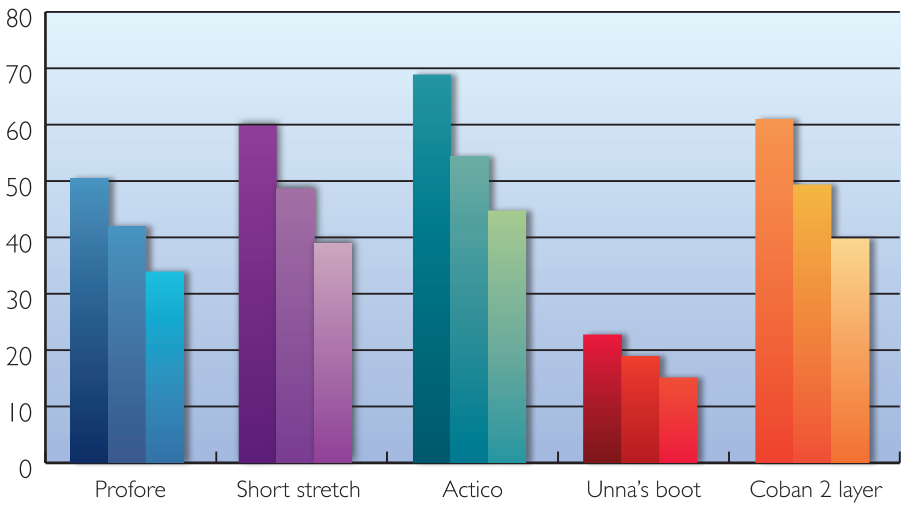

Figure 4. Theoretical graduated compression according to Laplace's law (in mmHg).

circumferences (*Table 1*). As can be seen in *Figure 4*, the modified Laplace equation showed that all of the tested compression systems theoretically provided graduated compression.

Measured pressure values — Study 1

In Study 1, 192 applications of the five compression systems were included in the analysis. Graduated compression was only observed in one of the 24 Actico applications (4.2%); two of the 24 Profore™ applications (8.3%); one of the 24 Rosidal®K short-stretch applications (4.2%); two of the 24 Unna's Boot applications (8.3%); and seven of the 96 Coban 2 Layer Compression System applications (13.5%).

Mean pressure values at the 22cm, 27cm and 33cm circumference transducers for each of the tested products are provided in *Figure 5*. None of the systems under investigation provided graduated compression.

Study 2

All 120 applications of the 2 layer compression bandage were included in the analysis. Graduated compression could only be observed in nine (7.5%) of the applications. Mean pressure values for all 120 applications are provided in *Figure 5*.

Study 3

All 432 applications of the 2 layer compression bandage were included in the analysis. Graduated compression could only be observed in 31 (9.1%) of the applications. Mean pressure values for all 432 applications are provided in *Figure 5*.

Discussion

There is a widespread belief that most of the compression systems currently on the market provide graduated compression, with a pressure of 35–40mmHg at the ankle, dropping off to about 15mmHg at the widest circumference of the calf.

The original Charing Cross four-layer compression system was developed to apply 40mmHg of pressure at the ankle, graduating to 17mmHg at the knee (Moffatt and Dickson, 1993). Blair et al (1988) state that because of the increased radius from ankle to calf, graduated compression will be applied automatically providing the same tension and overlap are used. They add that mistakes in the tension applied in any one layer of the four-layer system will tend to be averaged out.

Much of the literature supports the 40–17mmHg compression value as the ideal in healing venous leg ulcers (Moore, 2002). Many practitioners also take these values for granted and sub-bandage pressure measurements are rarely performed (Bowering, 1998; Eagle, 1999; Ukat et al, 2003; Trent et al, 2005; Kalodiki et al, 2007).

Cherry et al (1996) state that oedema reduction is associated with improved ulcer healing. Therefore, measuring the limb circumference to assess whether there has been a reduction in oedema, is another way of monitoring whether pressure bandaging has been effective.

When pressure values are reported in the literature, the authors often refer to Laplace's law, citing it as a reliable method for predicting sub-bandage pressure (Thomas, 2003). Thomas (2003) also explains that the pressures provided by compression bandages are the result of a very complex interaction between the properties of the materials used, the size and shape of the leg, the technique of the bandager and the activities of the patient.

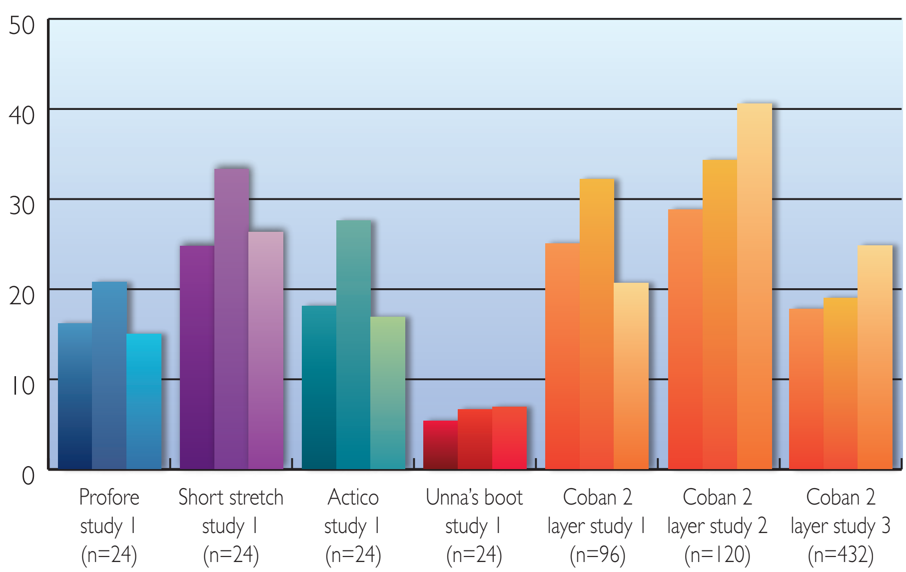

Figure 5. Measured mean pressure values in mmHg from all included studies.

It can be hypothesised that, if the properties of the materials as well as leg size and shape are controlled, as was the case in the three studies included in this paper, the modified Laplace equation can be used with confidence. If deviations from the modified Laplace equation do occur, they could be explained by the differences in bandaging technique.

Wertheim et al (1999), using the legs of healthy volunteers, measured the pressures exerted beneath compression stockings, where bandaging techniques are not influencing the measured pressures. They found that none of the measurements showed any graduated compression.

The discrepancies between the presented findings from study 1, 2 and 3, and the theoretical values presented in *Table 1* may be explained by a major difference between Laplace's law and Thomas' modified equation. In the latter, the circumference of the leg is used to calculate the expected forces, whereas in Laplace's formula, the radius of curvature determines the final pressure. However, the human leg, as well as the artificial leg that was used in the three studies, have no consistently curved structure.

In a cross-sectional view of a leg, which is not a perfect circle, many different radiuses of curvature can be seen. Subsequently, for each individual radius, a pressure can be calculated using Laplace's law. This means that the final pressure arrived at depends on the radius of the specific curvature on which a sensor is positioned, rather than on the circumference of the leg at the level of positioning.

The studies presented in this article have several limitations. First, the bandages were applied to artificial legs, which may or may not accurately model the human leg. Second, as discussed by Thomas (2003), sub-bandage pressures can be influenced by the technique and experience level of the bandagers.

While this criticism is valid for compression studies in general, all of the bandages in the three studies used in this article were applied by experts in the field of compression therapy. Furthermore, in Study 1, the experts applied the compression system they were most familiar with, minimising the potential for errors due to unfamiliarity.

Finally, the compression bandages in these studies were applied under controlled conditions and not in a true clinical environment. While this last criticism remains valid, it is true to say that these studies should have produced data that presented Laplace's law in its best light as the environment, subject, and bandagers were well controlled. However, the pressure calculations made using the modified Laplace's law equation did not accurately predict the pressure values found in these three studies. In fact, true graduated compression was observed in only 53 of the 744 (7.1%) applications.

Recently, Rabe et al (2008) recommended measuring sub-bandage pressures in future clinical trials. In addition, the importance of measuring the static stiffness index (the pressure in standing position minus the pressure in supine position) to describe the physical properties of a compression system was discussed by Partsch et al (2008). Measuring sub-bandage pressures is popular because of the availability of relatively inexpensive pressure measurement devices. The use of these devices is encouraged, but should be used to calculate the stiffness and thus the effectiveness of applied systems. Currently they are often incorrectly used to guide the applier to provide hypothetical levels of sub-bandage pressures.

Conclusion

This article illustrates that the theoretical pressure values calculated by the modified Laplace's law equation did not accurately predict the values found when compression bandages were applied by experts in three separate studies. The data from the studies clearly indicate that in vivo pressure values calculated using Laplace's law should be interpreted with care.

In addition, none of the compression systems tested in these three studies provided dependable graduated compression on the artificial legs used in the studies. It can be concluded, therefore, that the widespread belief that correctly applied compression systems provide pressure values graduating from 40mmHg at the ankle to 17mmHg below the knee, is based solely on theoretical mathematical equations and is not supported by the results of the experimental studies. WUK

Key Points

- Compression is generally considered to be the standard therapy for the treatment of venous leg ulcers.
- Compression controls oedema and supports venous blood flow to the heart.
- This article presents results from three studies that compared a new two-layer compression system with several other established systems. The aim was to evaluate the compression forces provided by the various bandages.
- Results from these three studies question the widespread belief that Laplace's law is a useful tool in predicting and calculating sub-bandage pressures.
- This article illustrates that the theoretical pressure values calculated by Laplace's law did not accurately predict the values found when compression bandages were applied by experts in three separate studies.
- The data from the studies clearly indicates that *in-vivo* pressure values calculated using Laplace's law should be interpreted with care.

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