BANDAGING AND PRESSURE GARMENTS: AN OVERVIEW

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INTRODUCTION

It should be stressed that one of the high-tech areas of medical textiles is the application of wound dressing materials, which includes bandages and pressure garments for enhancing the quality of life. In fact bandaging and wound dressing techniques originated from ancient practice that facilitates the further developments in improving the comfort and performance properties of value added products.

Wound healing is a natural process and dressings and medication enhance the process. There has been a sharp increase in the use of wound dressing materials in the recent past. The money spent in 1999 in the UK on modern woundcare products was £80 million[1]. In the EU the increase in sale of woundcare products accounts for 9.1%[2]. The modern dressings promote quicker healing of wounds and reduce the cost of nursing time.

Unlike wound management, pressure garments are mainly used for managing third–degree burns that not only affect the outer and inner layers of the skin but also deeper tissues. Pressure garments are used to treat the hypertrophic scars (overgrowth of scar tissues). They prevent and control the formation of hypertrophic scars by applying counter pressure to the affected area. When burned skin heals it can grow in an irregular scarring manner. Pressure garments help the skin to heal by pressing the healing skin down so that it grows in a flat manner. The continuous wearing of pressure garments prevents the thickening, buckling, and nodular formations seen in hypertrophic scars. The external pressure applied by the garments decreases inflammatory response and the amount of blood in the scar, reducing itching and prevents collagen from synthesising. In addition, pressure garments provide protection against injury. It should be noted that these garments must be worn for many weeks or months. It has been widely agreed that an ideal pressure garment should exert a pressure of 20mmHg on the underlying tissue, although the benchmark pressure has yet to be scientifically established. Pressure garments normally contain elastic yarns and a great deal of research and development work has been carried out worldwide to characterise and develop novel pressure garments[3-9].

COMPRESSION THERAPHY FOR VENOUS LEG ULCERS TREATMENT

Venous leg ulcers – problem

It is important that the arterial and venous systems should work properly without causing problems to blood circulation around the body. Pure blood flows from the heart to the legs through arteries taking oxygen and food to the muscles, skin and other tissues. Blood then flows back to the heart carrying away waste products through veins. The valves in the veins are unidirectional which means that they allow the venous blood to flow in upward direction only (Fig.1). If the valves do not work properly or there is not enough pressure in the veins to push back the venous blood towards the heart, the pooling of blood in the veins takes place and this leads to higher pressure to the skin. Because of high pressure and lack of availability of oxygen and food, the skin deteriorates and eventually the ulcer occurs. The initial indications of venous leg ulcers are the swollen veins (varicose veins) and blood clots in veins (Deep Vein Thrombosis - DVT), a growing problem for long-haul flights.

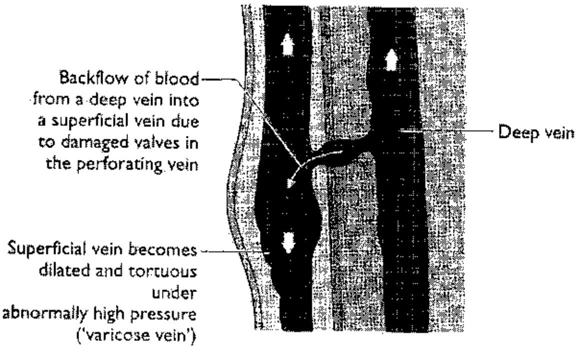

Figure 1. Illustration of Backflow of Venous Blood[10]

Venous leg ulcers treatment

It will be noted that venous leg ulcers are chronic and there is no medication or surgery to cure the disease other than the compression therapy. A sustained graduated compression mainly enhances the flow of blood back to the heart, improves the functioning of valves and calf muscle pumps, reduces oedema and prevents the swelling of veins[11]. Mostly elderly people are prone to develop DVT, varicose veins and venous leg ulcers. Venous leg ulcers are the most frequently occurring type of chronic wound accounting for 80% to 90% of all lower extremity ulceration[12].

Bandages

Bandages can be used for many purposes such as support, dressing retention and compression. Retention bandages are used to retain dressings *in situ*. Support bandages provide retention and prevent the development of a deformity change in shape of a mass of tissue due to swelling or sagging. Compression bandages are mainly employed for the treatment of venous leg ulcers and varicose veins. The aim of the use of compression bandaging is the reduction of venous hypertension which results from valvular insufficiency[13]. The application of external compression by means of bandage serves to increase the velocity of blood flow within the veins by providing support to the muscles. It has been demonstrated that venous return is faster and more efficient if the compression bandage is applied in a manner that gives sub-bandage pressure that are graduated from the ankle to the knee (greater at the ankle than at the knee)[14]. Elastomeric bandages made with rubber was first used in the late 19th century and this has now been replaced by Lycra or elastane which are light, strong, comfortable, and washable. These are either woven or knitted, and are designed to provide prescribed levels of compression stipulated by performance based standards[15].

Classification of compression bandages

Compression bandages are mainly classified as elastic and non-elastic. Elastic compression bandages are categorised according to the level of pressure generated on the angle of an average leg. Class 3a bandages provide light compression of 14-17mmHg, moderate compression (18-24mmHg) is imparted by class 3b bandages and 3c type bandages impart high compression between 25 and 35mmHg[16]. The 3d type extra high compression bandages (up to 60mmHg) are not often used because the very high pressure generated will reduce the blood supply to the skin. It must be stated that approximately 30-40mmHg at the ankle which reduces to 15-20mmHg at the calf is generally adequate for healing most types of venous leg ulcers[17]. Compression stockings provide support to treat DVT and varicose veins, and to prevent venous leg ulcers. They are classified as light support (Class 1), medium support (Class 2) and strong support (Class 3) [16].

Ideal compression bandages

Compression bandages are harmful if not applied properly. Compression bandages provide high tension as well as high pressure and, therefore, a thorough assessment such as magnitude of pressure, distribution of pressure, duration of pressure, limb radius and layers of bandage are essential before applying on a limb. The ability of a bandage to provide compression is determined by its construction and the tensile force generated in the elastomeric fibres when extended. Compression can be calculated by Laplace's Law, which states that the pressure is directly proportional to the bandage tension during application and the number of layers applied but inversely proportional to limb radius[18]. The structure of a compression bandage is, therefore, regarded as an important factor in producing a uniform pressure distribution. An ideal compression bandage should[19]:

- provide compression appropriate for the individual;
- provide pressure evenly distributed over the anatomical contours;
- provide a gradient pressure diminishing from the angle to the upper calf;
- maintain pressure and remain in position until the next change of dressing;
- extend from the base of the toes to the tibial tuberosity without gap;
- function in a complimentary way with the dressing; and
- possess non-irritant and non-allergenic properties.

Compression system

Compression can be exerted to the leg either by a single layer bandage or multilayer bandages. In the UK four layer bandaging system is widely used[20] whilst in Europe and Australia the non-elastic two layer short stretch bandage regime is the standard treatment[16]. A typical four layer compression bandage system comprises of padding bandage, crepe bandage, high compression bandage and cohesive bandage. Both the two layer and four layer systems require padding bandage (wadding or orthopaedic wool) that is applied next to the skin and underneath the short stretch or compression bandages.

A plaster type non-elastic bandage, Unna's boot is favoured in the USA. However, compression would be achieved by three-layer dressing that consists of Unna's boot, continuous gauze dressing followed by an outer layer of elastic wrap[21]. It should be realised that Unna's boot, being rigid, is uncomfortable to wear and medical professionals are unable to monitor the ulcer after the boot is applied. Three and/or four layer compression bandage regimes are also used in some hospitals in the USA[22].

A variety of padding bandages are used beneath compression bandages as padding layers in order to evenly distribute pressure and give protection. They absorb high pressure created at the tibia and fibula regions. It will be noticed that the structure of a padding bandage is regarded as an important factor in producing a uniform pressure distribution. Research has shown that the majority of the commercially available bandages do not provide uniform pressure distribution[23].

Present problems

During the past few years there have been increasing concerns relating to the performance of bandages especially pressure distribution properties for the treatment of venous leg ulcers. This is because the compression therapy is a complex system and requires two or multilayer bandages, and the performance properties of each layer differ from other layers. The widely accepted sustained graduated compression mainly depends on the uniform pressure distribution of different layers of bandages in which textile fibres and bandage structure play a major role. The padding bandages commercially available are nonwovens that are mainly used to distribute the pressure, exerted by the short stretch or compression bandages, evenly around the leg otherwise higher pressure at any one point not only damages the venous system but also promotes arterial disease. Therefore there is a need to distribute the pressure equally and uniformly at all points of the lower limb and this can be achieved by applying an effective padding layer around the leg beneath the compression bandage. In addition, the padding bandages should have the capability to absorb high pressure created at the tibia and fibula regions. Wadding also helps to protect the vulnerable areas of the leg from generating extremely high pressure levels as compared to those required along the rest of the leg[24]. The research carried out at Bolton Institute involving 10 most commonly used commercial padding bandages produced by major medical companies showed that there are significant variations in properties of commercial padding bandages[23, 25], more importantly the commercial bandages do not distribute the pressure evenly at the ankle as well as the calf region. The integrity of the nonwoven bandages is also of great concern. When pressure is applied using compression bandages, the structure of the nonwoven bandages may collapse and the bandage would not impart cushioning effect to the limb. The comfort and cushioning effect are considered to be essential properties for padding bandages because they stay on the limb for several days.

In the UK, multilayer compression systems are recommended for the treatment of venous leg ulcers[20]. Although multilayer compression bandages are more effective than single layer bandage in healing venous leg ulcers[16], it is generally agreed by the clinicians that multilayer bandages are too bulky for patients and the cost involved is high. A wide range of compression bandages is available for the treatment of leg ulcers but each of them having different structure and properties and this influences the variation in performance properties of bandages. In addition long stretch compression bandages tend to expand when the calf muscle pump is exercised, and the beneficial effect of the calf muscle pump is dissipated[26]. It is a well established practice that elastic compression bandages that have the extension of up to 200% are applied at 50% extension and at 50% overlap to achieve the desired pressure on the limb. It has always been a problem for nurses to exactly stretch the bandages at 50% and apply without losing the stretch from ankle to calf, although there are indicators for the desired stretch (rectangles become squares) in the bandages. The elastic compression bandages are classified into four groups (3a, 3b, 3c and 3d) according to their ability to produce predetermined levels of compression and this has always been a problem to select the right compression bandage for the treatment. The inelastic short stretch bandage (Type 2) system, which has started to appear in the UK market, has the advantage of applying at full stretch (up to 90%

extension) around the limb. The short stretch bandages do not expand when the calf muscle pump is exercised and the force of the muscle is directed back into the leg which promotes venous return[26]. The limitations of short stretch bandages are that a small increase in the volume of the leg will result in a large increase in compression and this means the bandage provides high compression in the upright position and little or no compression in the recumbent position when it is not required[27]. During walking and other exercises the sub-bandage pressure rises steeply and while at rest the pressure comparatively drops[28]. Therefore patients must be mobile to achieve effective compression and exercise is a vital part of this form of compression[29]. Moreover the compression is not in tact with skin when reduction in limb swelling because the short stretch bandage is inelastic, and it has already been stretched to its full extent.

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A COMPARISON OF ELASTIC AND NON-ELASTIC COMPRESSION BANDAGES FOR VENOUS LEG ULCER TREATMENT

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INTRODUCTION

There has been much discussion in the literature of the differences between elastomeric and non-elastomeric compression systems. It has been suggested that non-elastomeric systems, for example short-stretch layered regimen confer particular advantages such as greater safety over elastomeric systems[1,2], (Charing Cross four-layer bandage) cost-effective as they can be washed and reused[3] and patients are able to wear their usual footwear[4,5]. On the other hand, elastic systems, for example four layer bandage, are said to stay on longer without the need for reapplication thus reducing the cost of treatment[6].

This study compares elastomeric and non-elastomeric bandaging systems in respect of their ease of application, and impact on healing of venous leg ulcers.

EASE OF APPLICATION

The only reliable and valid method for checking bandage application is by placing small pressure sensors at predefined points on the patient's limb and wrapping the bandage over it. The bandage normally needs to be removed for retrieval of the pressure sensors. The systematic checking of bandaging technique requires considerable investment in personnel and pressure transducers, and a number of authors have commented on the reliability of the pressure measurement equipment currently available. Evaluations of bandaging technique are further complicated by the lack of an agreed pressure profile for compression bandages. In the UK, a combination of (a) ankle pressure of 25-40 mmHg and (b) a reduction in pressure from ankle to the calf, is usually cited as being 'ideal'[7]. There is, however, no 'ideal' pressure profile for the short-stretch bandage system to guide training. The theoretical 'ideal' pressures for the four-layer bandage are based on laboratory measurements of pressures and have not been correlated with bandage performance in healing ulcers[8-10]. Furthermore, published studies only measure the pressure at two or three points on the leg and, therefore, cannot conclude that the pressure reduces from ankle to knee without and bands of high or low pressure[10]. Bands of high or low pressure are sufficient to reduce venous return, in comparison with evenly graduated compression, and therefore current measurement techniques and training may be failing to identify potentially important problems with bandaging techniques[11].

Previous work has demonstrated that nurses bandaging technique is generally poor before training, with the majority applying them with greater pressures at the calf than at the ankle which would tend to reduce rather than increase venous return[10]. Furthermore, training makes only a modest impact on the proportion of nurses applying the bandages with a reduction in pressure from the ankle towards the knee. An evaluation of the impact of training on the bandaging techniques of nurses using a number of compression systems (elastomeric single and multi-layered and non-elastomeric) indicates that minority of nurses could apply compression bandages appropriately before training[10]. It was found that a proportion of community nurses applying a four-layer bandage regime appropriately, with graduated pressure (higher at ankle than calf), increased from 32% to 55% after training. The proportion of nurses who applied graduated compression using a short-stretch bandage also increased from 31% to 52% after training. For both bandage systems, therefore, in-service bandaging training decreased the proportion of bandages with higher pressure at the calf than the ankle but around 45% of nurses still applied a bandage with higher pressure at the calf, even after training.

It appears that there is no difference in the ability of UK community nurses to apply elastomeric and non-elastomeric bandage systems, but as the 'ideal' pressure profile used in this study was that for elastomeric systems, the validity of this finding is not clear. In addition, there were only 48 nurses in the evaluation of short-stretch bandages, and therefore it lacked power to detect important differences in application ability.

The impact of bandaging skill on patient outcomes, such as comfort, bandage slippage, pressure damage and ulcer healing remains unknown.

CLINICAL TRIALS

If one bandage system is more effective in healing ulcers, or is better at healing ulcers in certain types of patients (e.g. those with limited mobility) then this will be revealed in prospective randomised controlled trials. Case series are potentially misleading as often impressive healing rates reported are out of context, they do not allow one to determine which elements of the care contributed to healing. Randomised Controlled Trials (RCT) address all the risk factors for healing / non-healing (both the known and unknown risk factors) between treatment groups and, therefore, allow one to be confident that the only systematic difference between groups is in the intervention being investigated.

There have been a number of randomised controlled trials comparing non-elastomeric and elastomeric bandage systems. We have undertaken a systematic review of trials of compression systems for healing venous ulcers[12]. The systematic review identified a number of trials making comparison between non-elastomeric and elastomeric bandaging systems (Table 1). It should be noted that many of the systems were evaluated in only one trial.

Table 1. Summary of randomised controlled trials of compression regimens for treating venous leg ulcers (the names refer to the references at the back)

	MECH	NEC	Single Layer Elastomeric	Low Compression Layered
No Compression	Taylor[13,14] Eriksson[15]	Kikta[16] Rubin[17] Sikes[18] Charles[4,5]	NO TRIALS	NO TRIALS
MECH	Colgan[19,20] McCollum[21] Wilkinson[22]	Knight[23] Danielsen[24,25] Scriven[3] Duby[1,2]	Nelson[8-10] Travers[26] Colgan[19,20] Kralj[27]	Gould[28] Callam[29] Northeast[30] Duby[1,2]
NEC	Knight[23] Danielsen[24,25] Scriven[3] Duby[1,2]	NO TRIALS	Cordts[31] Partsch[32] (stockings trial) Hendricks[33]	Duby[1,2]

MECH : Multi-layer elastic compression (high pressure), e.g. elastic bandage and hosiery, 4 layer bandages, paste and high compression bandage
NEC : Non-elastomeric compression, e.g. Unna's boot and short-stretch bandages

An update of the Cullum review[12] has found eight small RCTs (573 people in total) comparing elastomeric and non-elastomeric systems. Meta-analysis of these RCTs found no significant difference in healing rates between multilayer high compression and inelastic bandages (RR for healing 1.0, 95% CI 0.85 to 1.14) (Figure 1). There are a number of potential problems with meta-analyses such as these. The trials may have different follow-up periods, and therefore pooling the data across time points may be inappropriate. In addition, only the trial by Partsch[32] fully reported results using survival curves, which indicate both how many people healed their ulcers and how quickly they healed. If two bandage systems have identical number of people healed, say at 6 months, but one group had quicker healing, then this clinically important outcome would be lost if one only reported 'number of people healed'. The lack of comparability of the various compression systems and the lack of power in these small studies have shown that we cannot be confident that there is no clinically important difference in healing rates for the two types of bandage system. Poor reporting of the mobility levels in the groups also means that we cannot determine whether non-elastomeric systems are more effective in people with some calf-muscle pump function, as is often alleged.

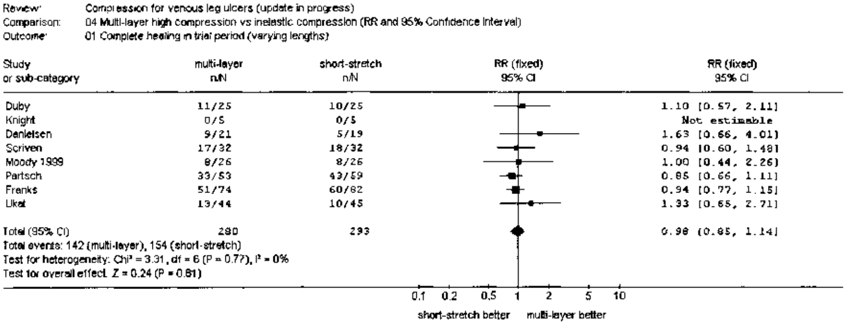

Figure 1. Meta-analysis of multi-layer high compression versus inelastic compression.

Non-healing outcomes

Three of the trials Partsch[32], Duby[1,2] and Scriven[3] reported the frequency of bandage application to allow one to determine whether the elastomeric systems required fewer reapplications, and only Scriven[3] reported the incidence of pressure damage. None of the trials reported any data on footwear problems. The majority of these suggested differences between elastomeric and non-elastomeric bandages, therefore, appear to be unsupported by data from RCTs.

Only three RCTs identified by the systematic review (Blair[34], Charles[4,5], Danielsen[21,25]) measured the pressure exerted by compression bandages, 2 placing the ankle sensor 2cm above the malleolus (one laterally, one medially) and 1 placing the ankle sensor 4cm above the medial malleolus. The variation in sensor placement and type of sensors used (Oxford Pressure Monitor and Medical Stocking Tester) means that the results cannot be easily compared.

CONCLUSIONS

Comparison between non-elastomeric and elastomeric bandage systems refers to differences in terms of ease/method of application, patient safety, effectiveness and cost. There is insufficient evidence from comparative studies of the two groups of bandage regimens. Large studies in which sub-bandage pressures and clinical outcomes (healing rates, pressure damage, bandage slippage and comfort) are measured are urgently needed. These should take into account the previous skill / experience of the bandager, and report bandage pressures along the length of the limb, measured during the whole period of bandage wear. Methodological weaknesses from previous studies, e.g. plethora of unique comparisons, underpowered studies and inadequate reporting, should be avoided.

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THE STUDY OF PRESSURE DELIVERY FOR HYPERTROPHIC SCAR TREATMENT

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ABSTRACT

Pressure garments made from elastic fabrics are commonly used to treat hypertrophic scars. Occupational Therapists in the UK hospitals do not commonly take into account the potential influence of either fabric properties or the body part circumference on the pressures exerted by pressure garments constructed with standard reduction factors. This investigation sought to establish the relationship between the pressures exerted on cylinder models by pressure garments (made from 4 different powernet fabrics) and the circumference of the cylinder model.

INTRODUCTION

Hypertrophic scars frequently develop following serious burn injury or other wounds healing by second intention (i.e. wounds whose edges cannot be sutured together). These scars are:[1-3]

- warm and red/purple in colour due to increased vascularity;
- raised, firm and whorl-like in structure due to increased collagen deposition;
- tender and may itch;
- contractile in nature and may lead to scar contracture if untreated;
- scars which remain within the original line of the wound; and
- active scars that often regress with time.

Pressure garments have been used in hospitals worldwide to prevent and treat hypertrophic scars since the 1970s. The popularisation of this method of treatment is most commonly attributed to the work done by Larson et al at the Shriners Burns Institute at Galveston in Texas[4]. The rationale for pressure therapy is based on the belief that pressure reduces collagen production within the developing or active scar. This belief is backed by years of medical experience and many case studies but has never been scientifically proven. Pressure garments additionally often alleviate the pain or itchiness associated with hypertrophic scars and tend to prevent the development of serious contractures (areas of contracted skin over flexor joints which reduce the range of motion).

Pressure garments are normally custom-made from elastic fabrics and are designed to exert a pressure of approximately 25 mmHg on the underlying tissue. This 'ideal' pressure has varied over the years and has never been scientifically established. This appears to be due, in part, to the difficulty in applying even pressure to the human body and the lack of actual garment/scar interface pressure measurement in most hospitals, the efficacy of this treatment and the fit of garments normally being assessed subjectively based on individual practitioner's experience. Some work has been conducted on garment/scar interface pressure[5] but no conclusions on the most effective pressure were drawn, much of this research being concerned with developing accurate means for pressure measurement.

There are several problems associated with current pressure garment treatment. Fundamental problems in treatment delivery include:

- lack of scientifically established guidelines on safe and effective pressure[6];

- pressure is difficult to apply evenly, particularly in concave areas of the body[7,8];
- blistering and scar breakdown may occur if too much pressure is applied too soon, resulting in treatment suspension[7,8];
- the effects of percentage body fat, age, sex, race, etc. on the interface and subdermal pressures delivered using similarly constructed garments is not fully understood;
- applied pressure decreases during the course of the day and the life of the garment;
- applied pressure varies with movement and the precise nature of these changes has not been measured; and
- the'reduction factors' used by occupational therapists are often arrived at in an arbitrary manner without considering the differences in fabric properties[9].

The aim of this investigation is to develop a system for calculating the dimensions of pressure garments so that they would exert a particular pressure on human limbs. The investigation is broken down into the following stages:

1. Measure the tension in the fabrics currently used to construct pressure garments made in, or supplied to, UK hospitals.
2. Construct a series of cylinder models to represent the range of human limb sizes.
3. Evaluate the effect of changing cylinder circumference on the pressures exerted by pressure garment samples.
4. Evaluate the effect of changing cylinder compressibility on the pressures exerted by pressure garment samples.
5. Evaluate the effect of changing the fabric used in pressure garment sample construction on the pressures exerted by the samples on cylinder models.
6. Evaluate the effect of changing the reduction factor used in pressure garment sample construction on the pressures exerted by the samples on cylinder models.
7. Evaluate the Laplace Law for predicting the pressures exerted by pressure garment samples on cylinder models.
8. Measure the pressures exerted by pressure garment sleeves to human limbs.
9. Evaluate the Laplace Law for predicting the pressures exerted by pressure garment sleeves on human limbs.

This paper discusses the method of measurement and results obtained from stages 1, 2, 3 and 7.

THE THEORY OF THE LAPLACE LAW

The Laplace Law has been widely used to calculate the pressure delivered to a cylinder of known radius by a fabric under known tension. However, it was originally developed by Laplace in 1806 to explain the surface tension phenomenon in liquids and their ability to form droplets[10] or soap bubbles[11].

The original theory was developed to relate the wall tension and radius of cylinders (e.g. blood vessels) to the pressure difference that existed between the pressure pushing the two halves of the cylinder apart and the wall tension pulling the two halves together. This equation can be written as:

$$\text{Pressure} = \text{Tension in the cylinder wall} \div \text{radius of the cylinder}$$

$$\text{or} \quad P = T \div r \qquad (1)$$

and is known as the Law of Laplace[11], although it is more commonly referred to as the Laplace Law. When this equation is applied to the aorta the tension in the aorta wall can be calculated and in one example was shown to be in the order of 2Nm^{-1} [11], i.e. relatively low when compared to elastic fabrics. This low tension in the aorta walls is only possible since the radius of the aorta is so small (approximately 1.5cm) and so allows it to contain blood at very high pressures.

There are several differences between the behaviour of liquids, for which the Laplace Law was established, and the behaviour of elastic fabrics and solid cylinders. These are:

- the tensions considered in the formation of the Laplace Law were very small compared to those found in elastic fabrics in pressure garment construction;
- liquids and blood vessel walls have very different properties to elastic fabrics;
- liquids, solid cylinders and human limbs have very different properties;
- the Laplace relationship required modification for inflated rubber balloons - which have many shared properties with bubbles. Therefore it is likely that modification will be required for elastic fabrics that are not continuous membranes; and
- in practice, movement between the pressure garment and the limb on which it is placed is likely to generate friction which is not accounted for by the Laplace Law.

The origin of the use of the Laplace Law for estimating the pressure delivered by pressure garments is unclear. The first specific reference to it is in a paper published in 1984[12], which states 'These observations in fact are adequately explained by the Laplace Law'. However, the paper had previously stated that ...'garment tension appeared much the same', suggesting that fabric tension was not actually measured. Therefore the assertion that pressure garments appeared to follow the Laplace Law was based on the observation that the measured pressure increased over areas of low radius of curvature and decreased or didn't exist on areas of high radius of curvature. Clearly areas of the body that are concave do not make contact with the pressure garment and therefore no pressure is exerted at all.

USING THE LAPLACE LAW TO PREDICT PRESSURES EXERTED BY PRESSURE GARMENTS

When patients are measured for pressure garments in hospitals it is the circumference of the limb or body part that is measured (not the radius). Therefore it would be more useful if the Laplace Law was amended to predict pressure from the fabric tension and circumference of the body part. Since $r = c \div 2\pi$, the pressure (in Pa) exerted by pressure garment samples made from a fabric with tension 'T' could be predicted for a cylinder of radius 'r' (in m) using the Laplace Law as follows:

$$\begin{aligned}\text{Pressure (Pa)} &= (T \div c) \div 2\pi \\ &= (T \times 2\pi) \div c \\ &= (6.283T)c^{-1} \qquad (2)\end{aligned}$$

This equation may be further modified to predict the pressure in mmHg, which is the most common unit of pressure referred to in literature regarding pressure garment construction and treatment. Since 1mmHg is equal to 133.322 Pa the Laplace predicted pressure in mmHg would be:

$$\begin{aligned}\text{Pressure (mmHg)} &= (2\pi T \div 133.322)c^{-1} \\ &= (0.047T)c^{-1} \qquad (3)\end{aligned}$$

TENSION IN FABRICS CURRENTLY USED IN PRESSURE GARMENT CONSTRUCTION IN THE UK HOSPITALS

Most (64%) occupational therapists who make pressure garments in the UK hospitals use a 20% reduction factor on each circumferential measurement of the patient (according to a survey of all the UK burn units carried out in 1997, 53% response rate). Therefore the fabric in these pressure garments is extended by 25% when they are fitted on the patients. Eighteen fabrics were collected from the UK hospitals and two commercial pressure garment manufacturers for evaluation.

METHOD

The fabric tension was calculated for all eighteen fabrics from the load at 25% extension using a Nene M5 constant rate of extension tensile testing machine. The experimental procedure was based on BS 4952:1992. The actual procedure employed is detailed below.

1. Sets of five looped samples were prepared from each fabric as described in Section 1.4.2.3 of BS 4952:1992 (7.5cm wide, 20cm looped gauge length), using a 3mm wide BS 304 seam (commonly used in pressure garment construction).
2. Samples were extended at a rate of 200mm/min to 25% extension, using a 100N load cell.
3. Samples were held at 25% extension and the load was noted after 30 seconds.
4. The load in N measured in each sample was halved to give the load for one side of the fabric loop. This was multiplied by 100/7.5 to give the fabric tension in Nm^{-1}.

RESULTS AND DISCUSSION

The tension of the fabrics currently used in pressure garment construction in, and for, the UK hospitals ranged from 27 to $177Nm^{-1}$ at 25% extension. Fig. 1 shows the range of (mean) pressures that would be exerted on a wrist (with a 15cm circumference) and a thigh (with a 72cm circumference) according to the Laplace Law assuming a 20% reduction factor was used in pressure garment construction. The predicted pressures at the wrist circumference ranged from less than half the recommended pressure to more than twice the recommended 25mmHg pressure. The closest predicted pressure at the thigh circumference was less that half the recommended pressure. Therefore, if accurate these predictions show that both the circumference of the limb and the fabric tension have a significant impact on the pressures delivered by pressure garments if current construction techniques are used. Therefore it was decided to conduct an evaluation of the Laplace Law for the prediction of pressure delivered by pressure garments made from the most popularly used fabric structure, i.e. powernet.

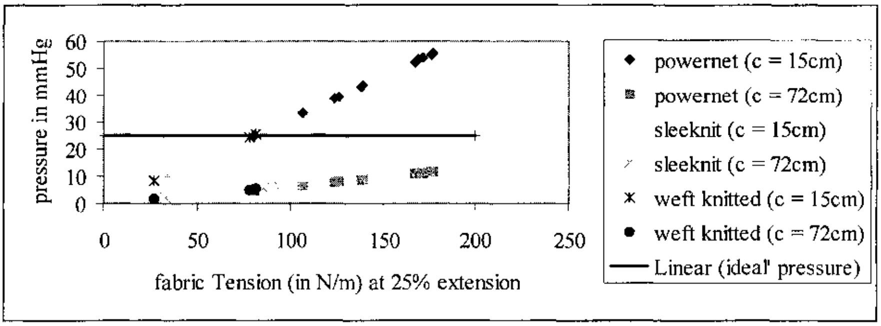

Figure 1 – Range of interface pressures predicted by the Laplace Law based on a wrist circumference of 15cm and a thigh circumference of 72cm

Evaluation of the Laplace Law for predicting the pressures exerted by pressure garment samples on cylinder models

Materials

One of the powernet fabrics collected to evaluate the fabrics currently used in pressure garment construction was selected as the main fabric for the pressure measurements that follow. It will be referred to as mp2. A further 3 powernet fabrics (pf2, pf3 and pf4) were produced for the secondary measurements. Therefore 4 different values of Tension were represented.

Cylinder models

12 rigid cylinders of various circumferences, representing a range of human limb sizes, were used. Expanded neoprene foam was glued around each cylinder to represent the compressibility of human tissue. The cylinder models were lettered A-L and the circumference of each was measured (see Table 1 for mean cylinder model circumference).

Determination of the effect of cylinder circumference on the pressures exerted by pressure garment samples - method

Main measurements

The pressure delivered to twelve cylinder models (A to L) by sets of five pressure garment samples constructed from fabric mp2 using a 20% reduction factor was measured using the following procedure.

1. A reduction factor of 20% was applied to the mean circumference of each cylinder model. (Table 1).
2. Five pressure garment samples were constructed from fabric mp2 for each cylinder model. Samples were prepared as for the fabric tension measurements described above except that they were 10cm wide and used the circumferential dimensions shown in Table 1.
3. The pressure exerted by each pressure garment sample on the appropriate cylinder model was measured 30 seconds after it was positioned.

Secondary measurements

Pressure garment samples made from pf2, pf3 and pf4 were tested on cylinder models B, E, G and K in order to determine if the effect of the cylinder circumference was constant regardless of the tension of the fabric used. The procedure followed was the same as that described in steps 1 to 3 above.

Table 1 - Cylinder model and sample circumferences (cm)

cylinder model	A	B	C	D	E	F	G	H	I	J	K	L
cylinder model circumference	15.2	19	22	24	30.4	35	37	44.1	52.8	55.3	85.2	95.6
sample circumference	12.2	15.2	17.6	19.2	24.3	28	29.6	35.3	42.3	44.2	68.2	76.5

Determination of the effect of cylinder circumference on the pressures exerted by pressure garment samples - results

Main measurements

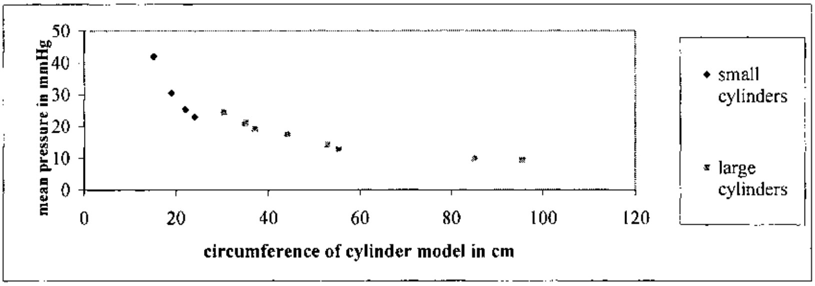

Figure 2 - Mean pressure exerted by pressure garment samples made from mp2 showing different trends set by small compared to large cylinder models

Figure 2 shows that as the circumference of the cylinder model increased the pressure exerted on it by similarly constructed pressure garment samples decreased.

The line of best fit for the large cylinder models E-L was described by the power law equation 4 below:

$$P = 402.7c^{-0.8357} \qquad (4)$$

Where P was the mean pressure in mmHg exerted on the cylinder model and c was the cylinder model circumference in cm. The coefficient of Determination R^2 for this equation was significant at the 99.9% confidence limit.

The line of best fit for the small cylinder models A-D was described by the power law equation 5 (R^2 for this equation was significant at the 99% confidence limit) below:

$$P = 1527c^{-1.3247} \qquad (5)$$

Therefore, 2 equations would be required to predict the pressure exerted by pressure garments made from fabric mp2 using a 20% reduction factor on cylinder models.

Secondary measurements

The relationship between increasing cylinder model circumference and decreasing pressure was confirmed when fabrics pf2, pf3 and pf4 were tested on cylinders B, E, G and K, (Figure 3). Again the line of best fit was described by a power law equation for each set of data. Despite the small number of data points the coefficients of determination for these lines of best fit were all significant at the 95% confidence level. This suggests that each of these equations could be used to predict the pressures exerted by pressure garment samples, constructed from the corresponding fabric using a 20% reduction factor, on a cylinder model. However, it would be necessary for more measurements be taken to improve the accuracy of the predictions. Although these fabrics were measured on only 4 cylinder models they did not appear to follow separate trends on the small cylinder models and the larger cylinder models as fabric mp2 did.

However, more measurements would be required to confirm that these indications were reliable.

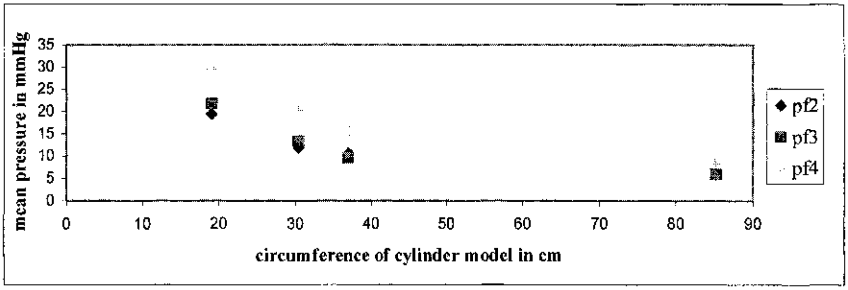

Figure 3 - Mean pressures exerted by pressure garment samples (made from pf2, pf3 and pf4 using a 20% reduction factor) on 4 cylinder models

Evaluation of the Laplace Law for predicting the pressures delivered by pressure garment samples to cylinder models of different circumference

Difference between predicted and measured pressures – main measurements

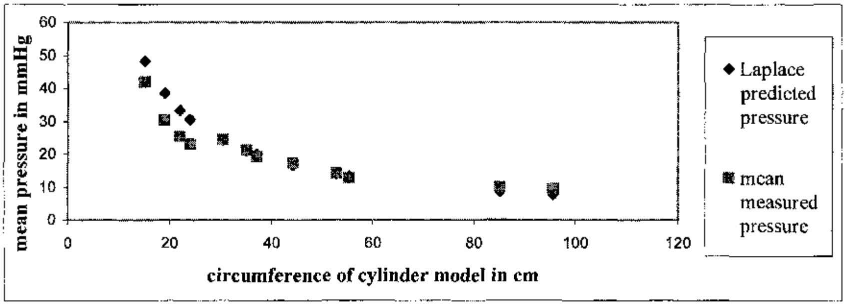

Figure 4 - Relationship between mean measured and predicted (using Laplace Law) pressure for mp2 using a 20% reduction factor

Figure 4 shows that the Laplace Law predicted the pressures exerted by pressure garment samples made from mp2 to 'large' cylinders E-L accurately, while it overestimated the pressures exerted on 'small' cylinders A-D. This confirms the trend noted above that fabric mp2 behaved differently on small cylinders compared to large ones.

Difference between predicted and measured pressures – secondary measurements

Table 2 shows that the measurements with fabrics pf2, pf3 and pf4 on cylinder models B, E, G and K confirmed that the Laplace Law accurately predicted the pressures exerted by these fabrics on both small and large cylinder models. (The error inherent in the pressure measurement system was ± 2.1mmHg.)

Table 2 - Difference between the mean measured pressure and that predicted by the Laplace Law on cylinder models B, E, G and K

cylinder model	B			E			G			K		
fabric reference	pf2	pf3	pf4	pf2	pf3	pf4	pf2	pf3	pf4	pf2	pf3	pf4
difference in mmHg	-1.8	-2.0	0.8	-1.0	-0.9	-1.8	-1.6	0.5	0.4	-2.0	-1.5	-1.6

CONCLUSIONS

1. A wide range of fabrics is currently used in the construction of pressure garments. These fabrics have a wide range of tensions, and consequently (according to the Laplace Law) would exert a wide range of pressures when made into pressure garments following the standard construction technique.
2. According to the Laplace Law if one reduction factor (e.g. 20%) and one fabric were used in the construction of pressure garments, then different pressures would be exerted on different parts of the same body and on different people.
3. The Laplace Law accurately predicted the pressures exerted by pressure garment samples on cylinder models of large circumference (greater than 30cm) made from a range of powernet fabrics.
4. The Laplace Law predicted the pressures exerted by pressure garment samples on cylinder models of small circumference (less than 25cm) with variable accuracy. A fabric currently used to produce pressure garments supplied to many UK hospitals did not exert pressures that were accurately predicted by the Laplace Law at small circumferences.

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EVALUATION OF PRESSURE PROFILE OF BANDAGES USING MANNEQUIN LEG

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ABSTRACT

There is an urgent need to focus research and development work towards the treatment of venous leg ulcers because about 1% of the adult population suffers from active ulceration during their lifetime in the UK alone and costs the National Health Service (NHS) £600 million per annum. Similarly, venous ulceration is a common disease affecting around 1% of adult population in Australia. The direct and indirect cost of the treatment for this condition in Germany is more than DM 1 billion. In the US about 2 million working days are lost each year because of leg ulcer problems and the treatment cost is enormous.

In an on-going research and development programme funded by the Department of Trade and Industry (DTI) and 5 major UK companies for developing novel compression therapy system for the treatment of venous leg ulcers, the Centre for Materials Research and Innovation (CMRI) has developed novel bandages and bandaging techniques. The results of the pressure distribution of developed padding and existing Type-2 short stretch as well as Type-3c high compression commercial bandages will be discussed. The Pressure Profiling Instrument developed at Bolton Institute which consists of 8 pressure sensors (2 at ankle, 3 at lower calf and 3 at upper calf) has been used for studying the pressure profile around the lower part of the leg. The pressure mapping of two-layer, three-layer and four-layer systems will be highlighted. The study as regards the development of novel compression bandages based on the results of the pressure profile programme will also be presented.

INTRODUCTION

Textile materials play an important and crucial role in designing appropriate structures for the healthcare and medical industries. It is forecasted that the share of hygiene and medical textiles would be 12% of the global technical textiles market and would account for US$4.1 billion[1]. It has been established that compression therapy by making use of compression bandages is an efficient treatment for healing various leg ulcers, despite surgical strategies, electromagnetic therapy and intermittent pneumatic compression. Venous leg ulcers are the most common type of ulcers and their prevalence increases with age. They are chronic and are caused due to poor venous return from the calf to the heart. In the UK alone about 1% of the adult population suffers from active ulceration during their lifetime. This represents 260,000 patients in the UK of which 55,000 potential or actual ulcer patients are in Scotland alone. The total cost to the National Health Service for venous leg ulcer treatment is about £600 million per annum. Similarly, venous ulceration is a common disease affecting around 1% of adult population in Australia[2]. The direct and indirect cost of the treatment in Germany is more than 1 billion DM[3]. In the US a large number of people suffer from leg ulcers as is evident from the fact that about 2 million working days are lost each year because of leg ulcer problem and the treatment cost is enormous[4].

In the past, the researchers in the Centre for Materials Research and Innovation (CMRI) at Bolton Institute have successfully designed and developed a number of novel textile structures such as wound dressings for wound management, cast cloths for orthopaedic casting and 3-D spacer materials for knee brace. In one of the current research programmes funded by the Department of Trade and Industry (DTI), Bolton Institute and five major medical textile companies are developing novel structures such as padding bandages and compression bandages that would be superior in performance to the existing commercial bandages and help to replace the currently popular four layer bandaging system used for the treatment of venous leg ulcers. The first stage of the programme has been completed with the development and characterization of superior high performance padding bandages. The superior properties of the developed padding bandages would pave the way for the development of a two layer bandaging system which consists of a padding and a high compression bandage. The results of the pressure distribution of developed padding and existing Type-2 short stretch as well as Type-3c high compression commercial bandages are discussed in the paper. The pressure mapping of two-layer, three-layer and four-layer systems are also highlighted.

MATERIALS AND METHODS

Materials

The novel padding bandages developed at Bolton Institute that possess superior water absorption and uniform pressure distribution are used – a) 100% hollow viscose nonwoven needle punched on both sides (NPB5) and b) 50% polyester/50% normal viscose nonwoven needle punched on both sides (NPB8).

Commercial compression bandages used are:

- Rosidal K (Type 2 short stretch; Lohmann - Vernon - Carus; 100% cotton);
- Actiban (Type 2 short stretch; Activa; 100% cotton);
- Tensopress (Type 3c high compression; Smith & Nephew (BSN Medical); 67% cotton/33% viscose blended yarn and elastomeric yarn);
- Setopress (Type 3c high compression bandage; SSL International; 46% polyamide/40% cotton/14% elastomeric yarn);
- Surepress (Type 3c high compression bandage; Convatec; cotton/viscose/polyamide/elastomeric yarn);
- Profore#3 (Type 3a light compression; Smith & Nephew (BSN Medical);
- Profore#4 (Type 3b moderate compression; Smith & Nephew (BSN Medical); and
- Crepe bandage (light support bandage; Boots; 100% cotton).

Methods

Mannequin Leg

A prototype electronic instrument developed at Bolton institute was used to investigate the pressure mapping of two-layer, three-layer and four-layer systems. The mannequin leg (Figure 1) simulates a lower limb and has definable tibia, calf and ankle regions. It has 8 pressure-measuring sensors (Figure 2) of which 2 are positioned at ankle, 3 at calf and 3 at below knee. The sensors are connected with an electronic board display unit via strain gauges. The padding bandage was wrapped around the mannequin leg followed by Type 2 or Type 3c bandages for two-layer system, Type 3a and Type 3b for three-layer system, and crepe bandage, Type 3a and Type 3b for four-layer system. All the bandages were wrapped around the leg at 50% overlap (two complete layers) by rotating the leg. The bandages were stretched at 50% extension by applying 1 Kgf load when wrapping around the leg. However padding bandages were applied without stretch. It should be mentioned that nurses normally apply the bandages at 50% overlap, and at 1 Kgf stretch (50% extension) for treating the venous leg ulcers.

The pressure developed at ankle, calf and below knee positions in the mannequin leg was read from the display unit and the values were corrected using the regression equations. Prior to the measurement, the pressure sensors in the leg were calibrated to the known pressure range of 0 to 300 mmHg by making use of a sphygmomanometer.

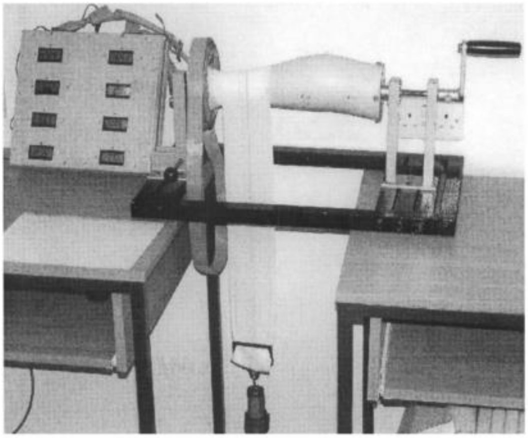

Figure 1. Pressure Profile Instrument (Mannequin Leg)

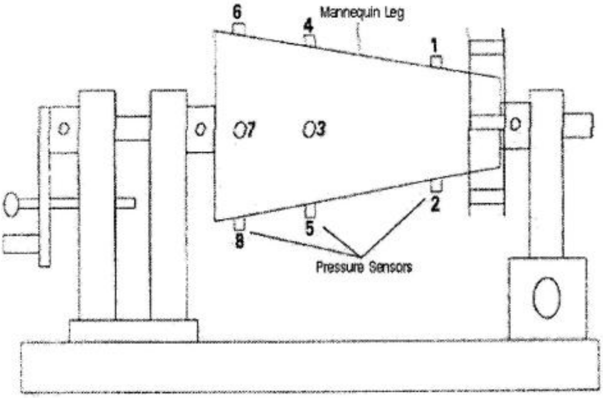

Figure 2. Schematic Diagram of Pressure Profile Instrument (Mannequin Leg)

RESULTS AND DISCUSSION

Compression bandages

It has been demonstrated that compression therapy that includes padding and compression bandages is highly effective and 'gold standard' treatment for venous ulceration[5] and the rate of ulcer healing is high[6]. A sustained graduated compression mainly enhances the flow of blood back to the heart, improves the functioning of valves and calf muscle pumps, reduces oedema and prevents the swelling of veins[7].

Compression bandages are mainly classified as elastic and non-elastic and it is reported that non-elastic bandages provide low or no pressure at rest and completely non-elastic bandages are no longer used in the medical treatment[8]. Elastic compression bandages are categorised according to the level of pressure generated on the angle of an average leg. Class 3a bandages provide light compression of 14-17mmHg, moderate compression (18-24mmHg) is imparted by class 3b bandages and 3c type bandages impart high compression between 25 and 35mmHg. The extra high compression bandages (up to 60mmHg) are not often used because the very high pressure generated will reduce the blood supply to the skin. It must be stated that approximately 30-40mmHg at the ankle which reduces to 15-20mmHg at the calf is generally adequate for healing most types of venous leg ulcers[9].

Compression can be exerted to the leg either by a single layer bandage or multi-layer bandages. In the UK four layer bandaging system is widely used whilst in Europe and Australia the non-elastic short stretch bandage regime is the standard treatment. In the four layer system the first layer is a nonwoven padding bandage that absorbs exudate and protects bony prominences from excessive pressure. The second layer is a crepe bandage which adds absorbency and smoothes the padding layer. The third layer is a light compression bandage that is highly conformable to accommodate a difficult limb shape. The fourth layer is a cohesive flexible bandage. It applies pressure and is cohesive in nature, which means the bandages stay in place and maintain effective levels of compression for up to one week.

A plaster type non-elastic bandage, Unna's boot is favored in the USA. However, compression would be achieved by three-layer dressing that consists of Unna's boot, continuous gauze dressing followed by an outer layer of elastic wrap[5]. It should be realized that Unna's boot, being rigid, is uncomfortable to wear and medical professionals are unable to monitor the ulcer after the boot is applied. Three and/or four layer compression bandage regimes are also used in some hospitals in the USA[10,11]. A recent Cochrane review has confirmed that multi-layer bandages are more effective than single layer bandage in healing venous leg ulcers[12]. The review also highlighted that compression increases ulcer healing rates when compared with no compression and high compression is more effective than low compression but there are no clear differences in the effectiveness of different types of high compression bandages.

Pressure mapping of bandages

Table 1 shows the pressure profiling work carried out using Type 2 short stretch and Type 3a, 3b and 3c compression bandages on pressure profile instrument (mannequin leg). Novel padding bandages developed at Bolton institute (NPB5 and NPB8) were used as first layer followed by either Type 2 or Type 3a, 3b and 3c bandages. Figures 2 – 7 show the actual pressure measured at ankle, calf and below knee positions after applying single-layer, two-layer, three layer and four-layer bandages. The interpretation of the results is summarised based on the following two major phenomena.

1. A sustained graduated compression, higher pressure at the ankle which gradually reduces to calf and upper calf according to Laplace's Law[13], aids the treatment of venous leg ulcers[14]. The graduated compression mainly enhances the flow of blood back to the heart, improves the functioning of valves and calf muscle pumps, reduces oedema and prevents the swelling of veins[7].

Table 1. Investigation of Pressure Mapping of Bandages

1. Existing Compression Bandage (Type 2 and Type 3c) Alone (Single layer)

a) Type 2 - Rosidal K and Actiban.
b) Type 3c - Tensopress, Setopress and Surepress.

2. Existing Compression Bandage (Type 2 and Type 3c) Plus Developed Padding Bandage (NPB5 and NPB8)

1. Two layer system:
   100% hollow viscose (NPB5); and
   3c compression bandage
   (Tensopress).
2. Two layer system:
   100% hollow viscose (NPB5); and
   3c compression bandage
   (Setopress).
3. Two layer system:
   100% hollow viscose (NPB5); and
   3c compression bandage
   (Surepress).
4. Two layer system:
   50%/50% P/V (NPB8); and
   3c compression bandage
   (Tensopress).
5. Two layer system:
   50%/50% P/V (NPB8); and
   3c compression bandage
   (Setopress).
6. Two layer system:
   50%/50% P/V (NPB8); and
   3c compression bandage
   (Surepress).
7. Two layer system:
   100% hollow viscose (NPB5); and
   Type 2 short stretch bandage
   (Rosidal K).
8. Two layer system:
   100% hollow viscose (NPB5); and
   Type 2 short stretch bandage
   (Actiban).
9. Two layer system:
   50%/50% P/V (NPB8); and
   Type 2 short stretch bandage
   (Rosidal K).
10. Two layer system:
    50%/50% P/V (NPB8); and
    Type 2 short stretch bandage
    (Actiban).
11. Three layer system:
    100% hollow viscose (NPB5);
    3a compression bandage (Profore #3); and 3b compression bandage (Profore #4).
12. Three layer system:
    50%/50% P/V (NPB8);
    3a compression bandage (Profore #3); and 3b compression bandage (Profore #4).

13. Four layer system:
    100% hollow viscose (NPB5);
    crepe bandage;
    3a compression bandage (Profore #3); and 3b compression bandage (Profore #4).

14. Four layer system:
    50%/50% P/V (NPB8);
    crepe bandage;
    3a compression bandage (Profore #3); and 3b compression bandage (Profore #4).

2. Approximately 30-40 mmHg at the ankle that reduces to 15-20 mmHg (50%) at the calf is generally adequate for healing most types of venous leg ulcers[9]. The ideal pressure just below the knee is around 17 mmHg[15].

It is stretched out that the sub-bandage pressure developed beneath the bandage at ankle, calf and below knee regions could be interpreted with the theoretical pressure calculated from the circumference of the limb and also the radius of curvature of the limb to determine whether the bandage system provides the required graduated compression (higher pressure at the ankle which gradually reduces to calf). Since the leg is not circular, the pressure exerted by the bandage system varies around the circumference at any given point on the leg particularly over bony prominences such as malleolus (ankle bone) and tibial crest (shin). Therefore it is appropriate to compare the sub-bandage pressure with the theoretical pressure calculated from the radius of curvature of the limb. However the realistic observation would be made when the sub-bandage pressure is compared with the theoretical pressure calculated from the circumference of the limb rather than the radius of curvature because:

- one of the main purposes of applying padding layer next to the skin is to make the leg a circular-cross section by protecting bony prominences. Compression layer is applied only after making the leg circular using adequate padding and, therefore, it is more appropriate to compare the pressure developed under the bandage system with the theoretical pressure derived from the circumference of the leg in order to determine graduated compression; and
- the widely accepted Laplace equation that determines the graduated compression takes into account of the circumference of the limb and not the radius of curvature.

Two-Layer Bandages

The sustained graduated pressure distribution of two-layer bandages is superior to single-layer in both Type 2 short stretch (Figures 3 and 4) and Type 3c high compression bandages (Figures 5 and 6).
The contribution of novel padding bandages (NPB5 and NPB8) in distributing sustained graduated compression is substantiated (Figures 3 – 6).
Both NPB5 and NPB8 performed well with Type 2 and Type 3c bandages (Figures 3 – 6).

There is not much difference in pressure distribution characteristics of NPB5 in conjunction with Type 2 and Type 3c bandages (Figures 3 and 5). However NPB 8 performed better with Type 2 than with Type 3c (Figures 4 and 6).
The Type 2 with NPB8 bandage system seems to fulfil the requirements of around 40 mmHg at the ankle, graduating down to about 17 mmHg just below the knee (Figure

4). However the pressure measured by sensor 2 at the ankle is very high (Figure 3). This trend is seen almost in all the bandaging systems (Figures 3 – 6).

The ankle pressure exerted by Type 2 with NPB5 system is high, although the pressure is graduating down to the knee (Figure 3).

The pressure level needs to be reduced considerably at the ankle in Type 3c with NPB5 or NPB8 system (Figures 5 and 6).

Three and Four Layers Bandages

There are conflicting trends in graduated compression profile between two-layer system and three or four-layer system. The pressure registered at ankle, calf and knee is always high in both three-layer and four-layer systems when both NPB5 and NPB8 are involved (Figures 7 and 8).

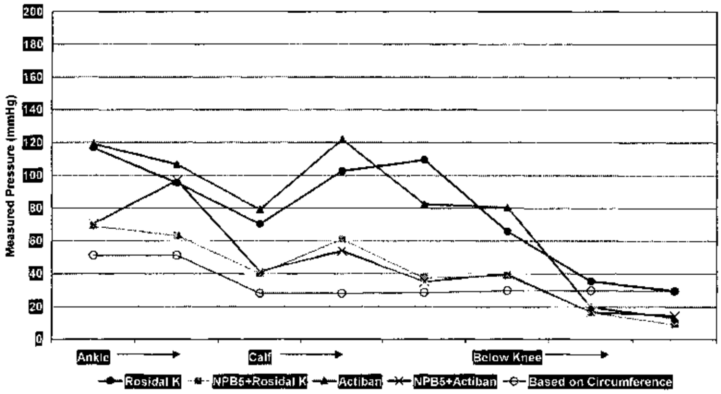

Figure 3. Comparison of Pressure Profile of Single and Two Layers of Type 2 with NPB5

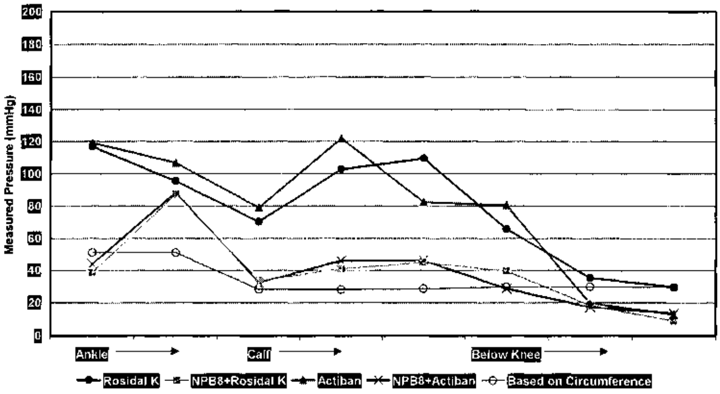

Figure 4. Comparison of Pressure Profile of Single and Two Layers of Type 2 with NPB8

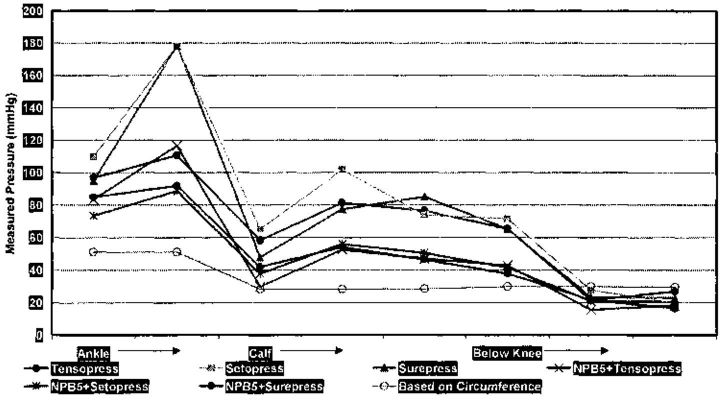

Figure 5. Comparison of Pressure Profile of Single and Two Layers of Type 3c with NPB5

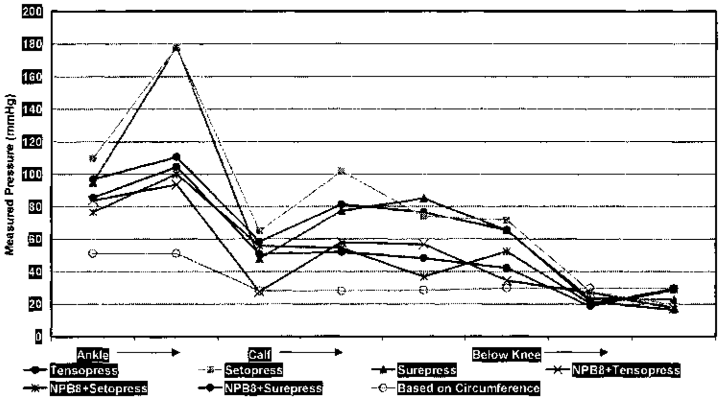

Figure 6. Comparison of Pressure Profile of Single and Two Layers of Type 3c with NPB8

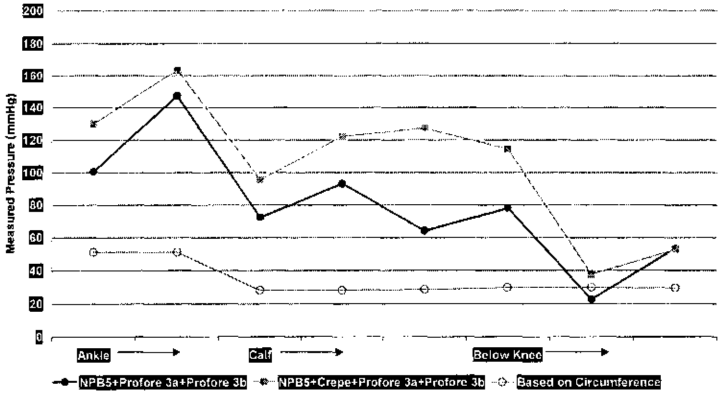

Fig 7. Comparison of Pressure Profile of Three and Four Layers with NPB5

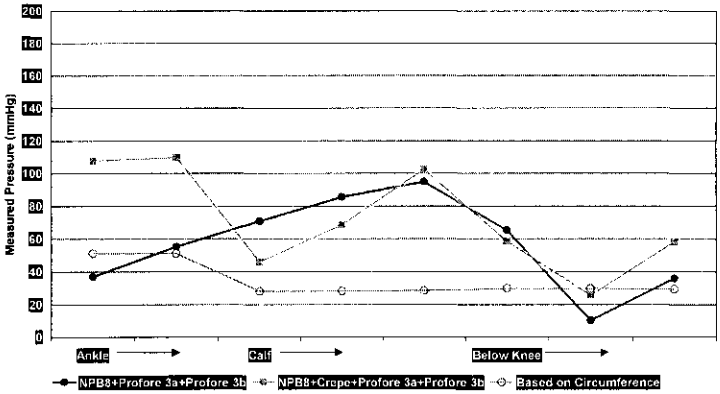

Figure 8. Comparison of Pressure Profile of Three and Four Layers with NPB8

CONCLUSIONS

The pressure mapping of novel padding bandages is analysed by making use of pressure profiling instrument (Mannequin leg). Both short stretch and high compression commercial bandages have been used to check the pressure distribution of novel padding bandages at two, three and four layer bandaging systems. The results showed that the two-layer bandaging system that contains novel padding bandages fulfill the requirements of around 40 mmHg at the ankle, graduating down to about 17 mmHg just below the knee. However, the pressure registered at ankle, calf and below knee positions is always high in both three-layer and four-layer systems. The study paves the way for developing novel compression bandages for two-layer system that could replace the currently used cumbersome four-layer systems.

ACKNOWLEDGEMENTS

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EFFECT OF FIBRE TYPE AND STRUCTURE IN DESIGNING ORTHOPAEDIC WADDING FOR THE TREATMENT OF VENOUS LEG ULCERS

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ABSTRACT

There is an urgent need to focus research and development work towards the treatment of venous leg ulcers because about 1% of the adult population suffers from active ulceration during their lifetime in the UK alone and costs the National Health Service (NHS) £600 million per annum. Similarly, venous ulceration is a common disease affecting around 1% of adult population in Australia. The direct and indirect cost of the treatment for this condition in Germany is more than DM 1 billion. In the US about 2 million working days are lost each year because of leg ulcer problems and the treatment cost is enormous.

The Centre for Materials Research and Innovation (CMRI) at The University of Bolton has recognised the problem and is carrying out research with an ultimate aim of developing superior novel padding and compression bandages as well as bandaging techniques. These not only enhance the healing of venous leg ulcers but also replace the cumbersome and costly conventional four-layer bandage technique by a simple two-layer system.

The paper discusses the development of padding bandages that have excellent performance and properties such as fluid absorption, wicking and uniform pressure distribution around the leg over the conventional commercial bandages. The influence of fibre type and fabric structure in enhancing the absorption, wicking and pressure distribution will also be analysed. The paper also critically appraises the testing and characterisation of existing padding bandages. The morphology of leg ulceration and the current compression therapy treatment are also discussed.

Overall the paper will carry, among others, two important messages to delegates: 1) the lack of desired properties of existing commercial padding bandages; and 2) the superior properties of developed bandages that are necessary for the treatment of venous leg ulcers.

INTRODUCTION

Venous leg ulcers are the most common type of ulcers and their prevalence increases with age. They are chronic and are caused due to poor venous return from the calf to the heart. In the UK alone about 1% of the adult population suffers from active ulceration during their life time. This represents 260,000 patients in the UK of which 55,000 potential or actual ulcer patients are in Scotland alone. The total cost to the National Health Service for venous leg ulcer treatment is about £600 million per annum. Similarly, venous ulceration is a common disease affecting around 1% of adult population in Australia[1]. The direct and indirect cost of the treatment in Germany is more than 1 billion DM[2]. In the US a large number of people suffer from leg ulcers as is evident from the fact that about 2 million working days are lost each year because of leg ulcer problem and the treatment cost is enormous[3].

During the past few years there have been increasing concerns relating to the performance of bandages especially pressure distribution properties for the treatment of venous leg ulcers. This is because the compression therapy is a complex system and requires two or multi-layer bandages, and the performance properties of each layer differ from other layers. The widely accepted sustained graduated compression mainly depends on the uniform pressure distribution of different layers of bandages in which textile fibres and bandage structures play a major role.

In the past, the researchers in the Centre for Materials Research and Innovation (CMRI) at Bolton Institute have successfully designed and developed a number of novel textile structures such as wound dressings for wound management, cast cloths for orthopaedic casting and 3-D spacer materials for knee brace. In one of the current research programmes funded by the Department of Trade and Industry (DTI), Bolton Institute and five major medical textile companies are developing novel structures such as padding bandages and compression bandages that would be superior in performance to the existing commercial bandages and help to replace the currently popular four layer bandaging system used for the treatment of venous leg ulcers. The first stage of the programme has been completed with the development and characterization of superior high performance padding bandages. In this paper the research outcomes involving the development of nonwoven padding bandages for compression therapy are discussed.

THE CAUSE OF VENOUS LEG ULCERS

It is important that the arterial and venous systems should work properly without causing problems to blood circulation around the body. Pure blood flows from the heart to the legs through arteries taking oxygen and food to the muscles, skin and other tissues. Blood then flows back to the heart carrying away waste products through veins. The valves in the veins are unidirectional which means that they allow the venous blood to flow in upward direction only. If the valves do not work properly or there is not enough pressure in the veins to push back the venous blood towards the heart, the pooling of blood in the veins takes place and this leads to higher pressure to the skin. Because of high pressure and lack of availability of oxygen and food, the skin deteriorates and eventually the ulcer occurs.

Major causes of venous leg ulcers

- Inefficient or non-functioning of valves in veins
- Inefficient or non-functioning of calf muscles
- Pooling of venous blood in veins
- Damaged or swollen veins (varicose veins).
- Blood clots in veins (DVT)
- Lack of movement such as prolonged sitting or standing, confinement to bed for long periods etc.

PADDING BANDAGES (WADDING OR ORTHOPAEDIC WOOL)

Padding bandages play a significant role in the successful treatment of venous leg ulcers. A padding of at least 2.5cm thickness is placed between the limb and the compression bandage to distribute the pressure evenly at the ankle as well as the calf region. Wadding helps to protect the vulnerable areas of the leg from the high compression levels required along the rest of the leg[4]. Padding can also be used to reshape legs which are not narrower at the ankle than the calf. It makes the limb more like a cone-shape so that the pressure is distributed over a pressure gradient with more pressure at the foot and less at the leg. Generally the longer a compression bandage system is to remain in place, the greater is the amount of padding needed. An ideal padding bandage should meet the following requirements:

- light weight and easy to handle;
- soft and impart cushioning effect to the limb;
- capable of preventing tissue damage;
- capable of distributing pressure evenly around the leg;
- good absorption and wicking properties;
- comfortable and should not produce irritation or any allergic reaction to the skin on prolonged contact;
- should tear easily by hand; and
- should be cheap.

Padding bandages are applied underneath the compression bandage. A typical four-layer compression bandage system comprises of padding bandage, crepe bandage, high compression bandage and cohesive bandage.

MATERIALS AND METHODS

Commercial and novel padding bandages

Ten most commonly used commercial padding bandages were procured from medical textiles companies for testing and characterization (Table 1). All these bandages are nonwovens. The novel nonwoven padding bandages designed and produced during this research work are given in Table 2. The fibre types and structures of the bandages are also given in Table 1 and Table 2.

Test methods

- Bulk density (calculated from area density and thickness).
- Tear resistance[5].
- Demand absorption and wicking (using an instrument developed at Bolton Institute).
- British Pharmacopoeia absorption method[6].
- Sinking time[7].
- Pressure transference (using an instrument developed at Bolton Institute).

The significance of the tests that determine the performance and properties of padding bandages is given in Table 3.

Demand absorption and wicking apparatus

The computerised two-in one combined absorption and wicking apparatus has been developed at Bolton Institute based on the work of Jackson[8]. The apparatus (Figure 1) consists of a porous plate that is connected to a water reservoir through a flexible rubber tube. The reservoir is placed on an electronic balance and a small weight change due to the absorption of water by fabric is recorded in the computer. The bandage was presented on the porous plate and a mass of 600 g was placed on it. The demand absorption as well as wicking was measured by making use of special software. A detailed procedure is discussed elsewhere[9].

Table 1. Commercial Padding Bandages

Bandage Code	Fibre type	Blend ratio	Structure
PB1	Polyester	100%	Needlepunched (one side)
PB2	Polyester	100%	Needlepunched (one side) & thermal bonded
PB3	Viscose	100%	Needlepunched (one side)
PB4	Polyester/Viscose	40%/60%	Needlepunched (one side)
PB5	Polyester/Polyolefin	85%/15%	Needlepunched (one side) & thermal bonded
PB6	Polyester	100%	Needlepunched (one side) & thermal bonded
PB7	Polyester/Viscose	50%/50%	Needlepunched (one side)
PB8	Polyester	100%	Needlepunched (one side)
PB9	Polyester	100%	Needlepunched (one side)
PB10	Polyester	100%	Needlepunched (one side) & thermal bonded

Table 2. Novel Padding Bandages (developed at Bolton Institute)

Bandage Code	Product	Fibre type	Blend ratio	Structure
NPB1	Single Component	Polyester	100%	Needlepunched (both sides)
NPB2	Single Component	Polyester (bleached)	100%	Needlepunched (both sides)
NPB3	Single Component	Hollow Polyester	100%	Needlepunched (both sides)
NPB4	Single Component	Viscose	100%	Needlepunched (both sides)
NPB5	Single Component	Hollow Viscose	100%	Needlepunched (both sides)
NPB6	Single Component	Lyocell	100%	Needlepunched (both sides)
NPB7	Binary Blend	Polyester/Viscose	75%/25%	Needlepunched (both sides)
NPB8	Binary Blend	Polyester/Viscose	50%/50%	Needlepunched (both sides)
NPB9	Binary Blend	Polyester/Viscose	25%/75%	Needlepunched (both sides)
NPB10	Binary Blend	Polyolefin/Viscose	20%/80%	Needlepunched (both sides) and thermal bonded
NPB11	Tertiary Blend	Polyester/Viscose/ Cotton (bleached)	33%/33%/ 33%	Needlepunched (both sides)
NPB12	Tertiary Blend	Polyester/Viscose/ Polyolefin	60%/25%/ 15%	Needlepunched (both sides) and thermal bonded

Table 3. Significance of the Tests with Respect to Padding Bandage

Test	Property	Desirable
Bulk density (area density/thickness)	Determines the bulkiness of bandage	An appropriate bulkiness, say $0.05 gcm^{-3}$ which facilitates easy handling, comfort (cushioning) and protects bony prominences
Tear strength	Determines the behaviour of bandage from being torn	Must be easy to tear by hand.
Absorption and wicking	Determines the absorption (saturation capacity) and wicking of bandage. The test also gives some information about the comfort of bandage	Must possess good absorption and wicking properties
Pressure transference	Determines the pressure distribution capability of bandage	Capable of absorbing high pressure exerted by elastic compression bandage and distribute the pressure uniformly around the leg

Pressure transference apparatus

The electronic apparatus (Figure 2a and Figure 2b) has also been developed at Bolton Institute. The apparatus consists of a wooden platform for presentation of specimen, a strain gauge device and an electronic circuit board. A pressure pin (9mm diameter) is attached on to the load beam of the strain gauge and a corresponding hole drilled through the wooden platform. The height of the pressure pin is adjusted so that it protrudes through the hole of the platform by 1mm.

The padding bandage is placed onto the wooden platform over the pressure pin and a series of known metal block weights ranging from 200g (3mmHg) to 4100g (60mmHg) of 200g are placed onto its surface. The strain gauge device detects the pressure transmitted through the bandages at each known pressure in increments created by the metal blocks. The amount of pressure absorbed and dissipated within the bandage structure and the actual pressure felt immediately below the bandage ie the patient's leg is determined. The transmitted pressure through the thickness of the bandage is the absolute pressure exerted on the patient's leg.

RESULTS AND DISCUSSION

Commercial padding bandages

Effect of bulk density

The bulk density determines the bulkiness of bandages. It is important to mention that an appropriate bulkiness, say 0.05 gcm^{-3} would be required to protect the bony prominences in the leg. Since padding bandage is applied next to the skin around the leg, it must be capable of imparting comfort and cushioning effect to the patient. It will be observed from Table 4 that the bulk density of all the commercial padding bandages are within the acceptable limit and PB1, PB3, PB4, PB7 and PB 9 registered higher bulk densities.

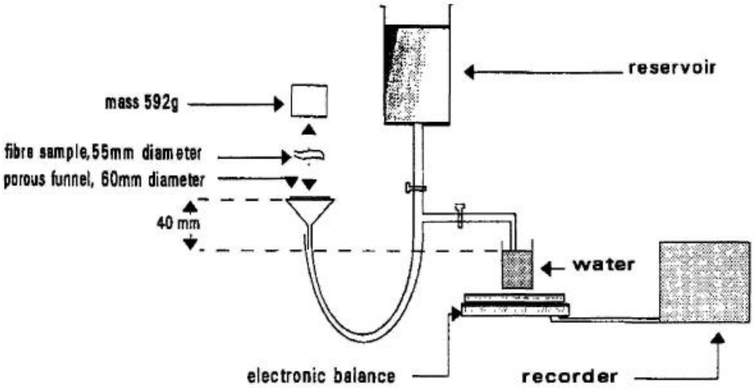

Figure 1. Combined Demand Absorption and Wicking Apparatus

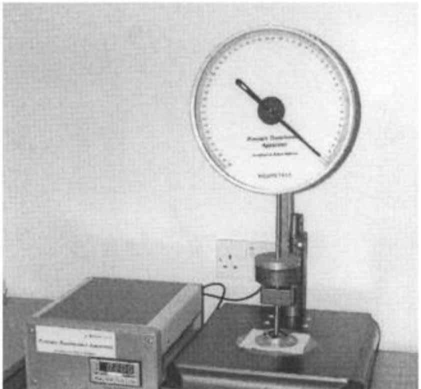

Figure 2a. Pressure Transference Apparatus

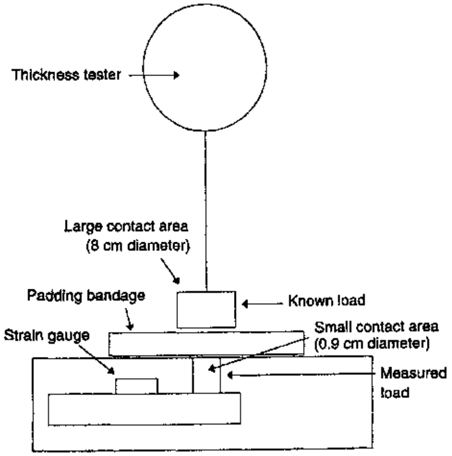

Figure 2b. Schematic Diagram of Pressure Transference Apparatus

Influence of tear strength

The tear strength has a significant influence as far as the wrapping of padding is concerned. An ideal bandage is generally torn by hand after wrapping around the leg and this gives more flexibility to nurses without looking for scissors. The results reveal (Table 4) that bandage PB5 has the lowest tear strength followed by PB1. It will be observed that there is no published benchmark or standard for tear strength that an ideal padding bandage should meet. Experience has shown that the bandage which possesses a tear strength of 5000mN or less, tested by using Elmendorf tear instrument, can be torn easily by hand.

Relationship between demand absorption and wicking

Table 4. Properties of Commercial Padding Bandages

Bandage code	Bulk density ($g.cm^{-3}$)	Impact tear strength (mN)
PB1	0.06	2560
PB2	0.04	4480
PB3	0.06	3600
PB4	0.07	3280
PB5	0.04	1440
PB6	0.05	3760
PB7	0.06	3840
PB8	0.04	4880
PB9	0.06	4560
PB10	0.05	4240

It is a common practice in hospitals that venous leg ulcers are treated by a combination of wound dressing, undercast padding and compression bandage which are either two-layer or multi-layer system depending on the severity of ulcers. The high absorbent wound dressing should be used to absorb exudate and other body fluids from the ulcer. The padding bandage that is wrapped on the wound dressing should also to be highly absorbent to accommodate leakage of exudate from the wound.

The demand absorption and wicking properties of commercial padding bandages are presented in Figure 3. The word 'demand absorption' is mentioned because in this particular test the liquid is available for absorption by the sample at the surface of the porous plate of the demand absorption apparatus only on demand. It can be observed from Figure 3 that the absorptions of PB1, PB2, PB5, PB6, PB8 and PB10 are high and almost similar. On the other hand, PB3, PB5 and PB7 wicked high amounts of fluid. Similarly the rate of absorption (Figure 4) of all the bandages is satisfactory except PB3, PB6, PB8 and PB10. The bandages PB4, PB7 and PB9 possessed higher rates of wicking.

Pressure distribution of commercial bandages

Padding bandage is applied beneath the compression bandage. The degree of pressure that is induced into the leg by the compression bandage is of major importance. It has been demonstrated that too high a pressure on the leg not only leads to further complications of venous system but also promotes arterial disease. In contrast, inadequate pressure cannot help to heal the venous ulcers. Even if the compression bandage is applied at the correct tension it is probable that excessive pressure will be generated over the bony prominences of the leg. Therefore there is a need to distribute the pressure equally and uniformly at all points of the lower limb and this can be achieved by applying an effective padding layer around the leg below the compression bandage.

The pressure distribution characteristics of commercial bandages are shown in Figure 5. Obviously, none of the bandages provides uniform pressure distribution up to 60mmHg. However PB5, PB6 and PB8 did distribute the applied pressure evenly only upto around 7mmHg and the efficacy of the even pressure distribution degrades

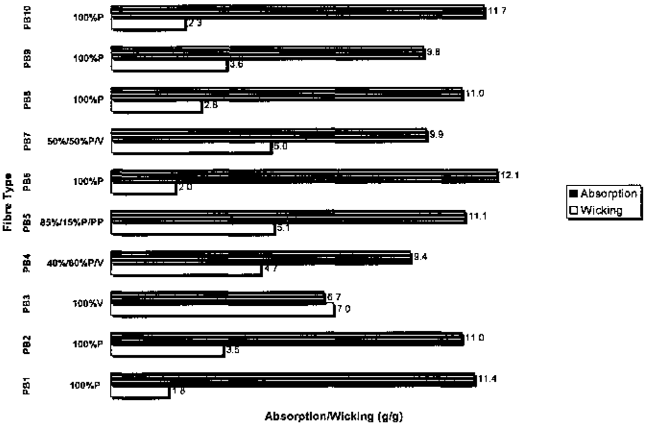

Figure 3. Demand Absorption and Wicking of Commercial Padding Bandages

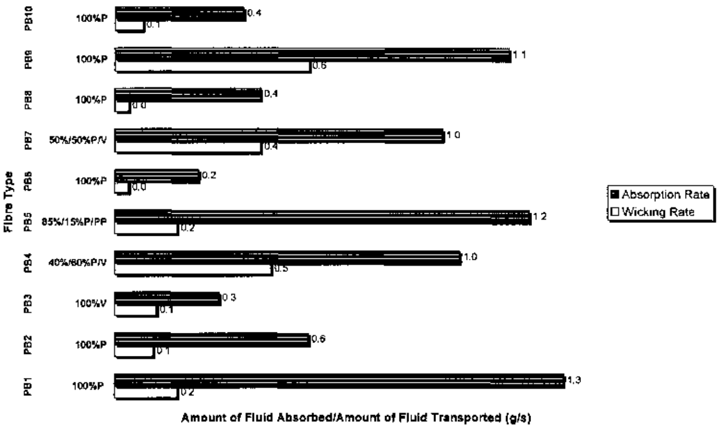

Figure 4. Rate of Absorption and Rate of Wicking of Commercial Padding Bandages

thereafter. It is vital that an ideal padding bandage should dissipate the pressure between 30 and 40mmHg, exerted by high compression bandage (Type 3c), uniformly around the limb.

Novel padding bandages

Physical properties

It is apparent from Table 5 that all the developed padding bandages possess suitable bulkiness. It is also observed from Table 5 that the tear resistance of bandages, except 100% hollow viscose (NPB5) is high and this means that the bandage cannot be easily torn by hand after wrapping around the leg. However this problem could be rectified by making perforations across the bandage at regular intervals.

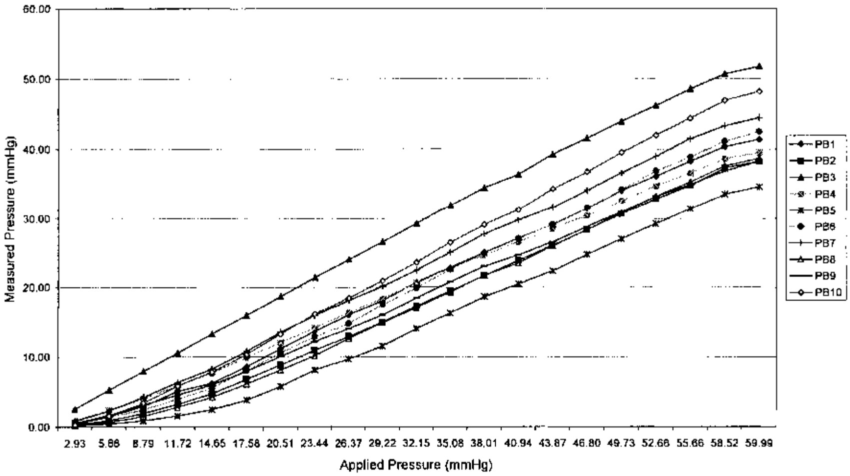

Figure 5. Pressure Distribution of Commercial Padding Bandages

Table 5. Properties of Novel Padding Bandages

Bandage code	Bulk density ($g.cm^{-3}$)	Impact tear strength (mN)
NPB1	0.05	19360
NPB2	0.04	8320
NPB3	0.04	16720
NPB4	0.06	7360
NPB5	0.04	4320
NPB6	0.06	16520
NPB7	0.05	15040
NPB8	0.08	11920
NPB9	0.05	10000
NPB10	0.07	7440
NPB11	0.04	5200
NPB12	0.06	22880

Effect of fibre type and demand absorption

Figures 6 and 7 revealed that fibre type has an influence on absorption and wicking and also on the rate of absorption and wicking. Good absorption was obtained in 100% hollow viscose (NPB5), 50%/50% polyester/viscose binary blend (NPB8) and 33%/33%/33% polyester/viscose/cotton tertiary blend (NPB11). Interestingly, the rate of absorption of these bandages is also high (Figure 7). A closer examination of Figures 6 and 7 indicated that there is no direct correlation between fibre type and

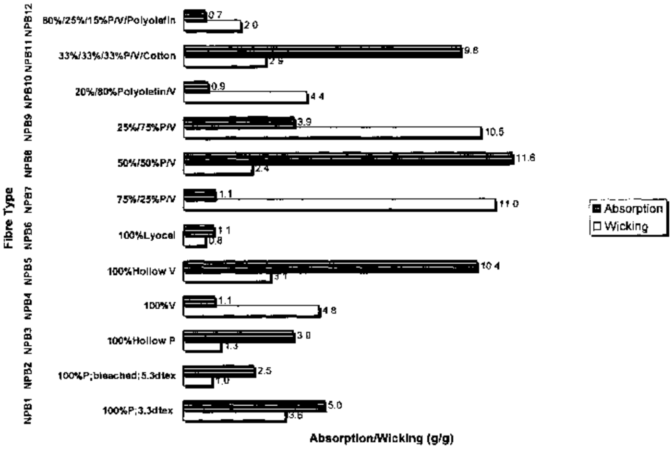

Figure 6. Demand Absorption and Wicking of Novel Padding Bandages

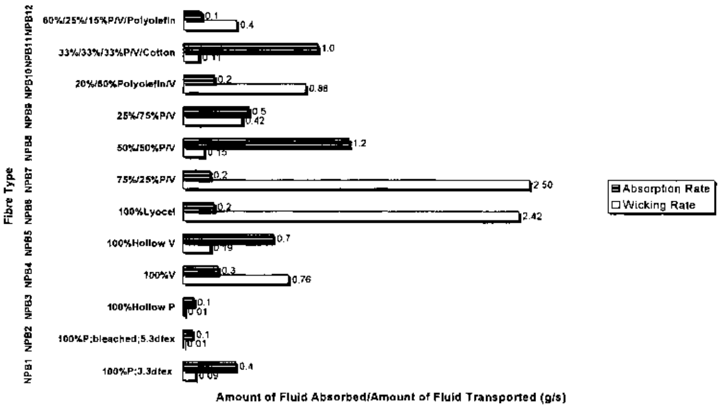

Figure 7. Rate of Absorption and Rate of Wicking of Novel Padding Bandages

absorption as well as wicking. It is normally expected that natural and regenerated fibres such as cotton and viscose absorb more fluid than synthetic fibres and the synthetics wick fluid faster than natural fibres. However, the absorption and wicking not only depend on fibre types but also various processing parameters such as machine specification and fabric structure.

Absorption of solution containing Na^+ and Ca^{++} Ions

British Pharmacopoeia method is also used to test the absorbency of dressings because it uses sodium and calcium ions, which resembles artificial blood, at body temperature. The method provides performance indicators that are useful to compare the absorbency of dressings. Dressings that absorb less than 12g of liquid per 100cm^2 are classified as low absorbency and dressings that absorb 12g per 100cm^2 of liquid or more are classified as high absorbency[6]. Figure 8 shows the absorbency of developed padding bandages tested by BP method and the rate of absorption tested by Sinking Time method. The absorbency as well as the rate of absorption of commercial bandages is given in Figure 9 for comparison.

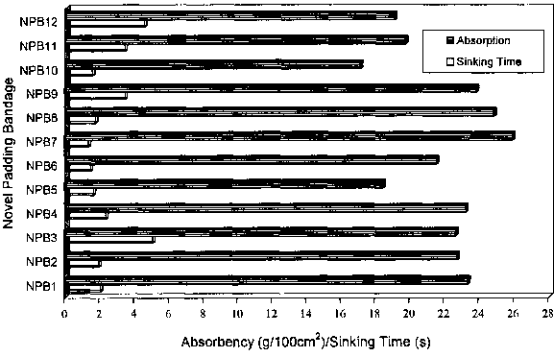

Figure 8. Absorption and Sinking Time of Novel Padding Bandages

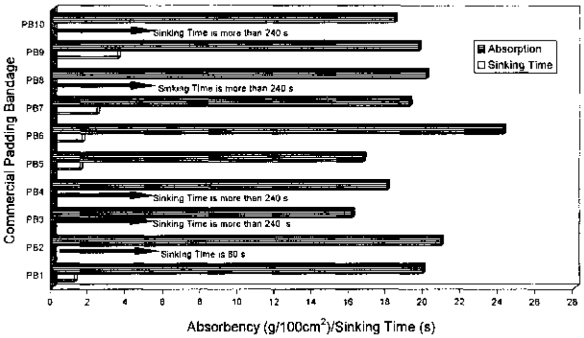

Figure 9. Absorption and Sinking Time of Commercial Padding Bandages

It is interesting to note that the absorption of developed bandages is significantly higher than that of commercial bandages, irrespective of fibre types and structures. Most of the commercial bandages required higher time to sink into the solution and this means that the rate of absorption is very low. Whereas, the rate of absorption of all the developed bandages is very high.

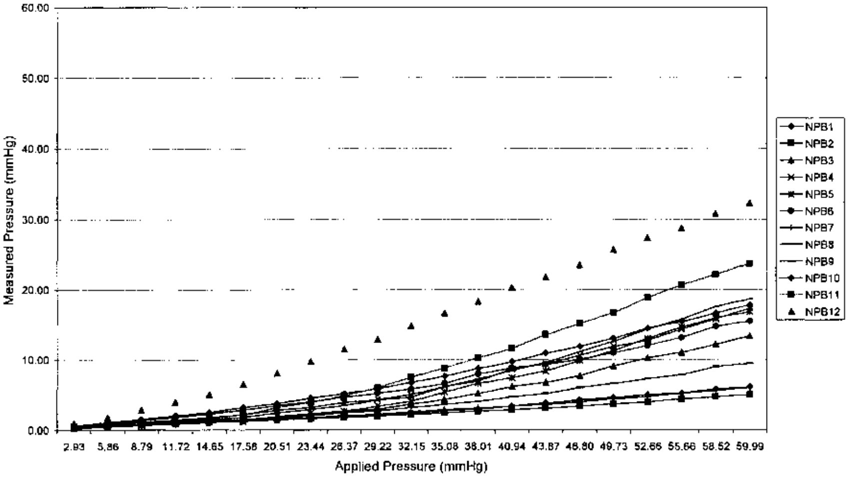

Figure 10. Pressure Distribution of Novel Padding Bandages

Pressure distribution of developed bandages

A significant improvement in distributing the applied pressure of the developed bandages, in contrast to the commercial bandages (Figure 5) can be observed in Figure 10. The bandages NPB1, NPB2, NPB3, NPB4, NPB5, NPB7, NPB8 and NPB9 imparted almost uniform pressure distribution up to the required 30 - 40 mmHg. It is obvious that even after 40 mmHg the pressure distribution of the entire novel padding bandages, except NPB11 and NPB12, does not degrade significantly up to 60 mmHg.

CONCLUSIONS

The paper has presented a brief overview of the venous leg ulcers and the significant contribution of padding as well as compression bandages in healing them. The study has clearly demonstrated that the performance and properties of the existing commercial padding bandages varied and none of the bandages investigated satisfied the requirements of an ideal padding bandage. The novel padding bandages developed during this research by making use of suitable fibre types demonstrated that the performance characteristics are superior to the existing commercial bandages. The research and development work revealed that the developed bandages have high absorption and uniform pressure distribution properties. The novel bandages are soft and provide cushioning effect to the leg. A completely new technique has been adopted for the manufacture of these bandages.

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ASSESSMENT OF FABRICS WORN ON THE UPPER LIMBS

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ABSTRACT

The EU Framework 5 funded DRIFTS project aims to improve the quality of life of tremor sufferers by producing a prototyping platform for a Dynamically Responsive Intervention for Tremor Suppression. The most debilitating tremor is in the upper limbs, preventing patients from writing, holding a glass without spilling the contents etc. Common treatments involve surgery, electrical stimulation to the brain and drug therapy but these may not be applicable to some groups of patient. The proposed solution is a wearable orthosis which must be comfortable to wear for long periods in terms of pressure exerted, moisture management (wicking and breathability) and neutral skin sensations. Additionally they must be aesthetically pleasing and be able to support or contain any devices for tremor suppression. Some of these parameters will of course alter with the age of the patient as skin thins and tactile sensations change.

There are a number of devices on the market for measuring interface pressure between a garment and the lower limb as well as graduated bandages relying on marked squares to set the required pressure for leg ulcers. There is also much interest in deep vein thrombosis attributed to long haul flights resulting in 'flight socks'.

The work reported here compares measurements of pressure determined on the HATRA leg with those from a commercial device. The work then explores whether this approach is suitable for measurements on the upper limbs and attempts to identify fabric types which would be suitable for prolonged wear.

INTRODUCTION

The EU funded project entitled 'Dynamically Responsive Intervention for Tremor Suppression (DRIFTS)' aims to improve the quality of life for tremor suffers by creating proof-of-concept prototypes of wearable active orthoses for the suppression of upper limb tremor while preserving natural movement. The development of a prototyping and evaluation platform will allow for the future elaboration of wearable ambulatory tremor suppression devices.

Tremor is characterised by involuntary oscillations of a part of the body. It is the most common movement disorder. The most accepted definition is: "an involuntary, approximately rhythmic, and roughly sinusoidal movement"[1].

Neurological tremor is the most common movement disorder encountered in daily clinical practice. The main central nervous system disorders associated with upper-limb tremor are Parkinson's disease, essential tremor, multiple sclerosis, cerebellar disorders, and brain trauma. Clinically, the tremor can be present as a rest (R), postural (P), and/or a kinetic (K) oscillatory movement. Rest tremor is typically associated with Parkinson's disease, the postural form is mainly observed in essential tremor and kinetic tremor is highly suggestive of a cerebellar disorder.

Frequencies of the different types of tremor

- Physiological tremor (P) (0-16 Hz)
- Essential tremor (P, K) (4-8 Hz)

- Cerebellar tremor (R, P, K) (2-5 Hz)
- Parkinson (R, P) (3-6 Hz)

Despite recent advances in the pharmacological treatment and the surgical management of movement disorders about 40% of the patients remain disabled by upper limb tremor. There are devices currently available to suppress tremor, however, they are neither aesthetically pleasing nor discrete. Two examples of commercially available devices designed specifically for tremor sufferers are the Comfy Feeder and the Neater Eater. These devices are clamped to the table. Through a counter balance spring a spoon is lifted from the plate and moved forward enabling the user to eat. This device is a 2-DoF dampage linkage.

Kotovsky and Rosen developed several prototypes of the Viscous Beam, as seen in Figure 1, based on the results achieved by the MIT Damped Joystick. With plates of Teflon filled with demithyl silicone fluid and covered with preformed surgical tubing, the principle behind is that the viscous fluid would act by dampening the tremor through bending stiffness. Unfortunately the results were not as good as expected[2].

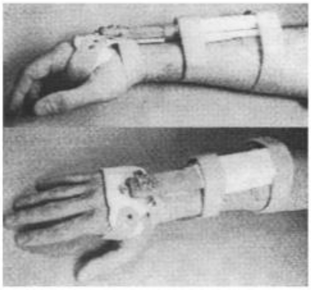

Figure 1. A viscous beam prototype[2]

Figures 2, 3 and 4 show other forms of wearable orthoses which are currently available. The devices are noticeably bulky and restrictive. These devices are for restricting movement of the limb or for limb support and are not for tremor suppression. Only the Viscous beam prototype is currently available for suppressing tremor. The DRIFTS project aims to create an orthoses which is aesthetically pleasing and comfortable.

Figure 2. Bledsoe arm brace[3]

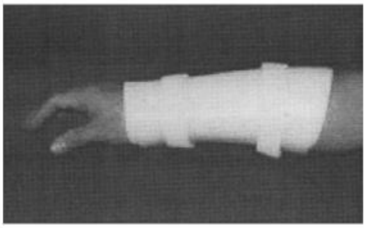

Figure 3. Ulnar gutter splint[3]

Figure 4. Multifit lined exeter wrist support[4]

COMFORT OF THE TEXTILE SUBSTRATE

The proposed solution for assisting tremor suffers is a wearable orthosis which must be comfortable to be worn on the body for long periods of time (8-16 hrs per day). The comfort of the orthosis can be determined by the pressure exerted onto the limb, good moisture management (the garments ability to wick liquid moisture away from the skin and moisture vapour transmission) and neutral skin sensations. The orthosis, in addition, must be aesthetically pleasing to the patient and be discretely worn under ordinary clothing. It must be easy to put on, operate and remove by the user and easily maintainable in terms of launderability. The wearable orthosis must be durable and able to support or incorporate any devices needed for tremor suppression such as actuators, sensors, batteries and wiring.

The orthosis must not give rise to friction, pressure or shear force to the underlying skin tissue as this will cause problems for prolonged users for example pressure sores and skin irritation. A suitable textile substrate having properties that would allow minimal resistance to the skins natural function within the comfort zone, have minimal influence on the microclimate conditions and will not provoke skin irritations and or activate sensory nocireceptors or mechanoreceptors.

Clothing worn next to the skin influences our state of comfort. Clothing can evoke tactile sensations that may alter our state of comfort. These sensations arise through the triggering of sensory receptors in or near the skin, when skin becomes in contact with fabric surface. The nature of the fabric surface will therefore have an effect on the sensations perceived. The touch group, the thermal group and the pain group are the three basic categories of skin-sensory receptors. Tactile sensations associated with comfort such as softness, stiffness, and clinginess are sensations conveyed by touch receptors. The sensation of prickle sometimes generated by clothing is described as a sensation having pricking-itch-like qualities sometimes causing skin inflammation[5]. Tests carried out by CSIRO[5] confirm the common observation that fabric-evoked prickle is enhanced as skin temperature increases and onset of sweating occurs.

The fabric and fibre choice are important when identifying an appropriate fabric to use for the orthosis. The comfort of the fabric will depend on many factors including fibre length which influences fabric prickle, fabric wickability, fabric shear, moisture vapour transmission and thermal insulation. Fabric breathability and thermal insulation are important as the fabric must not cause excessive perspiration which could be trapped against the skin, both for comfort and degradation to the sensors and actuators. This is achieved by the fabrics ability to wick moisture away from the skin by means of a capillary action, moving moisture along the outside of the fibre or through the fabric, transporting it away from the perspiring body. Shear is a vital property needed for the substrate. If the fabric shears it is liable to cause movement of an active device which needs to stay static on the limb during wear else the orthosis will fail to control tremor efficiently.

DESIGN

When designing the substrate, pressure needs to be considered along with the level of stretch and recovery required and seam types to be used. The fit of a garment is a very important factor in the overall comfort. The orthoses must give optimal fit and minimum pressure but keep applied devices as close to the skin as possible for sensing tremor and applying a load to counteract the tremor. The design of the substrate needs to incorporate suitable seam types which do not cause skin sensations or look unsightly. The seams need to be minimal and lie flat, possibly on the outside of the substrate to eliminate any skin irritation they might cause.

Good stretch and recovery is needed for a good fit for the orthosis. A small degree of stretch is needed on parts of the orthosis such as at the bend of the elbow to allow ease of arm movement and comfort for the patient.

Fabrics which are good to be worn next to the skin must be comfortable and dry. Cotton is comfortable, however when it is worn for long periods of time next to the skin perspiration is absorbed by the fabric and it may feel moist and uncomfortable next to the skin. Cotton is one of the preferred fabrics worn next to the skin but when worn tight fitting gives problems due to its high moisture retention, which can lead to a wet sensation. If sweat is trapped against the skin, irritation and skin swelling and softening can occur along with malodour. Some of the newer fabrics that afford good moisture management include Coolmax, Aquaduct, X-Static etc. Many also contain antibacterial materials to help prevent odour.

Different structures and compositions of fabrics were studied and compared for wear next to the skin. Among the fabrics considered include silver fabrics, antibacterial fabrics, auxetic fabrics and three dimensional warp knit spacer fabrics. Silver is widely recognised as a safe and effective broad spectrum antimicrobial agent for infection control. Antibacterial fabrics such as Amicor by Acordis and other fabrics like SeaCell Active by Zimmer AG are proving to be very interesting for incorporation into the DRIFTS project. The antimicrobial properties of these fabrics prevent odour and help ensure comfort and fabric freshness. Auxetic materials are materials with a negative Poisson's Ratio, meaning that they become fatter when stretched and thinner when squashed. Three dimensional warp knit spacer fabrics consist of two surface fabrics which are connected by pile yarns used as spacers. This design creates a ventilated layer of air, allowing heat and moisture to escape. Spacers come in a range of thicknesses depending on the end use and conform well to body shape. A range of fibre types are used such as polyester, nylon, cotton mix and blends with elastane. Spacer fabrics have been identified for further investigation as they offer good moisture management properties and low shear.

Pressure therapy is commonly applied to the leg. Pressure is applied for elimination of blood clots by pumping the blood back into the body and not allowing to build up in one area. Flight socks have recently been introduced to reduce the risk of having Deep Vein Thrombosis on long haul flights. A number of devices are available to assess pressure on the leg. These include the Salzmann pressure monitor, HATRA leg, Oxford Pressure monitor (Talley) and the Diastron bandage pressure monitor (PM510). Some of these devices could be used for the assessment of pressure on the upper limb.

Excessive pressure is one of the main concerns related to the application of loads to the body. There are several factors in relation with pressure which have to be taken into account, and these being safety, pain and comfort. The limits for comfort are usually lower than the thresholds to cause pain or any other safety hazard. Strategies to avoid safety problems and pain always try to distribute the load over a wide area in order to minimise the maximum pressure. Different skin receptors are involved in pressure and touch sensitivity. Some of them are specialised in touch, some other in pressure and finally, there are specific receptors specialised in vibrations (Pacini's corpuscles).

Pressure discomfort threshold has been studied[6] in nine subjects, all of them affected by tremor at the upper limb. Measurement points have been located taking into account the common placement of load transmission elements of the upper-limb orthoses. These points were dorsal and palmar side, over muscles and over bony areas in order to have a good representation of the different areas of the forearm. Recording equipment was a dynamometer. The indentor was an aluminium cylindrical cap with a contact flat surface of 1.3 cm^2 adapted to the dynamometer. The dynamometer was connected to a computer by means of a data acquisition card. Pressure was applied five times on each point. The sequence of the pressure application was randomised previously, to avoid the learning effect of the patient in each point. The study with patients revealed no significant differences in pressure sensitivity at different locations over the forearm. Differences between subjects have been identified. Many factors affect the perceived sensation when load is applied to the skin including contact area, pressure, amount of load, and duration of application.

METHODS

Next to the skin garments can be evaluated in a number of ways from measuring properties such as tog ratings and moisture vapour transmission to wearer trials. The DRIFTS project is still in the early stages, therefore, at this point only simple laboratory evaluation has been undertaken.

Tests carried out to measure fabric properties include the HATRA leg, Salzmann pressure monitor according to British Standards[7]. Thermal resistance was measured using the Shirley Tog Meter in accordance to British Standards[8]. Water vapour permeability was carried out in accordance to Control Dish Method[9]. Shear was assessed using the VITNO fabric shear angle tester[10], and wicking was carried out using the longitudinal wicking method. All testing was carried out under controlled conditions of temperature 20°C and 65% relative humidity.

The level of pressure which is supplied by the orthosis is crucial to ensure that the support functions correctly and does not cause added damage regardless of the build of the patient. Garments are often made to measure with a known reduction in size to give an applied pressure. Other methods use a printed pattern on the fabric which gives the correct pressure when pulled to give a square. For compression garments used on scars[11] the circumference of the body at the area of a scar, for example, is measured and a reduction of 20% is used to produce the garment, which is believed to produce the required pressure. The remaining areas of the garment are reduced by only 5% to ensure a comfortable fit and the location of joints are marked to ensure correct positioning of the garment. The HATRA pressure tester is designed to measure the compression exerted by hosiery or bandaging on the leg. The garment to be measured is mounted onto a steel leg form and the head is used to measure the fabric tension around the leg at any point along its length. The compression of the garment at any point is proportional to the fabric tension divided by the girth at that point. The device is usually used on the leg, however if readings need to be taken on the arm the girth needs to be at the smallest in order to accommodate the size of an arm. The equation used for determining pressure on the Hatra leg is:

$$\text{Pressure (mmHg)} = \frac{4 \times \text{Tension Reading}}{\text{Radius of curvature of former (cm)}^{12}}$$

The Hatra device measures the limb in a circular way, using a steal limb; however the shape of the leg with the bony shin and the muscles varying pressure is given around the circumference. Anand[13] has looked at ways to spread applied pressure for oedema.

This work has attempted to measure pressure on the forearm using the Salzmann monitor and compared values to that from the Hatra leg taking into consideration the difficulty of measuring pressure around the circumference of the limb on the Hatra leg. The Salzmann pressure monitor is a way of measuring pressure as the device is used on a human being and is able to measure any areas to see how much pressure is needed on different areas such as bony parts and fleshy areas. The Salzmann device[14] consists of a thin plastic sleeve with four paired electrical contact probes which are laid on a limb surface either a leg or an arm and covered with a bandage, a sock or other item such as the prototype orthosis. The sleeve is inflated with air until the contacts are broken when the pressure exerted by the air is greater than the pressure exerted by the outer compression layer. The transducer then gives a digital display of the pressure readings which can be printed out if need be. Readings can be taken with the limb in different positions and in different states such as relaxed and tense.

RESULTS AND DISCUSSION

A range of spacer fabrics and standard polyester and cotton were tested to compare benefits of spacer fabrics over traditional standard materials. The tests carried out include thermal insulation, wicking, water vapour permeability and fabric shear which are the most important when considering a fabric which does not allow excessive perspiration build up. Initial results suggest that the spacer fabrics tested all have similar properties (Table 1 and 2). When compared with standard fabrics results showed that all tested materials were breathable and had similar levels of thermal resistance dependant on fabric thickness, however spacer fabrics show less shear than other fabrics.

Table 1. Water vapour permeability and thermal insulation testing

Fabric	Thickness (mm)	Av.Derived WVP (g/m^2/day)	Av.Equiv thick'(mm)	Thermal (togs)	Warmth (togs/cm)	Thermal conductivity (m^{2}K W^{-1})
Stomatex	4.4	150.7	91.4	1.14	2.64	3.79E-02
Warp knit	0.7	15230	0.89	0.19	2.92	3.6E-02
Woven calico	0.5	13421	0.95	0.08	2.38	4.2E-02
cotton knit	0.6	15510.8	0.9	0.15	2.88	3.5E-02
Polyester woven	0.2	16730.1	1.02	0.11	5.97	1.7E-02
Spacer	1.4	6452.7	2.1	0.38	2.69	3.7E-02
Spacer	1.5	4211.8	3.6	0.26	1.70	5.9E-02
Spacer+lycra	2.1	4221.5	3.2	0.44	2.10	4.8E-02
Spacer	2.7	4179.9	3.3	0.58	2.15	4.6E-02
Spacer	3.7	3379.2	4.2	0.73	1.96	5.1E-02
Spacer	4	4559.7	3.1	0.84	2.10	4.8E-02

Table 2. Wicking and shear testing

Fabric	Thickness (mm)	Wicking After 10 mins (cm) Warp	Wicking After 10 mins (cm) Weft	Shear Warp ^{0}	Shear Weft ^{0}
Stomatex	4.4	2.3	2.2	21	21
Warp knit	0.7	7.3	6.7	31	39
calico	0.5	7.8	6.1	24	24
cotton knit	0.6	6.9	7.2	31.5	52
Polyester woven	0.2	5.6	4.9	23	25
Spacer	1.4	4.5	4.4	15	18
Spacer	1.5	9	10	18.5	19
Spacer+lycra	2.1	4.5	4.4	18	19.5
Spacer	2.7	4.9	4.8	16	17.5
Spacer	3.7	10	10	16	17
Spacer	4	10	10	17.5	18

Spacer fabrics are identified as offering good comfort properties and as having low shear. A range of spacer fabrics have been produced into the first prototype supports and tested on volunteers. Each spacer fabric was produced into a simple orthoses and worn by two volunteers for a day during waking hours under ordinary clothing. The volunteers were asked a range of questions about the fabric in terms of thickness, stiffness, irritation, warmth, perspiration and general comfort. The design was also considered and suggestions noted. Generally most of the spacer fabrics were accepted and some would be appropriate to use for the orthoses with a small degree of modification.

Testing was carried out initially on a prototype compression sock in order to determine how the results differ when tested on the two pieces of apparatus, the HATRA leg and the Salzmann pressure monitor. The pressure was measured at four identical points of the lower leg, at the ankle, 20cm from the heel, at the calf and 40cm from the heel using both sets of equipment on the Hatra leg form 3. The Salzmann was then used to measure the pressure of the sock on the leg of a human the same size as the Hatra Leg form 3 to compare the mock leg with a real leg. Results (Table 3) show that the Hatra and Salzmann give similar results when tested on the Hatra leg and when tested on a human.

Table 3. Pressure measured on the leg using Hatra and Salzmann testing devices

Apparatus	Ankle (mmHg)	20cm from heel (mmHg)	Calf (mmHg)	40cm from heel (mmHg)
Hatra leg	21	17	16	15
Salzmann on Hatra leg	11	9	9	10
Salzmann on human	16	13	13	12

In further investigative work, the Hatra leg and the Salzmann testing devices are to be used to measure pressure on the arm. The Hatra leg can be made to simulate an arm by removing the simulation calf and thigh areas of the Hatra leg. The circumference of the Hatra leg has been measured at different points and compared with measurements of the largest and smallest British men and women's upper limb circumferences[15] in order to determine if the Hatra leg could be adjusted and modified to simulate an arm. Preliminary studies suggest that the Hatra leg would be suitable for testing pressure of the upper limb.

CONCLUSIONS

Tremor is the most common movement disorder and despite recent advances in treatment about 40% of patients remain disabled by upper limb tremor. The wearable devices currently available are unsatisfactory. The proposed orthosis must have good moisture management however must not give rise to friction, pressure and shear forces to the skin. Numerous spacer fabrics have been evaluated against standard fabrics and can be seen to offer the required properties of good moisture management and low shear.

Pressure applied to the limb is important and the orthosis must give optimum fit and minimum pressure. The Salzmann pressure monitor and the Hatra leg have been used to measure and compare pressure applied to the leg. The use of the Hatra leg is seen as appropriate for assessing pressure on the upper limb.

The project is now entering year two of a three-year programme and as such results on design concepts and integration will be published at a later date.

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BANDAGING TECHNIQUES USING SHORT-STRETCH COMPRESSION BANDAGES

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ABSTRACT

This research work discusses the use of short-stretch compression bandages in the treatment of venous leg ulceration. It also presents two illustrations in the application of this type of bandage and sets out the basic difference between short and long stretch bandages. However, the bandaging techniques and hints are not necessarily exclusive for bandaging in the treatment of venous leg ulceration.

INTRODUCTION

Compression bandages have been used since the time of the ancient Egyptians, who used simple woven fabrics often coated with adhesives, resins and other medicaments as dressing to aid wound healing. Hippocrates is the first known medical source who described the relationship between venous disorders and leg ulcers[1].

Cooper in 1824[2] believed that compression bandaging allowed the venous valves to recover their lost action (if they are not permanently damaged). This lost action recovery was confirmed by Partsch[3] and Ruckley[4].

A comprehensive medical history and an accurate wound assessment, including Doppler ultra sound is essential to determine the aetiology of a presenting leg ulcer. Compression bandaging is not recommended for the treatment of arterial leg ulcers.

Graduated compression from the ankle to the calf is the principle treatment for venous leg ulceration[5]. This is achieved based upon Laplace's Law, which states that the pressure under the bandage is inversely proportional to the circumference of the leg[6]. As the circumference increases (from the ankle to the calf) the pressure will become less when applied tension is constant.

TYPES OF BANDAGES

There are several types of compression bandages used for the treatment of venous leg ulceration, i.e. short-stretch, long-stretch, multi-layer, cohesive, etc. The characteristics of the short-stretch bandage when properly applied provide adequate and sustained compression to aid in the reversal of venous hypertension, i.e. increase deep venous return and promotes wound repair[7].

The short-stretch bandage is to be applied at full stretch or just before it 'locks out' i.e. it is unable to be stretched any further. The bandage thus provides a 'resting' pressure, i.e. pressure from the bandage to the leg when the calf muscle is not active. When the calf muscle is active a 'working' pressure is produced from the muscle to the bandage.

The short-stretch bandage does not give way during the 'working' phase of the calf muscle because it is applied at full stretch. This means the pressure developed during the working phase is directed back into the leg using the full advantage of the calf muscle pump action to promote wound healing. It is like a ball hitting a brick wall that is bounced or reflected back.

In the case where a long-stretch or other type of extendable bandage is applied, the bandage will give way or extend when the calf muscle is exercised, i.e. 'working.' Some of the force from the calf muscle is not reflected back into the leg but dissipated into expanding the bandage. It is like a ball hitting a net. The net absorbs some of the force of the ball hitting it.

Advantages of short-stretch bandages

Short-stretch bandages provide an efficient, an adequate and a sustained amount of compression for treating venous leg ulceration. They are made from cotton fibres that make them biodegradable, washable and reusable. The cost effectiveness compared to a single use bandages is clearly evident. The time for a practitioner to apply one bandage is an advantage. A single bandage is less bulky than multi-layers. This makes it easier for patients to wear their normal shoes, carry on with their normal activities and exercise.

Bandaging techniques

The following two illustrations show bandaging techniques for the treatment of venous leg ulcers using short-stretch bandages. In order to provide and to maintain adequate compression, it is essential that the bandage remain firmly and securely in place on the leg. These two bandaging techniques have been used with good results in the healing of venous leg ulcers, reduction of leg ulcer associated pain and patient compliance[8,9].

Bandaging materials should be in place before bandaging is started. The following needs to be made ready:

a) Orthopaedic wool/undercast padding
b) 5 pieces of tape, 5 cm wide by 10 cm long
c) 1 short short-stretch bandage e.g. 10 cm by 5 m

Orthopaedic wool/ undercast padding is first applied to protect the entire leg or only the bony prominent parts of the leg.

Illustration 1

The Combined Bandaging Technique begins like the so-called simple spiral technique, i.e. where the bandage is rolled spirally in an even pattern up the leg from the base of the toes to the knee. However, in the Combined Bandaging Technique about mid-calf the spiral is sharply brought up to just below the knee and a full turn is made. Then the bandage is rolled down spirally covering the rest of the leg. See Steps 1 – 10.

Step 1: Begin at the sole of the 3rd toe and cover the base of the hallux.

Step 2: Roll the bandage over the foot and cover the heel.

Step 3: Roll the bandage over the instep of the foot.

Step 4: Roll the bandage over the malleoli.

Step 5: Roll the bandage up the leg with a 50% overlap.

Step 6: Roll the bandage up towards the knee sharply.

Step 7: Secure the bandage with a full turn below the knee.

Step 8: Roll the bandage back down the leg.

Step 9: Cover the remaining part of the leg.

Step 10: Secure with tape as indicated.

The Combined Bandaging Technique provides a straightforward and secure method of bandage application. It also gives extra support at the top of the calf muscle and helps to prevent bandage slippage. It is appropriate for both normal and champagne-bottle shaped legs.

Illustration 2

The second bandaging illustration is called the St. Charles Bandaging Technique. It is a method used to secure a bandage from the base of the toes to just below the knee. It is appropriate for both normal and champagne bottle shaped legs. This method also suits the patient who may be more mobile.

St. Charles bandaging technique

Step 1: Start bandaging at the malleolus with a full turn.

Step 2: Roll the bandage over the heel.

Step 3: Roll the bandage along the foot.

Step 4: Continue to bandage to the base of the toes.

Step 5: Roll the bandage back over the heel.

Step 6: Roll the bandage up the leg with a 50% overlap.

Step 7: Continue to bandage up the leg as needed.

Step 8: Roll the bandage up toward the knee sharply.

Step 9: Secure the bandage with a full turn below the knee.

Step 10: Bandage back down to cover the leg and fasten with tape.

The practitioner who may have had patients who experienced bandage slippage will soon recognize the benefit of the Combined Bandaging Technique and/or the St. Charles Bandaging Technique method.

Bandaging hints

1. Padding must be applied to protect vulnerable bony prominent parts of the leg or other areas of concern before bandaging.
2. One bandage is usually adequate for a leg with an ankle circumference between 20 and 25 cm.
3. Two bandages are indicated when the ankle circumference is greater than 25 cm. The second bandage is best applied using the opposite turning, i.e. if a clockwise turning was first used than a counter clockwise turning is recommended for the second bandage.
4. With the Combined Bandaging Technique it is often worthwhile to start with two complete turns at the base of the toes. Also cover the base of the hallux as this can be used as an anchor for the bandage.
5. As one hand wraps or turns the bandage on the leg the other hand can act as an iron to smooth or flatten out the bandage as it is applied.
6. These bandaging techniques can be applied over primary dressings including paste bandages.
7. At the beginning of the bandaging treatment when there is oedema, the bandage needs to be re-applied more frequently to prevent slippage and loss of compression. Once oedema is reduced the bandage can be left in place for 5-7 days.
8. Patients need to be encouraged to exercise their calf muscle by walking and both dorsal and plantar flexion is recommended. The more mobile patients need to find a balance between leg elevation (rest) and exercise.

CONCLUSIONS

Practitioners can benefit by a review of their bandaging methods in the application of compression bandages for the treatment of venous leg ulceration. Once the Combined Bandaging Technique is learned, the transition to the St. Charles Bandaging Technique will be a natural progression. The St. Charles technique when properly applied provides a secure method of bandage stability and sustained compression for the treatment of venous leg ulceration even if a patient's leg presents difficult or unusual conditions.

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