

SVETLANA MILOSAVLJEVIĆ  
PETAR ŠKUNDRIĆ

Textile Engineering Department,  
Faculty of Technology and  
Metallurgy, Karnegijeva 4,  
Belgrade

REVIEW PAPER

616.14-007.64:616-089.41 +615.468:677

## CONTRIBUTION OF TEXTILE TECHNOLOGY TO THE DEVELOPMENT OF MODERN COMPRESSION BANDAGES

*Although compression therapy is a key factor in the successful treatment of some circulatory problems in lower limbs, this form of therapy includes some risks if used inappropriately. Based on deliberate application of pressure to a lower limb, using a variety of textile materials, elastic or rigid, in order to produce a desired clinical effects, modern compression therapy presents a good sample of successful penetration of textile technology into the phlebology field of medicine. However, although compression therapy has been in use for over 150 years, there exists a low awareness among practitioners and patients on product usage, application techniques and benefits of appropriate selection of bandages for determined types of leg venous diseases. Also, not all manufacturers of compression textile materials seem to be conscious of end – users' needs. Simultaneously, impressive developments in the field of elastan fibers and modern knitting and weaving technologies, offer chances for realization of completely new types of compression bandages, capable of making an important contribution to the management of venous disease. In this review, starting from the brief account of pathogenesis and the presentation of compression therapy principle, an account of the contribution of all sectors in the textile technological chain to a modern compression therapy is given.*

*Key words: Compression therapy, venous diseases, elastan fibers, core-spun elastan yarns, knitted bandages, compression testing.*

Thanks to the need of surviving in an extremely competitive market, textile companies of some industrialized countries developed during last two decades a special sector of niche products, technical textiles. Together with classical clothing and home textile segments, the technical textiles as purely functional materials became vital in a whole range of applications. Thanks to their potential in existing and future markets, technical textiles are more and more gaining in strategic importance for many companies. Among a great diversity of technical textiles [1] medical textiles and biomaterials are very significant and increasingly important part of technical textiles industry, with global market estimated value in excess of US \$4 billion (excluding disposable hygiene products) with a production volume of around 1.65 million tones, which represents almost 12 % of total technical textiles market [2]. During last decade, textile materials in the medical field gradually have taken more important roles, finding their way into a variety of applications thanks to the results of an intensive research work. As essentially fiber based products, medical textiles cover today a huge range of applications, from diapers and surgical textiles, dressings, orthopedic bandages, compression devices, sutures, prostheses and filters for blood, to substrates for electronic sensing of vital life signs, as well as the

replacement of body parts through tissue engineering by supplying the structure for the growth of new cells. Among them recent developments in more traditional areas of wound care highlight the close cooperation between textile technology and medical science. In this sector of medical textiles, even the plaster has the potential to deliver a power health care effect through its specific skin care characteristics, and controlled delivery of medications [3]. However, nowadays traditional wound dressings (cotton gauze) are being replaced by more sophisticated products and management techniques that decrease health expenditure. Bandages, as one of the most important medical textiles with a range of uses, are now created in dependence upon their intended function. Elasticized woven fabrics, knitted hosiery (or tubular knitted hose with elastane fiber) and warp knitted spacer fabrics are widely used for healing of chronic wounds and especially for treatment of circulatory problems of lower limbs (as varicose veins and venous leg ulcers) through "compression therapy". However, low awareness among practitioners and patients, uneducated physicians on product usage and application techniques, low patient compliance due to frequent bandage changes or uncomfortable fittings [4] pose a significant challenge for participants in the compression therapy market. It is obvious that manufacturers of medical textiles for compression therapy that are conscious of end users needs are likely to gain a good market share.

In this paper, starting from understanding essential principles of compression therapy, the characteristics of compression bandages and techniques of their production are reviewed, and an account of their actual and future domains of application is given.

Author address: Prof. Dr. Svetlana Milosavljević, Textile Engineering Department, Faculty of Technology and Metallurgy, Karnegijeva 4, 11000 Belgrade, Serbia;  
E-mail: svet@afrodita.rcub.bg.ac.yu  
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### COMPRESSION THERAPY IN THE TREATMENT OF CIRCULATORY PROBLEMS

Compression has been used for many centuries as a method of treatment of some venous disorders of the lower limbs, as varicose veins and more severe diseases connected with them. Varicose veins affect up to 20 % of men and 30 % of women, this % growing with age [5]. The symptoms of the disease are swollen and twisted veins that are commonly visible beneath the skin of the legs (Figure 1) [6].

Though for most people varicose veins are mainly an aesthetic problem, for others they can cause a variety of medical complications like deep venous thrombosis (DVT) and leg ulcers (Figures 2 and 3) [7]. The treatment



Figure 1. Enlarged (varicose) veins



Figure 2. Deep Venous thrombosis (DVT)

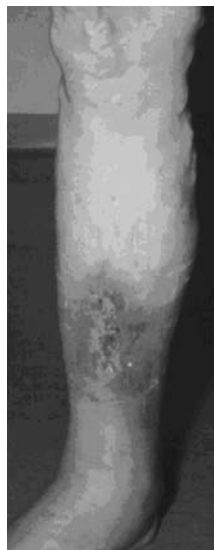


Figure 3. Venous ulcer

of leg ulcers as a chronic condition has been estimated to present a big problem for both patients and health service resources. The annual cost of treating venous ulcers reaches more than one billion dollars in USA and 400–600,000,000 pounds in UK [8]. Though they can be caused by a number of physiological or biochemical disorders, about 70 % of them are associated with venous disease. However, experience and research have shown that the majority of venous diseases, including venous leg ulcers, can be induced to heal by the application of adequate levels of external sustained graduated compression [9]. Though the application of compression as a method of treatment of leg problems was known for centuries, numerous contemporary studies [10] of the problem across the world highlighted the potential impact of modern compression therapy, as one of few healthcare interventions with a dramatic effect on outcome. Compression treatment of legs with circulatory problems is realized with the use of different types of bandages or medical hosiery that vary greatly in their ability to provide sustained compression. It is just the place where textile technology has to be involved, providing, by the use of its raw materials and technological operations, for medical textiles of appropriate structures and performances necessary for successful application in the treatment of venous diseases. Technological advances in the last decade concerning elastans have led to sophisticated developments in bandage and hosiery production, resulting in materials that overcome some traditional problems associated with comfort and aesthetics.

### PATHOPHYSIOLOGICAL EFFECTS OF COMPRESSION

Though the exact mechanisms of compressive action is up to now poorly understood, some physiological and biochemical effects of compression

are well known and physiological basis for compression therapy is well established. Effective textile materials used for production of compression bandages and medical hosiery are shown to have direct impact on venous as well as on lymphatic and arterial function and on the inflammatory processes [11]. Their influence on circulation disorders in lower limbs can be highlighted by an insight into the blood flow from the legs and the leg vein system. Though detailed consideration of the circulatory changes is out of the scope of this review, a simplified understanding of the causes of the venous hyperemia that is ultimately responsible for both the symptoms of chronic venous insufficiency and venous ulceration is necessary for understanding of management.

It is well known that blood is pumped from the heart to the legs through arteries and once it has given up the oxygen and nutrients it was carrying, blood returns to the heart through the veins. To do this, blood from the legs must flow forward, against gravity. This flow is assisted by one-way valves inside the veins, which prevent the blood from flowing backwards. The muscles of the leg help this flow: each time the calf and thigh muscles contract when walking, veins inside the leg are squeezed. In that way two mechanisms allow for the efficient return of blood in the legs: the calf muscle pump and venous valves. During walking, calf muscle movement propels blood upward while the one way valves prevent blood from flowing backward (Figure 4) [12].

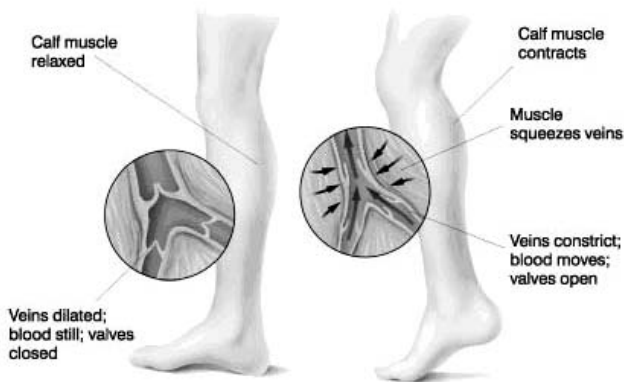


Figure 4. Valves in healthy veins and the role of "calf pump"

Blood from the outer layers of the leg collects into veins near to the surface, i.e. superficial veins being connected with the deeper veins inside the leg by perforator veins. When blood does not flow properly from the surface veins to the deep veins pressure can build up in the surface veins and this results in blood pooling and the visible sign of varicose veins (Figure 5) [12].

Only humans seem to be affected by the condition, suggesting it is related to their upright posture. However, this fact has been used by one of the producers of inelastic bandages to explain their effectiveness comparing them with the skin of giraffes

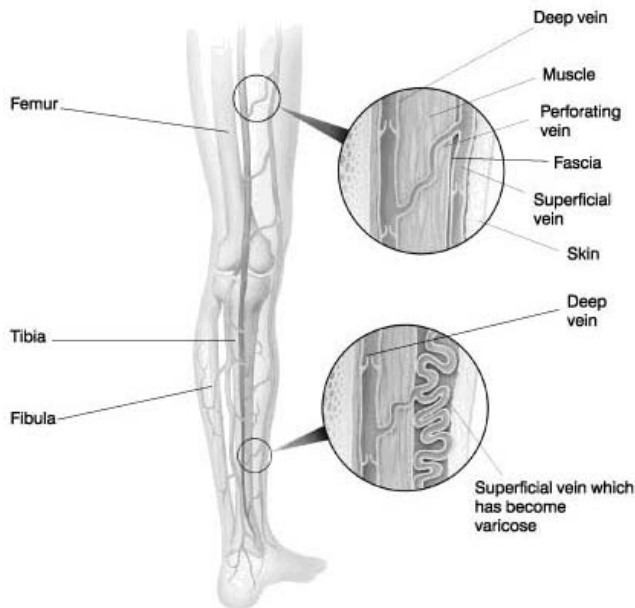


Figure 5. Veins in lower limbs

(non-elastic, non-stretchable) enabling them to withstand venous pressures of more than 250 mm Hg (three times that of humans) and never to suffer from lymphedema or venous disorders [13].

One of the basic problems causing the improper blood flow in lower legs is damage to the valves. When they are, after many hours of work, broken down, or are absent, the blood is flowing backward (Figure 6) [12, 14]. This causes the veins stretch and enlarge, they are bulging and twisted beneath the skin.

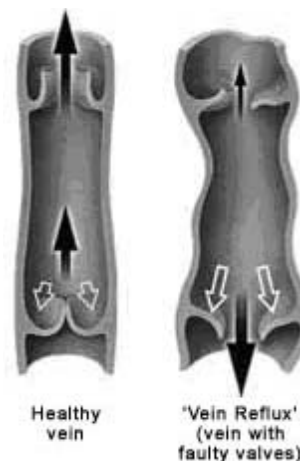


Figure 6. Normal and incompetent valves in healthy and in varicose veins

The mild common symptoms of varicose veins are aching and discomfort in the legs, particularly while standing, swelling of the ankles and alteration in physical appearance. However, complications of varicose veins bring to thrombophlebitis, and bleeding.

Interfering of poor blood flow in the veins with the way the skin exchanges oxygen, nutrients and waste products with the blood brings to chronic venous insufficiency, which can cause a number of problems including venous eczema and venous leg ulcers. These last are a sign of very weak blood flow in the veins which drain blood from the skin. Venous ulceration is a chronic and debilitating condition with a high rate of recurrence and compression therapy continues to be the cornerstone of the treatment. As a result of venous stasis a condition known as "deep vein thrombosis" (DVT) may occur, with the possible consequence, a fatal pulmonary embolism. DVT is characterized by forming of small blood clot, or thrombus, mainly in the deep veins of the legs. Breaking of the attached thrombus away from the wall of the vein and its carrying along with the flow blood as an embolus may provoke serious complication: if the embolus blocks a vessel the embolism will result, a pulmonary embolism being the most dangerous. It must be taken into account that there is also a greater risk of getting varicose veins during pregnancy and by over weighted persons. Other factors that have been blamed for varicose veins and complications as DVT are standing or sitting (as during transcontinental flights, known as "economy class syndrome [15]) for long periods, crossing legs while sitting, smoking and poor diet. However, there is not strong scientific evidence to support these theories [16].

#### DEFINITION OF COMPRESSION THERAPY

Compression therapy implies the deliberate application of pressure to a limb, using a variety of materials, elastic or rigid, in order to produce a desired clinical effect. It means, in the case of circulatory problems of lower limbs, to prevent and treat diseases of venous or lymphatic systems. It is usually achieved by the use of different systems of compression bandaging (Figure 7) [2] and medical elastic hosiery, both of them enabling the control and reduction of swelling in the treatment of venous disorders of the legs.



Figure 7. Use of a compression bandage

By forcing fluid from the interstitial spaces back into vascular and lymphatic compartments, the application of graduated external compression can help to minimize or reverse the skin and vascular changes described previously. Graduated external compression means that the necessary level of pressure is to be reduced progressively up the leg (the highest pressure at the ankle) in order to counteract a largely hydrostatic pressure within the veins of a standing subject [9].

#### SOME HISTORICAL FACTS ABOUT DEVELOPMENT OF COMPRESSION MATERIALS

Compression treatment has been used throughout of the history of medicine, stretching back thousands of years to the time of ancient Egypt and tribes living along the river Tigris. In phlebology, the branch of medicine concerned with the anatomy and diseases of veins, compression bandages were mentioned in the Greek Corpus Hippocraticum more than 2000 years ago (450–350 BC). The Roman legionnaires bandaged their legs tightly during long marches; Aurelio Cornelius Celso, a Roman author from the time of Tiberius recommended compressive linen bandages for treatment of venous ulcers. Throughout the medieval period, influenced by Arabic medicine compressive dressings were widely employed [8]. In 1343, surgeon Guy de Chauliac from Montpellier wrote about bandages when treating varicose veins and leg ulcers in his work *Chirurgica Magna*, as did Giovanni Michele Savonarola (ca 1430) and W. Harweys (1537–16190) [17]. After rubber was discovered a new era of elastic textile materials began, among them elastic compression bandages. However, such materials were not easily acceptable from patients: they had not good visual qualities and frequently had allergenic effects on skin. The development of compression therapy in Western Europe over the past two centuries may be divided in three phases: the start of ambulatory compression in London around 1880, empirical development of the compressive method in the period from 1900 to 1950, and finally, beginning 1950, rigorous scientific study of accumulated empirical data. In that period clinicians, assisted by physicists, physiologists and biologist, established the laws of "therapeutic counter-pressure" and transposed them to the textile industry [18]. This last phase resulted in new materials and textile structures that facilitated the use of adequate grades of pressure adapted to every individual case of circulatory problems in lower limbs.

Today, though little known or underestimated by many physicians, compression therapy (especially ambulatory elastocompression) remains the a fundamental therapy in phlebology, with rather promising future in prevention of vascular disorders in legs related to the actual living styles.

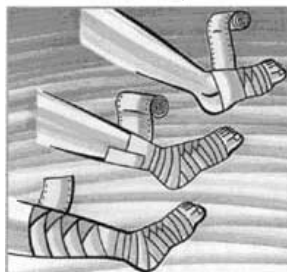
## TEXTILE PRODUCTS USED FOR HEALING AND PREVENTION OF VENOUS DISEASES OF LOWER LIMBS

Textile technology is involved in production of two types of products being used for realization of compressive force necessary for making up of difference in circulation usually caused, as already mentioned, by one or more illness/disease states. These are: compressive bandages and compression (medical) stockings. The difference between the two lies primarily in the sectors of application of each of them.

Both are large part of medical therapy, but bandages are always used as therapeutic means, while medical stockings serve predominantly as the preventive material or material enhancing the recurrence of varicose veins' problems after operation. Compression bandages are classified in two large groups: inelastic (minimally extensible, passive or short-stretch) and elastic (highly extensible, active or long-stretch). The first may be simply cotton bandages, or bandages impregnated with zinc adhesive. Elastic bandages, natural or synthetic, contain natural or synthetic elastic fibers in different percentages. The ability of bandage to sustain a particular degree of tension reflected in sub-bandage pressure is determined by its elastomeric properties being dependent on fiber composition and yarn and fabric structure. At some point the physical structure will prevent further stretching once a certain degree of extension is achieved, this condition being called "lock-out". This fact served to classify short-stretch bandages as those which should lock-out at 70% of extension, (ideally at 30–40% extension), and long-stretch bandages only locking-out at over 140% extension [10]. Consequently, today are produced bandages with small extensibility (<70%), medium extensibility (between 70 and 140%) and high extensibility (above 140%). In clinical practice only the two first types are used. Bandages could be extensible in the direction of their length (monoaxially) or in both directions of length and width (biaxially). The function of both inelastic and low-extension bandages is to offer more support than compression function. However, low awareness among practitioners and patients, uneducated physicians on product usage and application techniques, low patient compliance due to frequent bandage changes or uncomfortable fittings [4] pose a significant challenge for participants in the compression therapy market. It is obvious that manufacturers of medical textiles for compression therapy that are conscious of end users needs are likely to gain a good market share.

Elastic stockings represent a useful method of applying graduated compression to normal shaped legs in order to prevent serious complications as development or recurrence of venous leg ulcers. They are compressive medical garment being extensible in

Short-stretch bandages are more suitable than compression stockings immediately post-operative or in the case of a weeping ulcer. However, where compression is needed over a longer period of time, stockings are the best option.



Stockings give most compression at the ankle, with less at the knee and least in the thigh. This helps the return of blood from the leg.

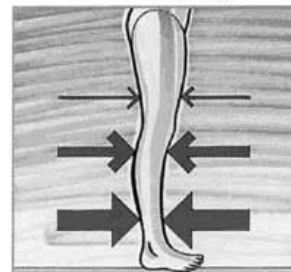


Figure 8. Compression bandages and compression stockings with graduated compression

both directions (length and width). Medical stockings have pre-defined measures and their gradient of compression decreases from ankle to knee [19]. It means that defined and graduated compression (in order to minimize or reverse the skin and vascular changes) of stockings is reduced from the base upwards, being 100 % at the ankle, 70 % at calf and 40 % at knee (Figure 8) [20].

The reason for ensuring graduated application of external compression, with the highest pressure at the ankle, is largely hydrostatic character of the pressure in the veins of standing subject that must be counteracted by progressive reduction of pressure up the leg (as the hydrostatic head is effectively reduced). The same condition must be fulfilled by compression bandages, but it is realized by special bandaging techniques (spiral or the "figure of eight"). As compression stockings are of limited value in the treatment of active ulceration, because of problems related to difficulty of their application over dressings, in such situations compression bandages represent the treatment of choice [9].

Much of the relevant broad based scientific material involving compression bandages and compression hosiery is found primarily in patent application information.

### CLASSIFICATION OF COMPRESSION BANDAGES

Compression bandages from the textile aspect belong mostly to narrow fabrics, which may be produced on weaving or knitting machines. From therapeutic point of view, their main property is sub-bandage pressure which is achieved with different classes of bandages using application in the form of spiral with 50 % overlap between turns (Figure 7 and 8) [20] or using application technique known as "figure of eight" (Figure 8), which produces larger number of layers and hence higher sub-bandage pressures.

Sub-bandage pressure may be calculated using the following formula derived from Laplace equation [21]:

$$P \propto t/R$$

where P is pressure, T is tension (determined mainly by the amount of force applied to the fabric during application) and R is radius.

For application of this simplest form of the equation it is necessary to use coherent units of measurement, i.e. Pascal for pressure, Newton as unit of force, etc. As none of these measurements is commonly used in medical practice, they are converted in more familiar units as mm Hg, centimeters and kilogram force (Kgf). Also, as the direct measurement of the radius of the limb R is virtually impossible, more familiar measure of circumference is preferred. Including all conversion factors as well as bandage width  $n$ , and number of bandage layers L, the formula to calculate sub-bandage pressure can be summarized as:

$$\text{Pressure (mm Hg)} = \{ \text{Tension (Kgf)} \times L \times 4620 \} / \text{Circumference (cm)} \times n \text{ (cm)}$$

Though bandages could be classified into different categories and classes, today there are no international nor European standards related to properties of compression bandages. Two kinds of standard – British and German – possess some differences [22,23]. According to British test method which characterizes bandages and predict their ability to maintain predetermined levels of compression, bandages may be classified into three distinct groups. Besides enabling an indication of the degree of extension required to produce the predetermined level of compression, this

test determines the change in bandage tension i.e. sub-bandage pressure in dependence on small changes in limb circumference and provides assurance, when applied correctly, of development of desired levels of compression beneath the bandage. In Table 1 types and classes of bandages according to British standards are presented [9]:

### SPECIAL COMPRESSION BANDAGES (Four – layer compression bandages)

About almost two decades ago, different systems of four layer compression bandages are developed and successfully used mostly for leg ulcers healing [24]. These bandages present high compression systems (with pressure beneath bandages of about 35–40 mm Hg), including a wool bandage applied from the base of the toes to just below the knee, followed by an elastic compression bandage applied in a figure of eight and by a final cohesive layer. Each component of the system has a special function. Orthopaedic wool provides a protective layer for the areas at risk of high pressure at bony prominences (foot and ankle). Due to the increased skin sensitivity in venous disease the padding layer should cover all vulnerable areas. The second layer is a crepe bandage which simply adds absorbency and smoothes down the orthopaedic layer before application of the two compressive bandages, making third and fourth layers. Both of these outer bandages are elastic, the first one being a highly extensible bandage that provides a sub-bandage pressure of approximately 17 mm Hg when applied with 50 % extension with 50 % overlap using a figure-of-eight technique. The fourth layer is elastic cohesive bandage the role of which it not only to maintain the bandage position, but also to

Table 1. Types and classes of compression bandages

System of bandage classification	Description and examples of some commercial products
Type 1: Lightweight conforming–stretch bandage (not exceeding few mmHg)	Simple dressing retention function (examples: Slinky, Stayform and J–Fast).
Type 2: Light support bandage	Short or minimal stretch bandages, used to prevent formation of oedema and give support to management of mild sprains and strains and also for the treatment of venous leg ulcers (examples: Elastocrepe, Leukocrepe and Comprilan).
Type 3: Compression bandage (for compression)	Deliberate application of pressure in order to control oedema and reduce swelling in the treatment of venous disorders of legs.
<b>Types of compression</b>	<b>According the ability of bandages to produce determined levels of compression</b>
Class 3a: Light compression bandages (14–17 mm Hg at ankle)	Low levels of compression for management of superficial or early varices and varicoses formed during pregnancy (examples: Tensolastoic and K–Plus–Parema)
Class 3b: Moderate compression bandages (compression in the order of 30 mm Hg on an ankle of average dimensions)	For varicoses formed during pregnancy, varices of medium severity, treatment of ulcers, control of mild oedema
Class 3c: High compression bandages (in the order of 40mm Hg on ankle)	For treatment of gross varices, post–trombotic venous insufficiency, management of leg ulcers and gross oedema (examples: Tensopress, Setopress and Surepress).
Class 3d: Extra–high performance compression bandages (in excess of 50 mm Hg)	Apply and sustain pressure on the largest and most oedemateous limb for extended period of time (examples: Elastic Web Bandage BP and Varico Bandage).

provide the higher level of compression (approximately 23 mm Hg). The two outer elastic bandages when used in combination provide a sub-bandage pressure of approximately 40 mm Hg. Four layer bandages may be modified in order to attain adequate sub-bandage pressures in patients with ankle circumference or limb shape outside the normal range. Four layer compression bandages attained great success and with their development many practitioners abandoned other types of compression bandages. Their success is probably related to the fact that they present a combination of elastic and non-elastic bandages. It has to be pointed out that there appears to be a "friction" of compression therapy between professionals, with one camp advocating the use of multilayer or long-stretch bandages and a second camp working only with short stretch bandages [25]. However, the bandage system should be selected for the patient, on the base of an understanding of different systems working principles along with the assessment of the patient individual needs. It means that among several different types of bandaging systems available, each may have advantages over the others for particular applications.

#### **MODERN TEXTILE TECHNOLOGY IN COMPRESSION THERAPY**

An intensive compression therapy, characteristic for recent 50 years, evolved together with the development of new textile fibers and with upgrading of some technological operations and textile machines. However, the most important contribution is related to recent successes in fiber and yarn technology, which normally imposed certain requests to adaptations of textile machines and testing procedures.

#### **Modern textile fibers for compression bandages**

Among textile fibers being used today for manufacturing of compression bandages, two groups of raw materials could be underlined: a) conventional fibers like cotton, viscose, polyamide and polyester filaments and b) elastan fibers. Textile materials used in compression therapy have been for years manufactured from cotton and viscose, using knitting and weaving techniques. Compression properties, which varied with the use of such materials in a very narrow extent, were attained mostly through the structure of yarns, i.e. by using different levels of twist. Such approaches to the production of compression textile materials remained current in the recent time for production of low-elasticity (short-stretch) bandages. The invention of nylon in 1937 was a stimulus for production of hosiery in general and consequently for compression hosiery and compression therapy as whole. This fiber in different contemporary forms (filament, textured) today presents the main element of bandages, together with other fiber components. Numerous products of renowned world producers composed of cotton and textured nylon could

be quoted. However, the most important event that strongly influenced compression therapy was the invention of elastan fibers more than 40 years ago. The main fact related to elastan fibers is that these fibers added in minimum % to a yarn essentially influence its elasticity, as well as the elastic properties of fabrics made therefrom. That was the reason why the use of elastan fibers increased by continual demand for stable, carefree garments with a good wear behavior. Particularly in the last years these fibers were increasingly used not only in traditional fields like corsetry and elastic bands, but also in hosiery and outerwear. The special properties of these fibers, especially of new types developed recently, recommended them for use in production of compression textile materials.

#### **Elastan fibers**

Elastomeric fibers known under the name "elastan" (Europe) but also "spandex" (USA) could be defined as synthetic fibers composed of linear macromolecules which contain minimum 85 % of their mass of segmented polyurethanes. In general terms it could be said that in this category enter fibers that have a great elasticity and deformability, with an average extensibility superior to 200 % (generally 4–8 times their initial length). Available fineness of elastan fibers are in an interval of 11 to 2600 dtex. After stopping of axial force, these fibers recuperate instantly and completely their initial form. Another important and distinctive element of elastan fibers is the fact that their great elasticity is derived from their chemical and not physical structure, adversely to filaments obtained by texturing which also present highly elastic fibers. The main advantages of these fibers being very similar to rubber and developed in order to eliminate some of disadvantages of rubber fibers (low strength, low chemical resistance, low dyeability and low frictional resistance) are: excellent breaking strength, elongation and modulus, good flexion resistance, soft compression, good abrasion resistance, good dyeing properties with acid dyes and excellent resistance to oxidation and influence of UV rays. Also, these fibers may be washed many times without problems, they are resistant to detergents, perfumes, chlorine etc. and may be thermofixed in order to maintain their permanent form. All these properties made elastan fibers ideal for accomplishment of requests necessary for application in manufacturing medical textiles for compression therapy. The most popular elastan fiber is Lycra (Du Pont, USA); also very distributed is Perlon U produced in Germany. Today these fibers are produced all over the world, from Holland to Japan [26]. These fibers could be processed in textile surfaces as bare elastans or as covered elastans. However, caused by the conditions of some processes or special demands on the products (compression therapy textile material presenting one of such examples) bare elastan filament fibers cannot be

used. Because of that in such fields the use of complex or combined elastan yarns is needed for realization of necessary elastic qualities of textile products.

### Combination (complex) elastan yarns for compression therapy

Generally, heterogeneous (combination, complex) yarns including different yarn components are produced in order to realize special yarn properties or favorable economic effects [27,28]. Combination yarns for modern compression bandages with elastan yarn component may be produced by different production methods. The most common of them are: single and double covering, ring twisting, doubling and stretching on two-for-one twisting frames [29], elastic twisting by hollow-spindle method, twisting on "Elasto-twister", core spinning, siro-spun and air-covering [30,31]. Idealized diagrams illustrating the structure of yarns produced by some of actual techniques for are presented in Figures 9 to 13 [32].



Figure 9. Single core yarn



Figure 10. Double core yarn

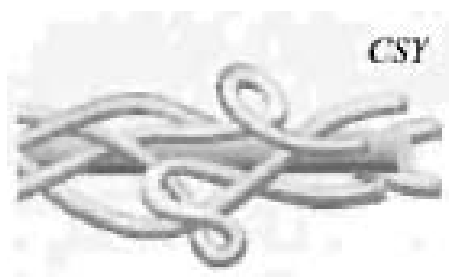


Figure 11. Core spun yarn

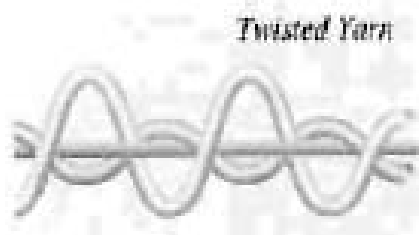


Figure 12. Twisted yarn with elastan filament



Figure 13. Air intermingled yarn

The techniques for the production of elastan heterogeneous yarns are rather different from each other. As a consequence, different yarn constructions enable advantages in using these yarns in different textile products. For narrow fabrics like compression bandages different types of "core yarns" and "core sheet yarns" may be used. These yarns in English speaking world are frequently related as CSY (Core Spun Yarn) (Figure 11). It is obvious that core spun yarns consist of core and sheet and that filament yarns or elastic filaments (natural rubber or synthetic elastan) are employed in the core, while the sheet consists of staple fibers. In general elastan fibers with counts 22, 44, 78 and 156 dtex are employed for elastic core yarns. Characteristics of the yarn that can be influenced through the sheeting are shown to be [33]: pre-determined setting of stress-strain ratio, longer life time due to the protection of elastan against the effects of wear, high temperature, chemicals, etc., secure anchorage of the yarn in the fabric (no slippage), increased life time due to the protection of elastan from UV rays, safe coverage (masking) of elastan which can not be dyed. All these properties render elastan combination yarns ideal for production of compression bandages.

### New yarns for compression bandages

Very recently, modified OE rotor spinning technique was used for production of core yarns. The Czech company RIETER CZ a.s., of Usti nad Orlici, perfected a technique for elastic rotor yarns developed several decades ago. The new process produces yarns with a less hairy, more uniform and thus more homogeneous surface structure than ring-spun core yarns and elastic twists. It is therefore ideal for processing elastan yarns.

In the new yarn known under the brand name Rotona<sup>R</sup>, Dorlastan<sup>R</sup> V 900 elastan fiber is fed through a hollow tube into the rotor [34] and the rotor yarn which is created in the rotor groove is warped around the filament which has a benefit in terms of yarn and fabric features as well as in downstream processing, as illustrated in Table 2 [33].

The core can be either hard or elastic, the fineness of elastic filaments being equal from 22 dtex to 156 dtex. The final yarn can be produced in the count range of Ne



Table 2. Comparison of different core yarn production techniques: rotor core yarn *Rotona*<sup>®</sup> versus ring core yarn

Feature	<i>Rotona</i> <sup>®</sup> Core yarn	Ring Core Yarn
Total knots resp. splices/kg yarn	0,1–0,2 (0,3–0,4)/bobbin	ca 8–12 splices + 0,3 knots
Core twist	Without Twist	With Twist
Hairiness	Lower	Higher
Filament damage	No	Risk
Elasticity	Better	Same (lower)
Relaxation	Better	Same (lower)

6 to Ne 40 from all available materials ranging from cotton, polyester, and viscose to blends or even regenerated fibres. The *Rotona*<sup>®</sup> structure comes close to the twisted core yarn but in the relaxed position it resembles the ring core twist where most of the filament is covered. Since the *Rotona*<sup>®</sup> behaviour is similar, the ring and twisted core yarns can be easily substituted but additionally there is a major benefit – *Rotona*<sup>®</sup> yarns are produced at much lower costs. Used as warp in weaving experiments for production of compression bandages, open-end core yarn showed excellent weavability, fiber abrasion was in normal range for covered yarns, only few warp end breakages occurred, the samples in loom state showed no elongation. A simple washing process in lukewarm water caused shrinkage, which created an appropriate elasticity, the shrinkage process being irreversible; that means that the bandage retained its full stretch capacity even after drying. Taking into account the fact that OE core yarns are less expensive than conventional covered yarns and that elastic open end yarns can offer bandages with a high degree of elasticity, it may be expected that they would present, after further tests necessary in order to optimize stretch-strain characteristics of yarns and the resulting fabrics, material of choice for medical application in compression therapy.

### STRUCTURAL PROPERTIES OF COMPRESSION BANDAGES

Narrow fabrics used for compression bandages may be produced as both woven and knitted textile surfaces. The different features of woven and knitted bandages are structure-related. While woven bandages (without elastan) are generally inelastic, due to their structure, knitted goods have a characteristic elasticity in either a transverse and longitudinal direction, depending on whether standard knitting or crochet knitting is employed [35]. However, in recent years, many of modern compression bandages are rather knitted than woven. In Figures 14–16 are presented microphotographs of some compression bandages structure [9].

Crepe bandages are manufactured in two following variants:

- With hard twisted yarn woven into warp. The characteristic appearance of the bandages is achieved

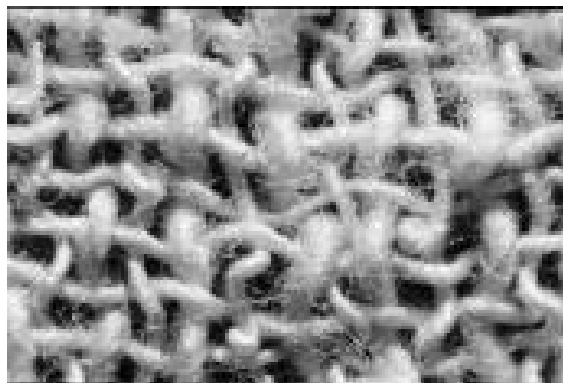


Figure 14. A woven cotton bandage

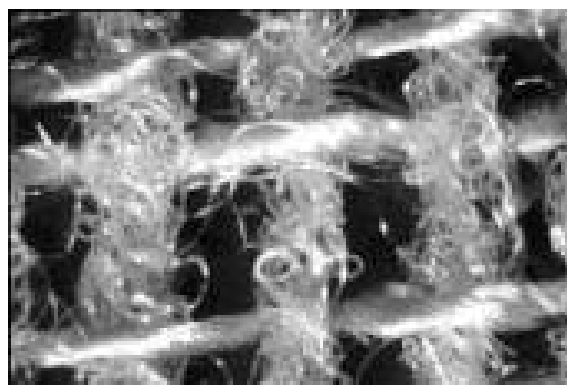


Figure 15. A woven bandage containing viscose and nylon

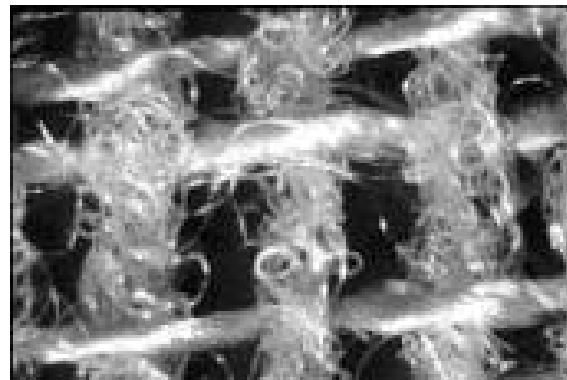


Figure 16. A knitted bandage containing viscose and nylon

by alternating use of s-twisted and z-twisted yarns, the resulting contraction producing a bulky, unstructured surface.

- The use of elastan, woven as a warp thread with a defined extension, which results in the typical surface when tension is released.

The elastic properties of simple woven cotton crepe-type compression bandages tend to be extremely poor, their therapeutically active level of pressure being very prone to fall down. If this fall attains some 63 % over a four hour period, it may be compared to significantly smaller drop of 10 % beneath a bandage containing elastan fibers.

Compression bandages containing elasthan or textured polyamide fibers present completely new products. Their structure is sometimes rather complex. A sample of woven compression bandage with crepe effect may be given as the subject of numerous patents. According to one of them [36] the bandage contains elastomeric yarns and composite warp yarns. The composite yarns comprise a staple fiber yarn and a textured filament yarn, which are twisted together; the staple fiber yarn forms loops, which gives the bandage a crepe effect. It is obvious that such a woven bandage avoids the use of high-twist cotton yarns used in conventional products which can shrink when the fabric is boiled and irritate sensitive skin. Produced by knitting technology, compression bandages offer considerable advantages over woven cotton crepe-bandages, as more elasticity and better conformability. By variation of yarn fineness the manufacturing of products which can be easily adapted to all limb forms is enabled, as well as acceptable visual properties and durability. In Figure 17 is presented compression bandage "3MTM Coban™ Self-Adherent bandage" having following benefits: sustained and reliable compression, lightweight, moisture resistance, length adaptable to different limb circumference. This type of bandage also allows skin to breath, preventing maceration [37].

However, in construction of compression bandages, the choice of yarns is of greatest importance: by selection of the appropriate yarns, the "power" or strength of a bandage may be finely controlled and thus,



Figure 17. Self-adherent bandage for sustained, reliable compression

thanks to the cooperation of textile industry and medicine, for the first time it has become possible to design an extensible bandage which will perform in a predetermined fashion in order to meet a specific clinical needs.

#### SPECIAL TEXTILE STRUCTURES FOR COMPRESSION BANDAGES

Spacer fabrics (known also as 3D or three-dimensional fabrics) are special textiles with favorable qualities for their potential use in oedema treatment in cases of chronic venous insufficiency and chronic lymphatic insufficiency [38]. They are actually being used instead of neoprene rubber, because they are, unlike neoprene, all textiles, do not smell, last indefinitely and are easily washable and do not absorb perspiration. The basic principle on which spacer fabrics are constructed is a combination of textile sheets with distance fibers as presented in Figure 18 [39], i.e. they are three-dimensional.

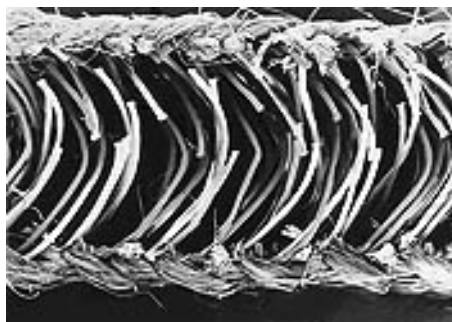
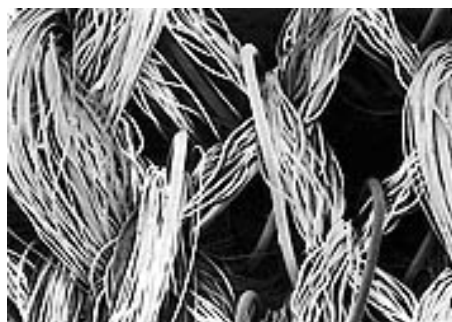
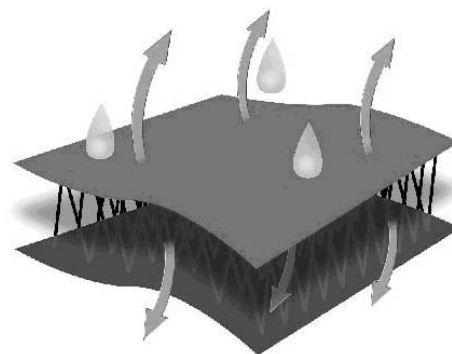


Figure 18. Spacer fabric: schematic presentation, details of the filament construction and scanning microscopy of spacer fabric demonstrating the monofilaments interconnecting the textile areas

Table 3. Some properties of synthetic and cellulosic fibers used in spacer fabrics

Fiber	Fiber type	Density g/cm <sup>3</sup>	Elasticity % dry/wet	Specific electrical resistance $\omega/cm$	Melting point °C	Water sorption %	Water holding %
Polyamid 6	Filament	1,14	20–45/105–125	$10^9$ – $10^{11}$	215–220	3,5–4,5	10–15
Polyamid 6.6	Filament	1,14	20–40/105–125	$10^9$ – $10^{11}$	255–260	3,5–4,5	10–15
Polyester	Filament	1,36–1,41	20–30/100–105	$10^{11}$ – $10^{14}$	250–260	0,2–0,5	3,5
Viscose	Filament	1,52	10–30/100–130	$10^6$ – $10^7$	175–190 <sup>a</sup>	12–14	85–120
Cotton	Staple fibers	1,52–155	20–50/100–120	low	From 180 <sup>a</sup>	7–18	42–53

<sup>a</sup>Decomposition

As it may be seen, two textile layers are held by spacer threads in a defined and flexible spacing. A direction-oriented moisture transport is given by specific fiber material (Table 3) and its arrangement and processing into the textile surface. By optimization of material and technologies a direct transport of fluids and heat is enabled.

Selected materials in which cellulosic fibers are combined with synthetic fibers, different densities of fiber connections with the textile sheets and precisely defined spacing, provide for excellent air permeability, thermoregulation and pressure balancing [40]. Among many important advantages of spacer fabrics, as breathability, insulation, durability, recyclability, for application in the field of compression bandages is of special importance their pressure resistance. Hence, with their mechanical and microclimatological qualities ensuring their use for medical textiles, spacer fabric-based compression bandages have been shown to be as effective as classical bandages but much more comfortable since there is the need of only one layer bandaging. However, the application of spacer fabrics for the prevention of chronic wounds is just beginning, though some producers of knitted fabrics developed advanced technologies for manufacturing these promising textile-technological solutions for medical use.

In new developments in the field of the medical textiles for healing of chronic wounds could be also counted embroidered textile layers. The porous structure in these types of bandages is made from PET multifilament yarns, whereas the stiff element for mechanical stimulation consists of PA monofilaments. The close control of three-dimensional fiber architecture, which combines different kinds of pores and holes for direct angiogenesis with stiff elements for a local mechanical stimulation of the wound ground, offered by embroidery seem to be, according to clinical pilot studies [41] promising in the treatment of venous leg ulcers.

## MANUFACTURING OF COMPRESSION BANDAGES

The recent successes in the field of textile machinery, above all characteristic for European

countries as Germany, Italy and Switzerland [42–44] contributed also to the development of advanced technologies of compression bandages manufacturing. Besides conventional weaving machines for production of narrow fabrics and conventional knitting machines for knitting narrow bands, in the field of compression bandages are present special machines for production of technical textiles; some of them can be used for medical textiles production, especially in crochet technology. As illustrative examples could be cited machines for weaving of narrow fabrics of the firm Jacob Muller from the series NF or machine MDRR42 (Figure 19) [45] of the same producer.



Figure 19. MDR<sup>R</sup>42 crochet machine (Jacob Mueller AG)

This machine sets new benchmarks in crochet technology, representing a highly specialized and well known segment in the textile machinery market. Crochet machines are considered a category of warp knitting machines as they produce single chains of warp threads which are then tied together by horizontal weft threads. Typical applications for the MDRR42 (Mueller Direct Raschelina) machine include the production of different

elastic and non-elastic tapes, including bandages. Taking into account the fact that the production of sophisticated, top-quality tapes requires a large number of weft threads which makes easy access to the machine difficult, design engineers of the new machine facilitated easy article switching and thus raised machine utility. Consequently the number of weft guide bars in the new MDR<sup>R</sup>42 crochet machine was raised to 24, which greatly increased the range of patterns available. At the same time an innovative and patented knitting principle was introduced, which permitted the individuality of each of the weft guide bars via a new type of control technology. Simultaneously, the machine has higher speeds and provides reduced machine noise and vibrations. Also, MDR<sup>R</sup>42 uses new drive principle, including linear motors which seem to present the drive technology of the future. With many other innovations (in the sector of weft feeder, direct drive, machine control by means of an industrial PC, etc) MDR<sup>R</sup>42 provides narrow fabric manufacturing tool which can meet the increasing demands of compression therapy medical sector, with regard to pattern and more competitive prices.

Another machine of the same producer, GWM1200 has the configuration specially designed for the manufacture of knitted fabrics of functional applications. This machine is ideal for production of 3D knits ("spacer knits") and other heavy technical knits. Here may be also cited new "HighDistance<sup>R</sup>" machine of the firms Cetex and Karl Mayer<sup>46</sup>, a double-bar raschel machine on which the resilient spacer fabrics are produced. However, as already underlined, the development in the sector of three-dimensional textile, especially spacer fabrics, though introducing a new dimension onto the market, has the potentials which still expect to be discovered.

Some firms are offering machines especially destined for production of different types of bandages, among them compression bandages. For example, the firm Ningbo Keguang Mechanical and Electro Products Co., Ltd (China) produces a range of machines for manufacturing narrow fabrics. The machine KGF955 used to knit the elastic and non elastic strips from cotton and other fibers, from light to heavy, among them medical bandages, is presented in Figure 20 [47]. The main technical characteristics of this machine are presented in Table 4.

A good review of machines for production of compression bandages, offered on the market, can be found in numerous websites.

#### TESTING OF COMPRESSION BANDAGES

Testing of compression bandages encompasses their mechanical properties as stress-strain relations which define their behavior during use. These relationships may be examined in the laboratory using a constant-rate-of-traverse machine, an instrument that records the tension in a test sample whilst extending it at



Figure 20. High speed shuttleless loom KGF955, (f. Ningbo Keguang Mechanical and Electrical Products Co., Ltd)

Table 4. Main technical data of KGF 955 machine

Model	8/30	6/45	4/65
Number of knitted strips	8	6	4
Width of the reed	30	45	65
Number of the flanges	6-14	6-14	6-14
Motor power (kW)	1.5	1.5	1.5
Rotation speed (rpm)	1400	1400	1400
Number of wefts	3.5 – 36.7/mm (8.9 – 93/inch)		

a predetermined rate. The relationship between extension and bandage tension obtained on the instrument ("load-extension curve") has two separate components (Figure 21): the extension curve (upper curve) which expresses the relationship between extension and tension as the bandage is extended or stretched, and the regain or retraction curve (lower curve) which records same parameters as the bandage is allowed to return to its unstretched state [48].

These two curves are rarely super-imposable and the difference between them is termed "hysteresis", adversely to truly elastic material such as a piece of rubber, where a direct relation exists between extension and applied force and relatively little hysteresis. Similar behavior, if tested in isolation, tends to show elastomeric yarns used for some compression bandages. Once incorporated into a fabric, however, their extensibility may be partly inhibited by frictional effects that take place between non-elastomeric yarns, which may be

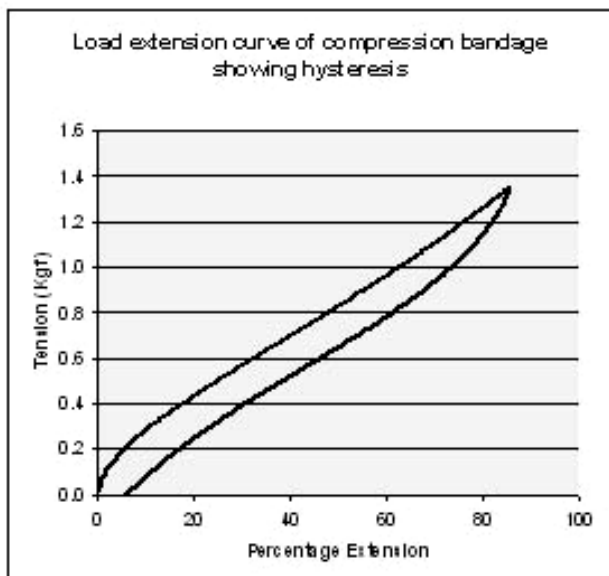


Figure 21. Hysteresis in extensible bandages

formed from cotton, viscose or some other chemical fibers. In dependence on bandage construction method, a significant part of the applied force may be dissipated on these textile components.

Bandages constructed from heavily twisted yarns providing a degree of elasticity also produce stress-strain curves that show a very rapid change in tension for relatively small changes of extension, particularly on the regain portion of the curve. Load-extensibility curves for a simple crepe bandage and an inelastic ("Comprilan", short stretch) bandage are shown in Figures 22 and 23.

The marked changes in tension caused by variation in extension during or after application of such bandages result in changes in sub-bandage pressure. On the contrary, bandages containing significant quantities of elastomer perform much better in this respect. Their behavior is also better in maintaining applied tension and "following-in" as leg circumference is reduced, with minimal affect upon sub-bandage

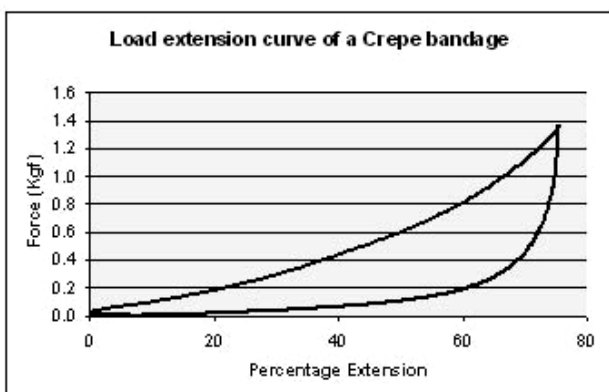


Figure 22. Load extension characteristics of a crepe bandage

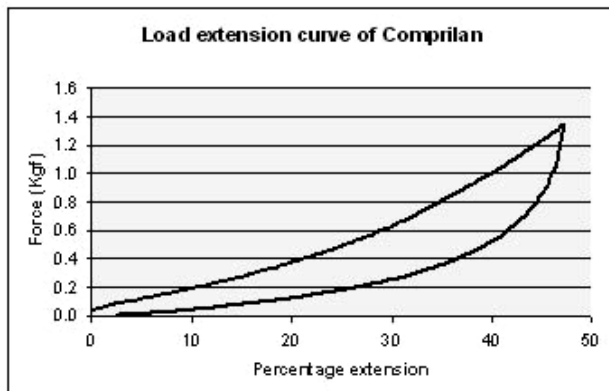


Figure 23. Load extension characteristics of a "short-stretch" bandage

pressure. One of the key features claimed for new, elastomer-including bandages is their relatively shallow extensibility curve over the working range, which should ensure that minor changes in extension have little effect upon applied sub-bandage pressure.

Taking into account the fact that compression bandages work by applying pressure to underlying tissue in order to produce therapeutic effect, it is important to be able to accurately and reliably measure that pressure and to understand its effect on the limb condition being treated. As already mentioned, different types of compression bandages have different compression characteristics, and these change with use, shape of limb, compliance of the tissue or through remediation of the condition for which it was applied [49]. Also, the hazards of too high a pressure should not be underestimated, as this leads to complications as cellulites, arterial insufficiency and even necrosis. Hence, it is very important that regular checks be made of compression bandages pressure. The difference should be made among testing sub-bandage pressure during their application (in medical institutions) and tests carried out to measure fabric properties.

As mentioned earlier, theoretical pressure produced by compression textile material may be calculated from modified La Place formula. However, this formula may be used only in laboratory practice. Among numerous attempts undertaken for development of a practical procedure for measurement of sub-bandage pressure, applications of different transducers inserted between the bandage and the skin could be cited. However, readily available transducers were too thick (2mm) for routine clinical work. They caused distortion of the bandage fabric which increased the measured pressure value. An elegant method is to use thin film sensing elements of which there are a number, but their bringing to clinical use still requires significant development. Some commercially available systems (<http://www.novel.de>, <http://www.talleymedical.co.uk>) of similar type are, unfortunately, expensive and only likely to be found in specialist centers.

Test carried to measure fabric properties usually include Hatra leg or Salzman pressure monitor<sup>50</sup>. The Hatra pressure tester is designed to measure the compression exerted by bandaging (or hosiery) on the leg. The textile material 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 bandage at any point is proportional to the fabric tension divided by the girth at that point. The equation used for determining pressure on the Hatra leg is given by the following relation:

$$\text{Pressure (mm Hg)} = 4 \times \text{Tension reading} / \text{Radius of curvature of the leg (cm)}$$

The Hatra Device measures the limb in a circular way, using a steel limb; however, the shape of the leg with bony shin and the muscles varying pressure is given around the circumference.

The Salzman pressure monitor is also a way of measuring sub-bandage pressure. It consists of a thin plastic sleeve with four paired electrical contact probes which are laid on the limb surface and covered with a bandage. 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. Readings can be taken with the limb in different position and in different states such as relaxed and tense.

It seems, however, that if modern sensing technology could be combined with modern weaving and knitting technologies, it may be possible to incorporate an easy and accurate assessment of bandage pressure within the bandage itself. The realization of this ideal is a challenge to the compression garment and materials industries.

## CONCLUSION

Textiles represent an ideal interface between skin and medical treatment facilities. For treatment of leg venous diseases, use of external compression realized by textile compression bandages remains one of the most effective ways to achieve healing of different conditions. As the pressure distribution of these bandages depends on special properties of fibers, fiber blends in yarns and yarns in fabric structures, it is hoped that an intensive research and development within the whole chain of textile technology will continually help medical professionals, especially phlebologists, to obtain a useful and powerful tool in healing different leg venous diseases. Already in the year 2040 the number of people over 60 years, in which venous diseases are very frequent, will amount to 40 % of the entire population. (In 1980 only 22 % of Europeans belonged to this age group) [51]. That is the reason, together with contemporary life styles, why compression bandages

will be very valuable to phlebologists in the coming years of 21<sup>st</sup> century, as they were over past and recent years. Close cooperation of medical professionals, physicians, surgeons, microbiologists, physiologists and textile scientists and specialists is of paramount importance for further achievement of new practical solutions in the sector of venous insufficiency. Also, the increasing life expectancy of the population as well as the challenges resulting from these developments, impose the necessity of medical sector to cope with problems arising from new technologies.

## ACKNOWLEDGEMENTS

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