15

Polyester and nylon based textiles in biomedical engineering

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15.1 Introduction

One of the most innovative and growing aspects of the textile industry is the field of medicine, healthcare and hygiene. The extent of the growth of this domain is due to constant improvements and recent innovations in both textile technology and medical procedures. The first recorded use of fibres in medicine was mentioned in 'Surgical Papyrus' 4000 years ago. In the 'Susanta Sambita' of Indian Literature, written approximately 2500 years ago, a variety of materials including horse hair, leather strips and cotton are mentioned. With the passage of time, textiles have found their way into a variety of medical applications. In addition to protective medical apparel, textiles in fibre and fabric form are used as implants, filters and surgical dressings. Recent decades have witnessed major developments in medical textile production, the materials they are made of, and the technology used to produce them. Textile materials and products that have been engineered to meet particular needs are suitable for any medical and surgical application where a combination of strength, flexibility, and sometimes moisture and air permeability are required. Materials used include monofilament and multifilament yarns, woven, knitted, nonwoven fabrics, and composite structures. The numbers of applications are huge and diverse, ranging from a single thread suture to the complex composite structures for bone replacement, and from the simple cleaning wipe to the advanced barrier fabrics used in operating theaters [1]. Table 15.1 summarizes the main type of textile structures used for various healthcare and medical devices, including implants.

Medical textiles account for a huge market owing to the widespread need for them, not only in hospital, hygiene and healthcare sectors but also in hotels and other environments where hygiene is required. There has been a sharp increase in the use of natural as well as synthetic fibres in producing various medical products. The world medical devices market is represented by the Global Harmonization Task Force (GHTF). The GHTF

Table 15.1 Fabric structure used in various healthcare and medical devices [2]

Fabric structure	Uses
Woven	Gauze dressings, compression bandages, plasters, scaffolds, vascular prostheses, surgical gowns, drapes and hospital textiles such as sheets, blankets, pillowcases, uniform and operating room textiles, implants, knee supports and braces
Nonwoven	Surgical gowns, caps and masks, absorbent layers, fleeces, wipes, protective clothing, diapers, feminine hygiene products, incontinence products, wound dressings, scaffolds, implants, and antidecubitus fleece
Knitted	Compression bandages, vascular prostheses, stents, heart, valves, ligaments and tendons, surgical hosiery, blankets, wound dressings, stockings, elasticated net garments, pressure garments, finger bandages, flat bandages and spacer materials for knee braces, implants, nets and hammocks
Crochet	Compression bandages for compression therapy, cast cloth for orthopaedic casting bandages, wound dressings, bandages and implants
Embroidery	Implants
Braided	Sutures, soft tissue ligaments and implants
Composite materials	Diapers, feminine hygiene, incontinence products, wound dressings, scaffolds, implants and support systems for treatment of pressure ulcers

comprises representatives from five founding members (European Union, United States, Canada, Australia, and Japan). On the basis of DRA's (David Rigby Associates) research, over 1.5 million tonnes of textile materials, with a value of US$ 5.4 bn, were consumed worldwide in the manufacture of medical and hygiene products in 2000. This is predicted to increase in volume terms by 4.5% per annum to 2010 to reach 2.4 million tonnes with a value of US$8.2 bn [3, 4]. The aim of this chapter is to highlight the applications of textiles in medical and applied healthcare sectors.

15.2 Textiles for biomedicine

15.2.1 Scaffolds for tissue engineering

Transplant surgery is the leading therapy to treat the patients suffering from organ failure or tissue loss. In 2001 in the United States alone, despite

24 076 lifesaving organ transplants, 6439 people died waiting for a transplant, leaving 84 798 registrations on the waiting list for an organ at the end of the year [5]. It is clear that organ transplant alone is not a viable solution to treating organ failure and tissue loss. There is a useful overview of the use of biotextile scaffolds for tissue engineering applications, demonstrating how polymer chemistry, fibre science, textile technology and engineering were integrating to make significant contributions to novel designs [6]. It was back in the 1980s that Professor D. F. Williams of the University of Liverpool, UK, first defined the term biomaterial as a nonviable material used in the fabrication of a medical device and intended to react with biological systems [7]. Following the same line of thinking, the term biotextiles was defined as a structure composed of textile fibres and designed for use in specific biological environment (e.g. surgical implants), where its performance depends on its interactions with cells and biological fluids as measured in terms of its biocompatibility and biostability [8]. Table 15.2 [9] is a partial list of some of the most common implant applications of textiles. It has been generally accepted that healing occurs more rapidly if an inert biomaterial is used which the body can tolerate more readily. Biomedical implants are used to aid or replace damaged tissues or organs. These materials are used in effecting repair to the body whether it is wound closure (sutures) or replacement surgery (vascular grafts, artificial ligaments, etc.) [10].

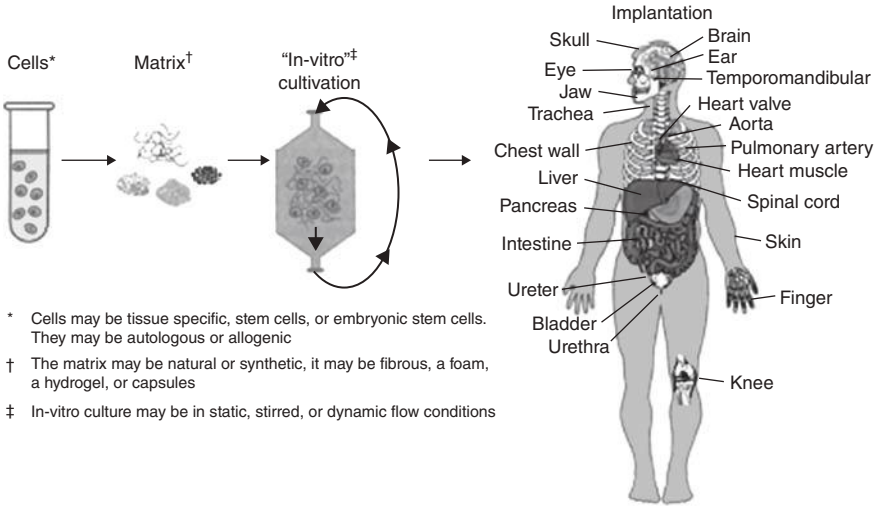
Tissue engineering may be defined as the applications of the principles and methods of engineering and lifesciences towards fundamental understanding of the structure function relationship in normal and pathological mammalian tissues, and the development of biological substitutes for the repair and regeneration of tissue and organ function [11, 12]. This work was pioneered by Langer and Vacanti in the early 1990s who summarized progress with matrices, cells, *in vitro* bioreactor systems, and the generation of devices with their own vascular supply (Figure 15.1). The strategy of tissue engineering generally involves the following steps:

(a) An appropriate cell source must be identified, isolated, and produced in sufficient numbers.
(b) An appropriate biocompatible material that can be used as a cell substrate (open system) or cell-encapsulation material (closed system) must be isolated or synthesized and manufactured into the desired shape and dimensions.
(c) The cells must be uniformly seeded onto or into the material and grown in a bioreactor.
(d) The engineered structure is placed into the appropriate *in vivo* site. Depending on the site and the structure, vascularization may be necessary [13].

Table 15.2 Implant applications of textile structures [9]

Application	Materials	Textile structures [monofilament (m), yarn (y), woven (w), braided (b), knitted (k), and nonwoven (n)]
Abdominal wall	Polyester	w
Blood vessel (vascular graft)	Polyester, polytetrafluoroethylene (PTFE), polyurethane	w, k
Bone plant	Carbon, PGA	y, w, b, k
Cartilage	Low density polyethylene, polyester, PTFE, carbon	w, b
Dental bridge	Ultrahighmolecular weight polyethylene (UHMWPE), carbon, glass, aramid	w, n
Dental post	Carbon, glass	y, b
Dural substitute	Polyester, PTFE, polyurethane, collagen	n, w, k
Heart valve (sewing ring)	Polyester	k, w
Intervertebral disc	Polyester, PTFE	w, k
Intramedullary rod	Carbon, glass	y, b
Joint	Polyester, carbon, UHMWPE	w, k
Ligament	Polyester, carbon, glass, aramid	b, w, k
Orthodontic arch wire	Glass	y, b
Skin	Chitin	n, w, k
Spine rod	Carbon	y, b
Suture	Polyester, PTFE, polyamide, polypropylene, polyethylene, collagen, polylactic acid (PLA), polyglycolic acid (PGA)	m, y, b
Tendon	Polyester, PTFE, polyamide, polyethylene, silk	b, w, y

Systems have been designed to be either open or totally integrated into the recipient, or closed (encapsulated) to provide protection from the host's immune system. Tissue-engineered devices can also use controlled drug-delivery methods to release growth factors that may augment angiogenesis or aid in new tissue generation [14–16]. A critical step of all tissue engineering techniques is the use of a tridimensional structure which, mimicking the extracellular matrix (ECM), serves as scaffold which is able to promote and guide actively the tissue regeneration process. The ability of the scaffold in releasing signalling molecules, such as growth factors (GFs), in a



15.1 Tissue engineering process [14].

controlled fashion is critical to achieve a successful tissue development and repair [17]. Hence, there has been a multitude of research work carried out in the last decade to design and develop various types of optimum scaffolds for tissue engineering (Table 15.3).

Scaffolds play a central role in tissue engineering [18, 19]. Textile structures are particularly attractive to tissue engineering because of their ability to tailor a broad spectrum of scaffolds with a wide range of properties. Textiles are interesting for biodegradable tissue engineering scaffolds. The cellular components will generate new tissue through production of an extracellular matrix, while the scaffold material provides structural integrity and mechanical stability during this process. Scaffold structure and porosity are key elements that will govern the formation of new tissue and subsequent neovascularization *in vivo*. There is a need for structural biocompatibility of the scaffold and the host tissue [18]. The optimum design of a scaffold for a specific tissue application requires consideration of microstructural, chemical and biological aspects. It is often difficult to isolate these aspects as they are interdependent and sometimes their effects are unknown.

Microstructural aspect

The microstructural aspect of scaffolds includes pore size, porosity, pore size distribution, pore connectivity and reproducibility of pores. These aspects are vital, as they provide the optimal spatial and nutritional conditions for the cells, and determine the successful integration of the natural

Table 15.3 Various scaffolds used in tissue engineering [9]

Tissue engineered biological substitute	Scaffold material	Scaffold structures [yarn (y), woven (w), braided (b), knitted (k), and nonwoven (n)]
Bladder	PGA	Textile (n)
Blood vessel	Polyester (Dacron), polyurethane, ePTFE, PGA, PLA, PGLA (Vicryl)	Textile (n, w, b, k)
	Collagen	Textile (k)
Bone	PGA, PLGA + hydroxyapatite fibres PLLA	Textile (n), Foam
Cartilage	PGA, PLLA, PGLA	Foam Textile (n)
Dental	DL-PLA, PGLA (Vicryl)	Foam (porous membrane), Textile (n)
Heart valve	PGA	Textile (n, w)
Tendon	PGA	Textile (n, y)
Ligament	Collagen PGA, PLAGA	Textile (y) Textile (b, n)
Liver	PGA, PLA, PGLA, polyorthoesters, polyanhydride	Foam, Textile (n)
	PLGA	3D Printed
Nerve	Collagen-glycosaminoglycan, PGA	Foam, Textile (n)
Skin	PGA, PGLA (Vicryl), Nylon Collagen-glycosaminoglycan	Textile (w) Foam

Note: PLAGA, PGLA, PLGA are copolymers of polyglycolic acid (PGA) and polylactic acid (PLA).

tissue and the scaffold. For example, Zeltinger *et al.* [20] studied the influence of two key scaffold design parameters, void fraction (VF) and pore size, on the attachment, growth, and extracellular matrix deposition by several cell types on disc shaped, porous L-PLA scaffolds with two VF (75% and 90%) and four pore size distributions (<38, 38–63, 63–106, and 106–150 μm). DmFb (canine dermal fibroblasts), VSMC (vascular smooth muscle cells), and MVEC (microvascular epithelial cells) showed uniform seeding on scaffolds with 90% VF for each pore size, in contrast to the

corresponding 75% VF scaffolds. Culture data from scaffolds with a 75% VF suggests that the structural features were unsuitable for tissue formation. Hence, there were limits of acceptable scaffold architecture (VF, pore size) that modulated *in vitro* cellular responses. Table 15.4 compares the various microstructural aspects of foams and textile structures.

Lee *et al.* [21] investigated the effect of interconnectivity of pores on cell attachment and proliferation as well as surface properties of PLGA scaffold for skin tissue engineering. The interconnectivity of pores determines the transport of nutrients and waste and thus influences the success of tissue engineering [22]. The reproducibility of scaffolds is also very important as it determines the dimensional stability of the scaffold as well as the consistency of tissue formation. In a typical textile scaffold, three levels of porosity can be achieved. The arrangement of fibres in the yarn determines the accessible space for cells. The inter-fibre space (or groove between two adjacent fibres) may be considered as the first level of porosity. It has been found that the fibroblasts preferentially organize themselves along the length of the PET fibres, grouping along the groove created by two adjacent fibres. It is interesting to see that fibroblasts are capable of bridging fibres which are as far as 40 μm apart. The inter-fibre gap or first level of porosity in a textile scaffold can be controlled by changing the number of fibres in the yarn and also the yarn packing density. Further variations in porosity can be achieved by using twisted, untwisted, textured, untextured, continuous or spun yarns.

The gap or open space between the yarns (it is open space inside the loop in the case of knits) forms the second level of porosity. In the case of knitted scaffolds, the porosity can be varied selectively by changing the stitch density and the stitch pattern. In the case of braided scaffolds, porosity can be varied by controlling the bias angle of the interlacing yarns. For woven scaffolds, it is possible to change the porosity by controlling the inter-yarn gaps through a beating action. During the seeding on woven, braided and knitted scaffolds with hepatocytes, it has been observed that the cells attach preferentially at the inter-yarn gaps or pores in woven and braided scaffolds, whereas they clump together on the ridges of curved yarns in the case of knitted scaffolds.

It may be noted that woven and braided scaffolds share similar surface topographies formed by the interlacing yarns. Knitted scaffolds, however, comprise curved yarns, which have a significant effect on the behaviour of hepatocytes. Unlike hepatocytes, the fibroblasts attach to the ridges of yarns irrespective of the scaffold type. The different behaviour of fibroblasts and hepatocytes may be due to their different cell sizes and shapes. It may be noted that the diameter of fibroblasts ranges from 10 μm to 20 μm, and they flatten out after attachment. The hepatocytes are larger with diameters in the range 15 μm to 30 μm, and they retain their spherical

Table 15.4 Microstructural aspects of scaffolds [9]

Fabrication	Foam/sponge	Nonwoven	Woven	Braided	Knitted
Pore size (μm)	0.5–500	10–1000	0.5–1000	0.5–1000	50–1000
Porosity (%)	0–90	40–95	30–90	30–90	40–95
Pore distribution	Random to uniform	Random	Uniform	Uniform	Uniform
Reproducibility of porosity	Poor to good	Poor	Excellent	Excellent	Good to excellent
Pore connectivity	Good	Good	Excellent	Excellent	Excellent
Processability	Good	Good	Excellent	Excellent	Good
Other comments	Current techniques are associated with processing undesirable residues such as solvents, salt particles	Equipment cost is high. Control over porosity is always questionable	Shapes are limited	Limited to tubular or uniform cross-sectional shapes	Limited by the low bending properties of current biodegradable fibres

structure even after attachment to the scaffold. Furthermore, a third kind of porosity can be introduced by subjecting the textile structures to secondary operations such as crimping, folding, rolling, stacking, etc. In other words, it may be stated that the flexibility of microstructural parameters is tremendous in the case of textile scaffolds [9].

Mechanical aspect

The mechanical aspect of scaffolds, such as structural stability, stiffness and strength, have considerable influence on cellular activity. For example, in tissues like bone, cell shape is influenced by mechanical forces. Cell shape modification takes place as a result of external forces including gravity, and also of internal physical forces. Cell shape modification also depends on the nature (constant or cyclic), type (uniaxial, biaxial, multiaxial, etc.) and magnitude of the mechanical stimulation. Mechanical stimulation also affects the release of soluble signalling factors and the deposition of extracellular matrix constituents [9, 23]. Researchers are making use of these observations in the case of bone tissue engineering. They are applying external mechanical stimulation to promote tissue formation [22, 24]. Therefore, in bone tissue engineering, the scaffolds are designed to withstand severe physiological loads [24]. In blood vessel applications, the scaffold needs to be strong enough to withstand physiologically relevant pulsatile pressures and at the same time match the compliance or elasticity values of a native blood vessel [25, 26]. The mechanical aspects of various scaffolds are compared in Table 15.5. Of all the scaffolds, knits display considerable deformability and good compliance owing to their looped yarn arrangement. Hence, they are suitable for bladder [27, 28] and blood vessel tissue engineering applications [29].

Biological aspect

There is increasing evidence that scaffold surface chemistry influences cellular activity. The surfaces with amine groups are best for the CHO (Chinese hamster ovary) cell adhesion, spreading and growth probably owing to the positively chargeable character in an aqueous cell culture medium; a large portion of cell or serum protein surface is recognized as being negatively charged, resulting in electrostatic interaction between the surfaces. For surfaces with neutral functional groups; hydroxyl groups showed better cell spreading than amide groups, probably due to specific hydrogen bonding between the surface hydroxyl groups of the polymer and the polar groups of the cell surfaces. So the surface with COOH group showed poor cell adhesion due to the presence of negative charge [30]. Boyan *et al.* [31] showed that osteoblast response varies with the material

Table 15.5 Mechanical aspects of the scaffolds [9]

Fabrication	Foam/sponge	Nonwoven	Woven	Braided	Knitted
Stiffness	Low	Low	High	High	Medium
Strength	Low	Low	High	High	Low
Structural stability	Good	Poor to good	Excellent	Excellent	Poor to good
Drapeability	Poor	Good	Poor	Poor	Excellent
Other comments	Isotropic behaviour	Isotropic behaviour	Anisotropic, with good properties parallel to fibres and poor properties normal to fibres	Anisotropic, with good properties in axial direction and poor properties in transverse direction	The behaviour can be tailored from isotropic to anisotropic

on which cells are cultured, and attributed this to differences in the surface chemistry, charge density and net polarity of the charge. Van Wachem *et al.* [32] investigated the *in vitro* interaction of human endothelial cells (HEC) and polymers with different wetabilities in a culture medium containing serum. Optimal adhesion occurred onto moderately wetable polymers.

Modification of synthetic polymeric scaffolds by natural polymers (components of extracellular matrix (ECM)) like collagen [33–36], gelatin [2, 37], fibronectin [38], laminin [39] improve their biological behaviour. Since these biopolymers belong to animal origin, so they are not antigenic and immunogenic, and they have high affinity for cell adhesion and their proliferation due to presence of specific peptide sequence. So, the combination of various factors, such as scaffold material, structure, physical, chemical, mechanical, and biological properties, cell types, *in vitro* or *in vivo* conditions, etc., determines the success of tissue engineering.

Fabric structure and design aspect

Textile fibres, yarns, fabrics, composites and 3-D shaped fabrics from woven, knitted, nonwoven, braided and embroidery processes play a vital role in the manufacture of various implants, including the replacement of diseased or non-functioning blood vessels and segments of the aorta or other big arteries. It is even feasible to produce vascular prostheses as fine as 2 to 3 mm in diameter [10].

Woven

The first commercial prostheses were woven on two sets of yarn that had a high fabric count. This provided a type of graft which was rigid, tightly woven, and had a low permeability, therefore bleeding is reduced [40]. Risbud *et al.* [41] reported cell growth on the scaffolds consists of a woven PET fabric with well defined macropores and coated with biodegradable chitosan-collagen membrane. Both collagen and chitosan are shown as suitable substrates for hepatocyte attachment, growth and differentiation. The degradable polymer membrane could create a concentration and pressure gradient on two sides of the membrane that will vary with the diffusion and perfusion properties of the scaffold with degradation. Karamuk *et al.* [42] coated the woven PET fabric on one side with a thin biodegradable film (PLGA), in order to obtain a polar structure for developing the scaffold for liver cell culture. The development of a composite structure ensures the stability of the membrane during *in vitro* degradation, independent of the mesh size. Similarly, Dacron fabric may absorb cyclodextrin

(CD) which has been observed to show optimum behaviour as vascular grafts [43].

Nonwoven

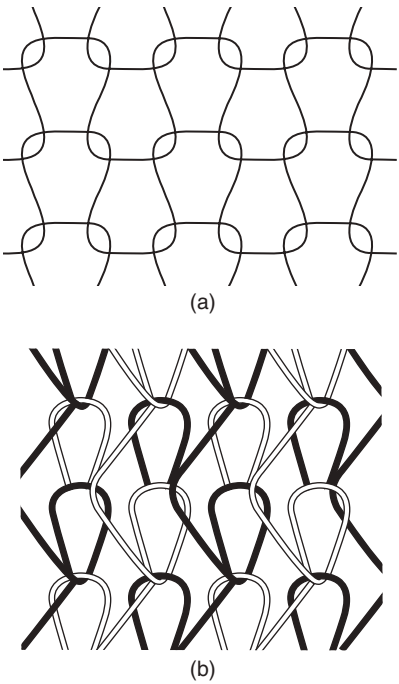
Nonwovens are open porous, three dimensional structures in which the cells can proliferate and be supplied with nutrient solution. This is an important advantage, as the surface, on which cells can grow, is very large in relation to the amount of biomaterial implanted. Nonwovens have fibrous characteristics similar to collagen which are not shared with non-textile materials. Spun bonded nonwovens are generally made by applying bonding agents or molten adhesives. These processing aids reduce pore size (but highly porous, 96% pre-volume), change surface properties and often render nonwoven nonbiocompatible. Staple fibre nonwovens are the fibres cut online and carded, laid down on a conveyor belt, strengthened by calendaring, and finally needled. But the major disadvantage associated with this is shrinkage after implantation in patients because the fibres cannot be fully oriented by online drawing resulting in incomplete crystallization. An advantage of the staple fibre nonwoven process is the possibility of mixing fibres with different resorption rates, such as resorbable with non-resorbable fibres. Microfibre fleeces are small tubular prosthesis. Porosity is less (70%) than spun bounded nonwovens, but pore size can be large (up to 300 μm). Solvent spun microfibre fleeces are small calibre vascular prostheses. Pore size can be extremely small (1 μm) but porosity is also low (60%) [44].

The novel nonwoven PLGA structures produced by the electrospinning process have been developed for tissue engineering applications. The electrospun structure with 500 to 800 nm diameter features a morphologic similarity to the extracellular matrix (ECM) of a natural tissue, which acts to support and guide cell growth [45]. Cells on such surfaces are sensitive to topography. Electrospinning can be altered to influence either the surface topography of the fibres themselves or the larger topography of the web of spun fibres [46]. For example, a change in the chain conformation in nylon 6 and nylon 12 due to electrospinning occurs, implying that a high stress is induced on the electrospinning jet as the fibres are being formed, and this stress alters the chain conformation of the nylon backbone [47]. Ma *et al.* [48] had also prepared polyethylene terephthalate nanofibre mats (PET NFM) by electrospinning for blood vessel engineering. The electrospun PET NFM was first treated in formaldehyde to yield hydroxyl groups on the surface, followed by the grafting polymerization of methacrylic acid (MAA) initiated by Ce(IV). Finally, the PMAA-grafted PET NFM was grafted with gelatin using water-soluble carbodiimide as coupling agent. The gelatin grafting method can obviously improve the spreading and proliferation of

the ECs on the PET NFM, and moreover, can preserve the EC's phenotype. A bilayered tubular scaffold composed of a stiff and oriented PLA outside fibrous layer and a pliable and randomly oriented PCL fibrous inner layer (PLA/PCL) was fabricated for blood vessel tissue engineering by sequential multilayer electrospinning (ME). The resulting scaffolds achieved the desirable levels of pliability (elastic up to 10% stain) and proved to be capable of promoting cell growth and proliferation [49]. Nonwoven scaffolds based on the PET, PGA and PLA have been developed for tissue engineering of the anterior cruciate ligament and cartilage [50, 51].

Knitted

In this type of fabric, the yarn used is enveloped around each other in two directions, warp knit (lengthwise) and weft knit (transversely) (Figure 15.2 [18]). The difference between both is that the weft-knit fabric loosens and the warp-knit does not. This type of construction provides more pores in the centre of loops of the knitted yarn than the woven fabrics. The knitted prostheses can also elongate thereby affecting its dimensional stability. The knitted polyester vascular prosthesis has become the standard vascular



15.2 Knitted polyester vascular graft structure: (a) weft knitting; (b) warp knitting [18].

graft for replacement of arterial vessels of 6 mm and greater. The knitted structure, by its nature, is porous, which is what is required for incorporation by tissue ingrowth from the host [2]. A major problem of arterial grafts (as with other vascular grafts) is the induction of clotting by the graft's surface. To circumvent this problem, grafts are usually clotted with the patient's own blood before implantation to reduce seepage through the knitted structure. Pre-clotting has been found useful in delaying or preventing thrombosis [2]. Branched hybrid vascular prostheses have also been developed on the base of type I collagen with minimal reinforcement by a knitted fabric mesh made of segmented polyester.

Embroidery

Embroidery is generally defined as the decoration of woven or knitted textile fabrics or other surfaces, e.g. leather, through the application of threads or other decorative objects (beads, cords, applications), by sewing them in or on, in an arrangement designed to achieve a pattern on the ground fabric [52]. What was until recently unthinkable has now come about: medicine has discovered embroidery. This is particularly advantageous with relatively small motifs. As opposed to weaving, where threads are arranged at rigid angles, embroidery also enables rounded patterns. Additionally, made-up embroidery goods are dimensionally stable – unlike knitted fabrics. This technology allows implants to be constructed in such a way that embroidered, three-dimensional structures become functional in tissue engineering [52]. Hernia patches, implants for intervertebral disc repair and a graft stent for the repair of aortic aneurysm have been designed by Ellies and coworkers [53].

In the development of medical textiles, polyester is frequently used. If specialized biocompatible materials are used, they are brought in at a later, more advanced stage of development, due to their high cost (up to US$4000/kg). Various synthetic or natural polymer fibres feature very specific structural and mechanical properties, favoured by tissue engineering as bone, cartilage or skin replacements [10]. Karamuk *et al.* [54] carried out tests with embroidered materials that decompose inside the body. These were threads made of polyglycolic acid (PGA). In vitro tests showed that forces in embroidery goods can be controlled by embroidery technology; in this way, the mechanical properties of the textile can be adapted to those of the body tissue, and inflammatory reactions can be avoided.

Braided

A braid exhibits a locking angle, i.e., an angle between the carrier bundles of the braid which when reached prevents the individual carrier bundles

from moving independently of each other thus resulting in a dramatic increase in stiffness. The scissoring effect of an opening and closing braid can damage ingrowing tissue. Braids are not the ideal structure for tissue engineering where there is expected to be regular loading and un-loading of the developing tissue [56]. Plain tubular braids may be used as prostheses for the replacement of injured ligaments in joints, like the human knee joint [57, 58]. The simple reciprocal relation of braiding position to pick counts allows an easy determination of the limits of the braiding machine on the design and manufacturing of braids. This is important for the calculation of the stress-strain behaviour of the prosthesis, which should be adapted to the individual situation within the joint as well as to the intended implantation position [57]. Irsale *et al.* [58] focused on prototype manufacturing of polymeric stents. The prototype is an integrated braided and tubular narrow woven fabric assembly.

The braided structure manufactured with polyester monofilaments acts as the reinforcing component, and the tubular narrow woven fabric tightly covering it acts as the sealing component. Prototypes of bifurcated braided stent for abdominal aortic aneurysm applications are also manufactured with braiding of polyester monofilaments [58].

Composite materials

Textile composites are produced by impregnating matrix materials into their dry preforms to hold the multidirectional yarns together. This is generally done by liquid moulding techniques such as resin transfer moulding, structural reaction injection moulding, and resin film infusion. For example, Peltola *et al.* [59] prepared a composite from P(L/DL)LA by the sol-gel method. Fibres having active surface properties or suitable porous structure can be used as such or as a bioactive part in composites. Braided fabrics can be used in textile composites e.g. bone plates [60]. The integral structures of braided textile composites enable them to endure twisting, shearing and impact better than do woven or knitted fabrics. Due to their higher impact resistance/tolerance and stability or conformability under tension in the braided yarn system, the braided fabrics can be designed for multidirectional conformity [61]. Branched hybrid vascular prostheses have been developed on the base of type I collagen with minimal reinforcement by a knitted fabric mesh made of segmented polyester. The inner diameter was prepared by pouring a cold mixed solution of bovine smooth muscle cells and collagen into a corresponding tubular mould and by subsequent thermal gelatination, followed by seven-day culturing. Reinforcement with an elastomeric mesh improved mechanical strength of the hybrid tissue and created compliance matching with native arteries. A branched or bifurcated hybrid graft with mesh reinforcement is expected to be

applicable to arterial replacement in a branching region [62]. Huang *et al.* [63] evaluated the mechanical properties of the multilayered knitted fabric-reinforced composite laminates. These understandings are believed to be useful in the design of composite structures. Moutos *et al.* [64] presented a micro-scale 3D weaving technique to generate anisotropic 3D woven structures as the basis for novel composite scaffolds that are consolidated with a chrondocyte-hydrogel mixture into cartilage tissue constructs. Other biomedical applications of textile reinforced composites are dentistry and orthopaedics [65].

Surface activation for bifunctionalization of scaffold

Textile materials offer the possibility to combine compliance and porosity in scaffolds for organ reconstruction where it can support the three dimensional growth of cells to produce functional tissue [27]. Scaffolds have also been made from extracellular protein matrix components, such as collagen, laminin or fibronectin. These materials show excellent cell adhesion, biodegrability and biocompatibility but suffer from the disadvantage that they cannot be freely or reproducibly processed into stable objects with three dimensional shapes of good mechanical strength. Conversly, scaffolds made from thermoplastic polymers have excellent strength and ductility and can be processed into various shapes and products, but do not have surfaces that readily interact with cells. These textile surfaces therefore need to be modified in such a way that the surface acquires chemical functionality that may attract extracellular matrix proteins and later cells [27]. The surface modifications of synthetic polymers are necessary to make them bioreceptive. Various researchers worked on surface modification of different types of biomaterials used for various purposes. Commonly techniques used for surface modifications are as follows.

Grafting process

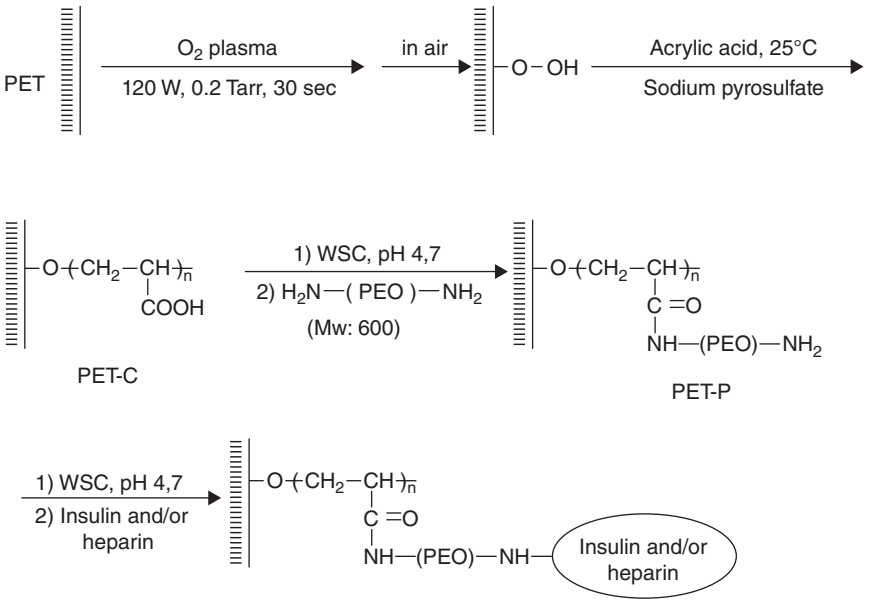
Grafting technology has long been known in polymer chemistry, but the modification of the polymer surface by grafting is a fairly new technology. Two methods are available for the grafting of a polymer surface: coupling reaction of existing polymer chains; and graft polymerization of monomers on to a preexisting polymer.

Plasma induced grafting on polyester

When polymeric materials are exposed to plasma, radicals are created in the polymeric chains. These radicals can initiate reactions when they are in contact with monomers in a liquid or gaseous phase. Inelastic collisions

of electrons in plasma with a polymer surface generate radicals at the surface of a polymer through excitation of the polymer molecules. As a result, a grafted chain is formed on the surface of the polymeric material. The grafted surfaces may provide active sites for the binding of protein molecules. For instance, the poly (acrylic acid) grafted PET surface may be immobilized with collagen by a dip coating process [27, 33]. The collagen immobilized surface provides an excellent surface for the growth of smooth muscle cells. Cells adhere on the surface and grow rapidly. In an another study, Bisson *et al.* [37] proposed a scaffold model for bladder reconstruction by plasma induced graft polymerization of acrylic acid on PET films which subsequently allowed collagen (Type I and Type III) immobilization and human smooth muscle cell expansion.

PAA-grafted PET films, onto which serum proteins of the culture medium adsorbed spontaneously, proved to be better matrices than films on which collagen has been immobilized. Insulin and heparin co-immobilized PET (PET-I-H) was also prepared by grafting of polyethylene oxide (PEO) onto PET-AA followed by reaction first with insulin then with heparin (Figure 15.3) [66]. Hsu *et al.* [67] prepared lactide grafted



15.3 Schematic diagram showing the immobilization of insulin and/or heparin on PETs [66].

polyurethanes by exposing the polyurethane films to argon plasma discharge, followed by grafting L-lactide onto the plasma treated surface. The grafted surfaces showed enhanced attachment and growth in both 3T3 fibroblast and human umbilical vein endothelial cell culture tests. L-lactide monomers grafted onto polyurethane substrates could therefore be useful in facilitating the endothelial cell seeding process in small vascular applications.

Radiation grafting on polyester

The material surface may be designed to exhibit a desired physico-chemical nature by selection of monomer and grafting procedure. While gamma radiation [68, 69] induced grafting leads to modification of both the surface and the bulk, UV, ozone, and plasma modification only affect the surface leaving the bulk intact. PET surfaces prepared by grafting using these techniques have for instance been evaluated as biomaterials for artificial hair transplants [70] and for the immobilization of biomolecules such as heparin and insulin [66]. Knitted PET fabric has been modified by radiation induced graft polymerization of methacrylic acid (MAAc)/*N*-vinylpyrrolidone (NVP) monomer. The influence of reaction conditions on the degree of grafting and the physical structure of the grafted fabric was investigated in this study. The grafted surfaces have also been evaluated for collagen immobilization and for seeding of urothelial cells with the ultimate aim of using this for applications in urology. Jou *et al.* [71] also grafted acrylic acid (AA) on PET fibre by a radiation method. The resulting fibres were further grafted with chitosan (CS) via esterification followed by collagen (COL) by gluteraldehyde (GA). The results indicate that by grafting with CS and immobilizing with COL, PET fibres exhibited both antibacterial activity against pathological bacteria and improvement in the proliferation of fibroblast.

15.2.2 Sutures

Sutures are probably the largest group of devices implanted in humans and can be used in skin, muscle, fat, organs and vessels. Although they seem to be of small concern to the medical community, few devices have been made of so many different materials. The suture market currently exceeds US$1.3 bn annually. By definition: a suture is a thread that either approximates and maintains tissues until the natural healing process has provided a sufficient level of wound strength or compresses blood vessels in order to stop bleeding [72]. The United States Pharmacopoeia (USP), European Pharmacopoeia (EP) and British Pharmacopoeia (BP) are the official compendia for the suture industry, which sets standards and guidelines for

Table 15.6 Suture sizes

P	Diameter	Tensile strength
4-0	0.2 mm	7.5 N
3-0	0.3 mm	12.3 N
2-0	0.35 mm	19.6 N
0	0.4 mm	22.3 N
1	0.5 mm	37.3 N

Table 15.7 Performance comparison of various suture materials [75]

Sutures	Tensile strength	Tissue reactivity	Handling	Knot security	Memory
Nylon, monofilament	High	Low	Poor	Poor	High
Nylon, braided	High	Moderate	Good	Fair	Fair
Polyester	High	Moderate	Good	Good	Fair
Polyglycolic acid	Good	Low	Fair	Good	Low
Polyglycolide-lactide	Good	Low	Good	Fair	Low
Polycaprolactone	Good	Low	Poor	Poor	High

suture manufacture. Suture sizes are given by a number-representing diameter ranging in descending order from 10 to 1 and then 1–0 to 12–0, 10 being the largest and 12–0 being the smallest at a diameter smaller than a human hair [73]. Table 15.6 shows the suture sizes.

Properties of sutures

The ideal suture is strong, handles easily and forms secure knots. It is important that the suture causes minimal tissue inflammation and does not promote infection. It should be able to stretch, accommodate wound oedema and recoil to its original length with wound contraction. It should also be inexpensive. Since no single suture possesses all of these features, it is the physician's task to weigh the advantages and disadvantages of the available suture materials [74]. The comparative information on the performance of various sutures is summarized in Table 15.7.

Knot strength

It is a measure of the amount of force necessary to cause a knot to slip and is directly related to the coefficient of friction of a given material [76].

Bayraktar *et al.* [77] investigated the knot performance of various sutures and observed that knot performance depends on the surface properties. For a braided structure, the coefficient of friction is higher because the threads in the braids have mobility, which increases the knot holding capacity. Therefore, there is no knot untying before the break for the braided structures. Monofilament sutures however have very smooth surfaces, which allow them to pass easily through the tissue. At the same time, it decreases the knot holding capacity.

Elasticity

This refers to the intrinsic tension generated in a material after stretching, which causes it to return to its original length. Elasticity is a desirable feature, since it allows the suture to expand during wound oedema without causing strangulation or cutting of tissue, and to recoil during wound retraction, thereby maintaining wound edge apposition [74].

Memory

This refers to the inherent tendency of a suture material to return to its original shape after being manipulated and is a reflection of its stiffness. A suture with a high degree of memory is stiffer, more difficult to handle and more likely to become untied compared with suture material that has less memory.

Tissue reactivity

This refers to the inflammatory response generated by the presence of suture material in the wound. This response peaks within two to seven days and is a function of the quantity of material present as well as its type and configuration [76, 78, 79] Everett's [80] studies have shown that an excessive inflammmatory reaction may lead to the softening of surrounding tissues and result in decrease in wound strength. It was also observed that nylon and polyester sutures produce the strongest inflammatory reaction during the first five days. Sutures of superior tensile strength and knot security not only minimize the risk of suture line disruption but also reduce the amount of foreign material left in the wound by allowing the use of finer sutures and fewer knots. This, in turn, reduces tissue reaction and infectious complications [74]. Because of the various features, the choice of suture material for any given wound closure should not be made arbitrarily, but rather with careful attention to the physical and handling properties of the suture, as well as its propensity for eliciting tissue reaction and promoting infection [74].

Classification of sutures

Sutures can also be classified into two categories: absorbable and nonabsorbable. The application of the two categories depends on the type of procedure and the physician's preference. Table 15.8 shows the absorbable and non-absorbable sutures [81].

Absorbable sutures

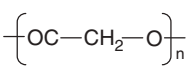
Absorbable sutures have ability to be 'absorbed' or decomposed by the natural reaction of the body to foreign substances. They are used internally and are designed to lose strength gradually over time by chemical reactions such as hydrolysis. It is important to note that not all absorbable sutures have the same resistance level to absorption, but each can be formulated or treated in order to obtain a desired decomposition rate and be excreted in urine or faeces, or carbon dioxide in expired air [82–84]. Currently, the most commonly used absorbable sutures are synthetic substances: polyglycolic acid and polyglactic acid.

Nonabsorbable sutures

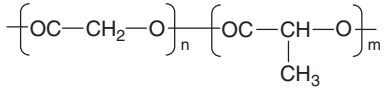
Nonabsorbable sutures are those, which do not lose their tensile strength for a long period of time. Generally, these sutures are used for closing cutaneous or oral incisions where the sutures can be easily removed e.g. nylon, braided polyester.

Polyglycolic acid suture

Introduced in 1970, polyglycolic acid (Dexon) (Figure 15.4), a polymer of glycolic acid, was the first synthetic absorbable suture. It was hailed for its excellent tensile strength and knot strength, as well as delayed absorption and markedly diminished tissue reactivity compared with catgut. In animal studies, the absorption of polyglycolic acid suture was found to be about 40% after seven days [85]. By 15 days, it has lost more than 80% of its original strength [86, 87]. By 28 days, this material retains only 5% of its original tensile strength, and it is completely dissolved by 90 to 120 days [88]. Polyglycolic acid is absorbed by hydrolysis, reducing the inflammatory response. As a monofilament, Dexon is stiff and difficult to work with. Therefore, it is available in braided form for easier handling. Dexon also



15.4 Polyglycolic acid.



15.5 Polyglactic acid.

comes with a synthetic coating (Dexon Plus) to facilitate known typing and passage through tissue.

Polyglactic acid suture

Polyglactic acid (Vicryl) (Figure 15.5), the second synthetic sulture material to be marketed (in 1974), is a copolymer of lactide and glycolide, manufactured with a coating composed of polyglactin 370 and calcium stearate. This lubricant coating gives Vicryl excellent handling and smooth typing properties. Technical studies have shown Dexon to have slightly greater tensile and knot strength than Vicryl [89], but the differences are clinically insignificant. Like Dexon, Vicryl material retains only 8% of its original tensile strength by 28 days. However, complete absorption of Vicryl is more rapid, occurring between 60 and 90 days [87]. Like all synthetic polyesters, Vicryl degrades by hydrolysis and causes minimal tissue reaction. Vicryl is a braided suture, and comes in violet-dyed and undyed forms. When used in skin surgery, the dyed form can sometimes be seen beneath the skin surface. A buried Vicryl or Dexon suture may occasionally be extruded through the suture line.

Polyamides

Polycapramide (nylon 6) and polyhexamethylene adipamide (nylon 66) are the preferred polyamides. The other homopolymers, such as polyhexamethylene sebacamide (nylon 610), polydodecanamide (nylon 12) and polyhexamethylene isophthalamide (nylon 61), and copolymers and blends can be used. The polyamides used to make the sutures have a high molecular weight of 48000–55000. The tensile strength of the sutures varies between 132 KPSI to 145 KPSI. The sutures can be used as monofilaments or made into braided multifilament [90–93]. As a monofilament, nylon (Ethilon, Dermalon) is the most widely used non-absorbable suture in skin surgery. It has high tensile strength, minimal tissue reactivity, excellent elastic properties and low cost. The major drawback to nylon is its high degree of memory. A greater number of knot throws (three or four) are required to hold a given stitch in place.

Nylon hydrolyzes at a slow rate. Studies in rabbits have shown that buried nylon retains 89% of its tensile strength at one year and 72% by two years

[94]. At this point, degradation apparently stabilizes; Nylon sutures retain approximately two-thirds their original strength after 11 years [95]. Thus, nylon should not be classified as a true nonabsorbable suture but rather as a very slowly absorbable suture.

Polyester suture

Braided sutures are generally obtained by using a circular braiding machine. The number of yarns composing the braid depends on the required diameter of the suture [96]. Polyester yarns were made from filaments having a weight-average molecular weight of more than 35 000, a tenacity of about 7–8.5 g/denier, an elongation to break of less than 35% and shrinkage of about 0.5–2% in boiling water. The filament should have shrinkage in hot air at 3–5% (compared with its original length). The commercially available filaments meeting these requirements include Trevira High Tenacity type 712 and 787 polyester yarns from Hoechst. The polyester yarns are made up of such filaments having a denier preferably in the range 1.4–3.1. The polyester filaments are extruded in bundles (yarns) having a denier preferably of 20–350. The yarns are twisted and then braided into sutures using conventional constructions that have a sheath and, optionally, a core. However, in order to provide the best combination of suture properties, the sutures may be braided using the preferred constructions shown in Table 15.8.

The braided suture can be hot-stretched at a temperature of 160–250°C to 9–28% of its original length. The suture may also be coated with a material such as 0.1–10 wt% polybutylate, which is applied using a suspension drop coating system [97]. Braided polyester sutures are often used in cardiovascular surgery where a strong, non-absorbable suture is needed to help permanently repair tissue. However, surgeons have complained of suture roughness, which can sometimes make it difficult to secure a knot. The application of a lubricious coating can reduce suture roughness, but

Table 15.8 Preferred constructions for a braided polyester suture [97, 98]

Suture size	Sheath yarns	Carriers	Core denier	Picks
2	90–150	12–18	380–500	40–50
1	55–90	14–18	310–360	40–50
0	60–80	14–18	180–250	40–50
2/0	45–65	14–18	80–140	40–50
3/0	35–55	10–14	40–50	40–50
4/0	35–55	6–10	–	40–50

too much coating can make the suture slippery to handle and can result in tied knots coming undone.

Developments in sutures

The concept of utilizing a suture as drug delivery system has been a subject of great interest in modern surgery. The delivery of antimicrobial agents near the wound closure coupled with slow release ability results in a remarkable improvement in the healing process. Sutures themselves have very little or no intrinsic biological activity, but when associated with antimicrobial agents, the entire complex molecule behaves as a germicide reservoir to prevent proliferation of a microorganism. A variety of antimicrobial agents are known which can inhibit the growth and metabolism of microorganisms. These antimicrobial agents can be bonded to the polymeric backbone either reversibly or irreversibly and are subsequently released to the surrounding medium and inhibit the growth of microbes.

Antimicrobial sutures

Microbes are the tiniest creatures not seen by the naked eye. They include a variety of microorganisms like bacteria, fungi, algae and viruses. In the majority of polymeric implants and intravenous catheters, Staphylococci play a predominant role. Staphylococci is the most frequently implicated microorganism in infection occurring in the drainage system of cerebrospinal fluid [99, 100], in venous catheters and sutures [101], in continuous ambulatory catheters [102], in heart valves [103] and in hip as well as knee prostheses [104]. Negative effect on the vitality of the microorganisms is generally referred to as antimicrobial. Antimicrobial agents are the chemical compounds that possess the ability to kill or inhibit the growth and metabolism of microbes thus preventing proliferation and subsequent infection [105, 106].

These can be broadly classified into two classes:

Class I: Those useful in treatment of disease e.g. antibiotics. Antibiotics are defined as specific chemical compounds formed by living organisms that are capable of inhibiting life processes of other organisms when used in small quantity (Table 15.9).

Class II: Those useful in prevention and control of diseases e.g. disinfectant and antiseptic. By convention, chemical agents, which are used to destroy microbes on inanimate objects, are disinfectants, while those applied on living tissues, especially wounds, are antiseptics (Table 15.10).

Table 15.9 Class 1 compounds and their mode of action

Chemical agents	Mechanism of action
Penicillin, Cephalosporin	Inhibition of bacterial cell wall and cell membrane synthesis
Amphotericin B, Nystatin	Disruption of bacterial cell wall
Sulphonamides, Nitrofuran, Ketoconazole, Miconazole	Inhibition of bacterial metabolism
Griseofulvin	Inhibition of nucleic acid synthesis
Nlidixic acid, Norfloxacin, Ciprofloxacin	Inhibition of DNA synthesis
Rifamycin, Rifampicion, Actinomycin D, Ethidium bromide, α-Amanitin	Inhibition of RNA synthesis
Streptomycin, Tetracycline hydrochloride, Kanamycin, Doxycyclin, Chloramphenicol, Amikacin	Inhibition of protein synthesis

Table 15.10 Class 2 compounds with their mode of action

Chemical agents	Mechanism of action
Phenol and phenolic compounds	Disruption of plasma membrane, denaturation, inactivation of enzyme
Chlorhexidine	Disruption of plasma membrane
Halogens	Iodine inhibits protein function and is a strong oxidizing agent, chlorine forms the strong oxidizing agent hypochlorous acid, which alters cellular components
Alcohols	Denaturation of lipids
Heavy metals and their salts	Denaturation of enzymes and other essential proteins
Surface active agents soaps and detergents	Mechanical removal of microbes through scrubbing
Anionic detergents	Not certain; may be involved in enzyme inactivation or disruption
Quaternary compounds	Enzyme inhibition, protein denaturation and disruption of plasma membrane
Organic acids	Metabolic inhibition, mostly affecting moulds
Aldehydes	Protein inactivation
Oxidizing agents	Oxidation
Gaseous sterlants	Denaturation

Preparation of antimicrobial sutures

The antimicrobial activity in sutures can be achieved by the following methods:

1. Blending or incorporation of volatile or nonvolatile antimicrobial agent while processing

2. Coating or absorption of the antimicrobial agent onto the filament
3. Graft polymerization followed by immobilization of antimicrobial agents onto the grafted surface.

Incorporation of bioactive agents including antimicrobial agents into polymers by blending has been commercially applied in surgical implants and other biomedical devices. This is a pretreatment technology, where the antimicrobial agent is introduced during the processing stages. For this, the additive characteristics have to be compatible with blending conditions, e.g. particle diameter, heat stability, chemical stability and effect on fibre quality [107].

Heavy metals, such as gold, silver and copper have also been used to introduce antimicrobial activity in suture [108–116]. Allard and Song [117] described another type of system in which polymer and active agent are mixed and melt together and then melt spun to a diameter greater than 1 mm. Different polymer matrix being used are polyethylene, polyester, polyglycolic acid and polylactic acid. Yabushita *et al.* [118] patented surgical suture with strong tensile strength. High density polyethylene and chlorohexidine hydrochloride were mixed, extruded and drawn to give monofilament with antimicrobial activity against *Staphylococcus aureus (S. aureus)*. Of all antimicrobials, silver substituted zeolites are the most widely used to impart antimicrobial activity in polymers [119–120]. Zeolites are mainly composed of an aluminosilicate framework of alkali earth metal. Framework contains regular cavities occupied by Na^{+}, k^{+}, Ca^{2+}, Mg^{2+}, etc. These cations are easily exchangeable by other metals like Ag^{+}, Cu^{2+} and Zn^{2+} to impart antimicrobial activity against general bacteria. These substituted zeolites are incorporated into polyesters at the level of 1–3% [121]. These metal ions inhibit the multiplication of microorganisms by two mechanisms [122]. It destroys or passes through the cell membranes and makes a bond with thiol group of cellular enzymes. As a result, it leads to alteration of the microbial metabolism and suppression of growth of microorganism. In second possible mechanism, the formation of active oxygen occurs, where these metal ions catalysed the formation of oxygen radicals that destroys the molecular structure of bacteria.

PVP-Iodine (PVP-I) complex is also one of the most widely used products in the sphere of surgery. The slow release of free iodine from the complex gives prolonged antimicrobial activity from the doped material. Antimicrobial nylon sutures have been prepared by blending of nylon 6 with PVP-I complex using a melt spinning process [123]. Depending upon the blend ratio, a pre-weighed quantity of chips was added to the saturated solution of the PVP-I complex and these chips were then spun and drawn at the temperature to obtain a monofilament with good strength. The

sutures have polar bonding between nylon and PVP-I complex, which results in the slow and controlled release of iodine from the sutures. Alternatively, silver may be used as an effective antimicrobial agent, e.g. a blend of nylon fibre and silver coated nylon fibre (known as X-static) may be used for suture application [113]. This fibre exhibits bactericidal property against *E. coli*, pseudomonas, klebsiella, staphylococcus and streptococcus species. The rate of killing (decrease of survival) increased with increase in silver ion concentration of the fibre extract, as determined through atomic absorption spectrometry.

In the post-processing technology, the most common technique for applying the antibacterial agent is coating. Antimicrobial agents that cannot tolerate the temperature used in polymer processing are often coated onto the material after fabrication. The antimicrobial agents are linked to the surface through physical bonds or anchored by the cross-linking on the fibre. Antimicrobial sutures having long lasting antimicrobial properties and good physical properties are prepared by coating a multifilament suture with a solution of an antimicrobial agent and segmented urethane polymer. Stephenson [124] coated polyester sutures with copolymer of polyquaternary polyurethane and polyanionic polymer such as heparin followed by treatment with antimicrobial agent streptomycin sulphate. The resultant antimicrobial suture gave a zone of inhibition of 0.55 cm against *Bacillus subtilis*. Antimicrobial coating on polyester suture was carried out by depositing an antimicrobial biocompatible metal by vapour deposition technique [125]. In one of the studies, it was found that immersing catgut, Dacron, silk, or chromic sutures for 24 h in a 5% or 50% aqueous solution of silver nitrate did not appreciably reduce adherence of *S. aureus*, as compared with that of unsoaked sutures [126]. Dacron and silk suture coated with a silver-zinc-allantoin complex did, however, reduce the number of adherent *S. aureus* colonies by 88% and 99%, respectively. The investigators attributed the differences in *in vitro* efficacies of the differently coated sutures to the fact that silver nitrate firmly binds to the suture material, whereas the silver-zinc-allantoin complex provides slow release of silver ions sufficient to inhibit bacterial adherence [127].

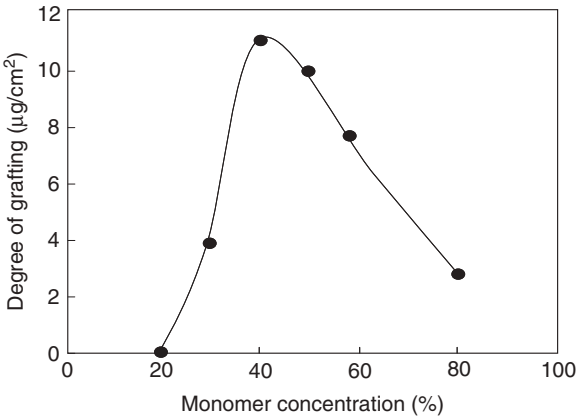
Blacker *et al.* [128] used silver doped bioactive glass powder (AgBr) to coat absorbable Vicryl and non-absorbable Mersilk surgical suture. Stable homogeneous coating on the surface of the suture was achieved by using an optimized aqueous slurry dipping technique. The *in vitro* bioactivity of the suture was tested by immersion in simulated body fluid (SBF). After three days of immersion in SBF, bone-like hydroxyapatite formed on the coated suture indicating the enhanced bioactive behaviour. *In vitro* antimicrobial evaluation of polyglactin 910 suture coated with triclosan has shown attractive results. The antibacterial activity of the coated suture was

evaluated against *S. aureus* and *S. epidermis* and produced zones of inhibition after five and ten passes through fascia and subcutaneous tissue. Knotted suture with triclosan gives a bacteria-free zone having volume of 14.5 cm^3 for *S. epidermis* and 17.8 cm^3 for *S. aureus* [129].

Iodine can be attached to polyamide sutures to provide them antimicrobial property. Antimicrobial nylon suture has been prepared by coating the monofilament with iodine [130]. Nylon 6 monofilament was treated with iodine by immersing the filament in a saturated solution of iodine in acetone and was tested for iodine release and antimicrobial properties against *E. coli* and *S. aureus* by zone of inhibition method. It was found that it showed a comparatively slower release of iodine as compared to blended suture since in coated suture iodine is present mainly on the surface so initial release is higher, then it decreases. It was also observed that a clear zone of inhibition was formed around 6 mm in the case of *E. coli* and 8 mm in the case of *S. aureus*.

Multifilament nylon suture has been made antibacterial by doping with iodine [131]. Iodine doped sutures exhibited good antibacterial activity against *E.coli, S. aureus, P. aeruginosa* and *K. pneumomea*. The surface of the polyamide sutures has also been modified by binding of drug doxycycline [132]. The modified suture showed the release of drug into and around the wound over 10–18 days. Lin *et al.* [133] reported that nylon 66 fibres could be rendered antimicrobial by chemical binding of heterocyclic *N*-halamine functional groups to the nylon 66 molecules at the amide nitrogen, using formaldehyde as a linking agent followed by chlorination. Biocidal swatch tests showed that the nylon fabrics containing *N*-chlorinated hydantoin functional groups provided a 7.2 log reduction of *S. aureus* and 7.1 log reduction of *E. coli* at contact time of only 10 min, whereas unchlorinated fibres gave no reduction of bacteria even at a contact time of 71 s.

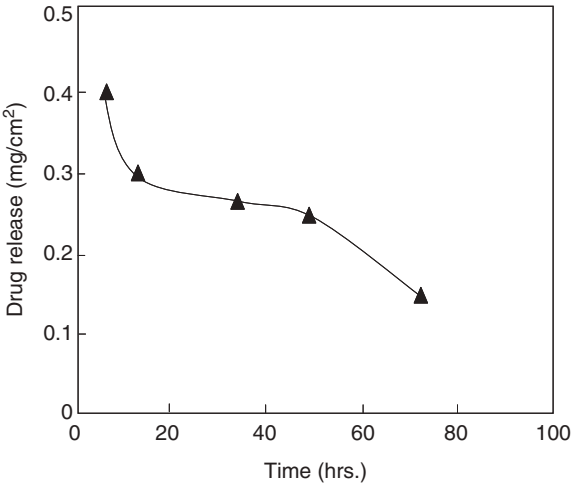
The radiation, plasma and chemical methods of grafting have occupied the attention of numerous researchers for many years [134–136]. Graft polymerization offers an effective approach to introduce desirable properties into the polymers without affecting the architecture of the polymer backbone [137, 138]. Grafting of hydrophilic monomers provides a good platform for the introduction of antimicrobial activity. The grafted side chains contain functional groups to which various bioactive materials can be attached. These functional groups include amine, carboxylic acid and hydroxyl groups, which can be utilized further for the attachment on antimicrobial drug [139, 140]. This approach of graft functionalization has been successfully used for the development of polypropylene sutures by incorporating acrylonitrile and vinylimidazole grafts into the suture matrix [141–145]. Both tetracycline hydrochloride and ciprofloxacin have been immobilized onto the modified sutures and their effectiveness against dif-



15.6 Variation of degree of grafting with monomer concentration [146].

ferent microbes has been evaluated. An antimicrobial polyester suture is prepared by graft modification of the filament in such a way that the filament retains its physical properties and attains its antimicrobial nature. In a recent study [146] the antimicrobial polyester suture was prepared by graft polymerization of acrylic acid on the surface of the suture; in order to keep the bulk unaltered grafting was carried out by using vacuum plasma. As a result, the polyester surface acquires functionality of carboxyl group while the bulk remains unaltered. It has been observed that the monomer concentration plays a crucial role in graft management and a maximum in grafting is achieved at a monomer concentration of 40% (Figure 15.6). The acrylic acid grafted surface offers excellent functionality for the interaction with chitosan molecules which is an attractive route to produce antimicrobial suture material. The chitosan coated sutures were loaded with ciprofloxacin as the antimicrobial drug. This loading helps in the enhancement of the antimicrobial nature of the suture and hence provides better healing process. Ciprofloxacin has been observed to be released slowly from the suture and continued up to 3–4 days (Figure 15.7). This is interesting from the point of view of drug availability at the wound site till the suture is removed in 4–5 days.

Antimicrobial nylon sutures have also been developed by the graft polymerization of acrylic acid on a nylon 6 suture followed by immobilization of the antibiotics [147]. Penicillin (Pe), neomycin (Ne) or gentamycin (Ge) have been used to obtain antibacterial properties against gram-positive and gram-negative bacteria by zone of inhibition method. The release of antibiotic from the grafted suture proceeds in two stages: (I) rapid release lasts up to 1 day, which is due to absorption of drug onto the surface; (II) sustained release, lasts up to 12 days, which is due to



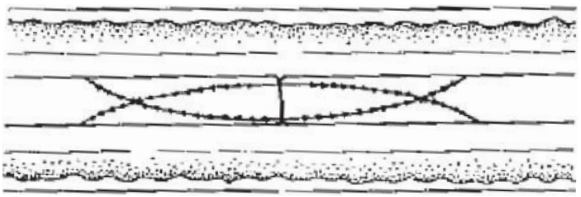
15.7 Amount of drug release with time [146].

hydrolysis. Similarly, the modification of PET suture by grafting with acrylic acid followed by attachment of antibiotics penicillin, neomycin or gentamycin has also been developed. It was found that the release of penicillin from PET fibre was much faster than other biocides [148].

Barbed sutures

In 1992, Dr Gregory Ruff of Duke University Medical Center started working on an idea of a barbed suture for cosmetic applications. Dr Ruff took the idea of a barbed suture and applied it to an absorbable suture material made of polydioxanone. The advantage of using an absorbable polymer suture is that it does not need to be removed and it does not require knots to make it secure. The knotless design has significant potential in reducing scar tissue due to the absence of a significant foreign-body reaction caused by knots. The barbed configuration anchors the suture into the tissue and provides adequate tissue adhesion while the wound heals under minimum residual tension and pressure [149]. The success of this novel wound closure device requires the suture geometry to be well characterized and monitored during manufacture for two reasons: quality control (measuring uniformity of the barb geometry) and the need to determine the effect of tissue holding capacity and the barb geometry. Quill Medical, Inc. currently produces this barbed monofilament suture from polydioxanone in size 0 (size 0 has a diameter of 0.30 to 0.39 nun), while other sizes are under development.

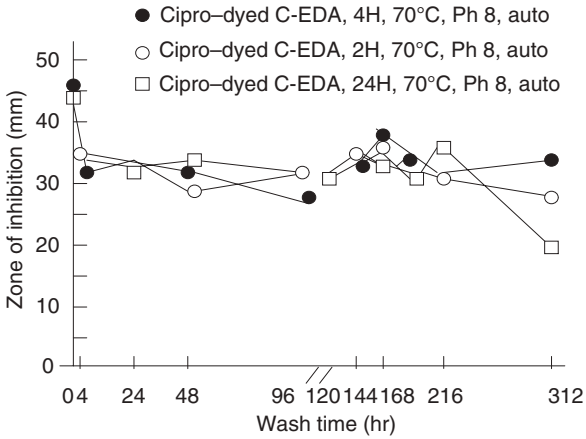
15.8 Bidirectional barbed suture showing mid-point [150].



15.9 Barbed suture in tendon repair application [149].

The monofilament sutures contain up to 78 barbs manufactured in a spiral pattern around the circumference of the suture. The barbs are divided into two groups facing each other in opposing directions around the mid-point (Figure 15.8). The two sets of barbs divide the suture into two sections, right and left. Internal wound closure yields the best results when using an absorbable material. Using nonabsorbable wound closure material requires removal of the device after the wound has healed. This can lead to additional visits to the physician or surgeon and the use of more invasive surgical procedures. The fact that polydioxanone is absorbable makes it an ideal candidate for internal wound closure. Current sutures require the tying of surgical knots. The throws of these knots are often pushed through a transdermal cannula, which can be tedious and difficult for the surgeon as well as resulting in inferior knot performance. The knotless barbed suture can also be applied through a cannula and, without the need for tedious knot throwing and pushing, it is likely to reduce surgery time and create a more consistent method for tissue approximation.

McKenzie's [150] article describes the use of a nylon-barbed suture for repair of the long flexor tendon of the hand (Figure 15.9). The knotless designed suture increases the flexibility and longitudinal movement of the tendon that would normally be limited by the presence of knots. The polymer suture can be engineered to maintain the required strength for the duration of the complete healing process. In addition, the absorbable barbed suture does not require removal after the repair is healed, thus reducing the number of visits to the surgeon as well as the trauma associated with a follow-up intervention.



15.10 Antimicrobial activity of C-EDA segments dyed with Cipro for 2, 4, and 24 h [178].

15.2.3 Wound dressings

Wound management has recently become more complex because of new insights into wound healing and the increasing need to manage complex wounds outside hospital. The wound is a synthetic environment in which numerous cellular processes are interlinked in the process of repair. Modern dressings are designed to facilitate the function of the wound rather than just to cover it. Principles of wound dressings are changing, especially in relation to debridement of wounds and control of the wound environment. Occlusive dressings which allow debridement in a fluid environment are equal to traditional wet or dry dressings. There are some advantages in allowing wounds to heal in a moist environment which facilitates cellular migration and epithelialization. Straightforward surgical and traumatic wounds require low cost and low technology dressings. The place of more costly and complicated wound dressings has to be defined in terms of cost, labour saving and patient comfort, in addition to any putative advantages in the speed of wound healing [151]. Several studies have been carried out to develop wound dressings based on different textile fabrics. However, studies involving nylon and polyesters are very limited.

Smith and Nephew is a world leader in advanced wound care management. They are selling this wound dressing under the brand name Acticoat™. The wound dressing contains silver nanocrystals that kill bacteria *in vitro* in as little as 30 minutes two to five times faster than other forms of silver. The silver nanocrystal wound dressing is gaining rapid worldwide acceptance in burn and wound care centres. Its sale is continuously growing

at double digit rates. The revenue from sales has increased from £1.7 million in 1999 to £6 million in 2003. The product is now being sold in more than 30 countries [152].

Phaneuf *et al.* [153] have developed a novel lightweight bioactive compression wound dressing based on polyester that provides durable infection resistance and localized haemostatic properties. Polyester (Dacron) material with polyurethane inlaid into the structure is utilized as the base material to provide the required physical properties (i.e. elasticity, durability). The surface is modified to develop functional groups. An antibiotic (ciprofloxacin) is incorporated into the material via textile dyeing technology, and a biologically active protein, thrombin, a pivotal enzyme in the blood coagulation cascade, is covalently attached to the modified surface.

15.2.4 Bandages

It should be stressed that one of the high-tech areas of medical textiles is the application of bandages for enhancing the quality of life. In fact, bandaging techniques emanate from ancient practice that facilitates further developments in improving the comfort and performance properties of value added products. Bandages are designed to perform a whole variety of special functions depending upon the type of wound and medical requirements. They can be woven, nonwoven or knitted and are either elastic or non-elastic [1].

Types of bandages

Bandages can be classified in a number of different ways but possibly the most useful method is one based upon their function as follows. The ability of a bandage to perform one or more of these functions is largely determined by its elastic properties, although the thickness, weight and conformability of the fabric are also important. Table 15.11 shows the different types of bandages, their fibre types and fabric structure [1].

Compression bandages

Compression bandages are mainly employed for the treatment of venous leg ulcers and varicose veins. It may be noted that, in the United Kingdom, there are some 400000 leg ulcer sufferers, 70% of whom have ulcers that are venous in origin [154]. The aim of the use of compression bandaging is the reduction of venous hypertension which results from valvular insufficiency [155]. The application of external compression by means of a bandage serves to increase the velocity of the blood flow within the veins

Table 15.11 Different types of bandages, fibre types and fabric structure [1]

Bandage type	Fibre type	Fabric structure
Compression	Cotton, polyamide, elastomeric yarns	Knitted, woven
Orthopaedic	Cotton, viscose, polyester, PP, polyurethane foam	Nonwoven, woven
Adhesive	Cotton, viscose, polyester, PP, glass, plastic film	Woven, nonwoven Knitted
Light support	Cotton, viscose, elastomeric yarns	Woven, nonwoven Knitted
Retention	Cotton, polyamide, elastomeric yarns, viscose	Woven, nonwoven Knitted

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 graduates from the ankle to the knee [156]. Elastomeric bandages made with rubber were first used in the late nineteenth 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 [157]. Compression bandages are mainly classified as elastic and nonelastic. Elastic compression bandages are categorized according to the level of pressure generated on the ankle of an average leg [158].

Light compression bandages are able to provide and maintain low levels of pressure, between 14 and 17 mmHg on an ankle of average dimensions. The clinical indications for products of this type include the management of superficial or early varices, and varicosis formed during pregnancy. In general, they are not suitable for controlling or reducing existing oedema, or for applying even low levels of pressure to very large limbs. Examples include K-Plus – Parema, and Tensolastic. Moderate compression bandages may be used to apply compression between 18 and 24 mmHg on an ankle of average dimensions. They are indicated for the treatment of varicosis during pregnancy, varices of medium severity, the prevention and treatment of ulcers and the control of mild oedema. High compression bandages may be used to apply high levels of compression between 25 and 35 mm Hg on an ankle of average dimensions. Indications for these bandages include the treatment of gross varices, post-thrombotic venous insufficiency, and the management of leg ulcers and gross oedema in limbs of average circumference. Products in this category are not necessarily able to achieve these levels of pressure on very large limbs that have been further enlarged

by the presence of oedema. Examples include Tensopress, Setopress and Surepress. Extra-high performance compression bandages are capable of applying pressures up to 60 mmHg. The power in the bandages is such that they can be expected to apply and sustain these pressures on even the largest and most oedematous limbs for extended periods. This group includes Elastic Web Bandage BP (Blue Line Webbing) and Varico Bandage [159].

Compression can be exerted to the leg either by a single layer bandage or multilayer bandages. 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.

Studies conducted to assess the relative effectiveness of different compression bandages and compression stockings in the treatment of venous leg ulcers incorporated 27 products manufactured by different companies. The studies included comparisons between compression and no compression; between elastic multilayer high-compression bandages and non-elastic high compression bandages, as well as non-elastic multilayer high-compression bandages; between multilayer high-compression bandages and single-layer high-compression bandages; between alternative multilayer systems; and between compression stockings and compression bandages. It was concluded that compression increases ulcer-healing rates compared with the situation when there is no compression. High compression is more effective than low compression but should only be used in the absence of arterial disease. It is generally accepted that composite bandage systems are most effective when a long-stretch or short-stretch bandage system is used. A comparative study after 15 weeks' treatment of patients with venous ulceration indicated that the ulcer-healing rate for the long-stretch bandage was 58% as compared with 38% for the short-stretch bandage. Similarly, a calcium alginate dressing combined with a four-layer bandage system has been proved to be successful in treating a patient with chronic ulcerations to his upper arm [1].

In another study, it was found that non-occlusive hydrofibre dressings were suitable for the treatment of exudating venous leg ulcers. The hydrofibre-dressing group demonstrated a significantly lower frequency of dressing changes than that with alginate-fibre dressings. More patients achieved a seven-day wear time with the hydrofibre dressing than with alginate-fibre [1].

Orthopaedic bandages

Orthopaedic bandages play a significant role in the successful treatment of venous leg ulcers. A padding of at least 2.5 cm 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 [160]. Padding can also be used to reshape legs that 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 [161].

An ideal orthopaedic bandage should meet the following requirements:

- Light weight
- Soft and impart cushioning effect to the limb
- Capable of preventing tissue damage
- Good absorption and wicking properties
- Should tear easily by hand
- Comfortable and should not produce irritation or any allergic reaction to the skin on prolonged contact.

Commercial padding bandages

The most commonly used commercial padding nonwoven bandages, the fibre types and structures of the bandages are given in Table 15.12.

Table 15.12 Commercial padding bandages [162]

Bandage code	Fibre type	Blend	Structure
PB1	Polyester	100%	Needle punched (one side)
PB 2	Polyester	100%	Needle punched & thermal bonded
PB3	Viscose	100%	Needle punched (one side)
PB 4	Polyester/viscose	40%/60%	Needle punched (one side)
PB 5	Polyester/polyolefin	85%/15%	Needle punched (one side) & thermal bonded
PB 6	Polyester	100%	Needle punched (one side) & thermal bonded
PB 7	Polyester/viscose	50%/50%	Needle punched (one side)
PB8	Polyester	100%	Needle punched (one side)
PB9	Polyester	100%	Needle punched (one side)
PB10	Polyester	100%	Needle punched (one side) & thermal bonded

Table 15.13 Significance of the tests with respect to padding bandage [162]

Test	Property	Desirable
Bulk density	Determines the bulkiness of bandage	An appropriate bulkiness, say 0.05 g/cm^3 which facilitates easy handling, comfort and bony prominences
Tear strength	Determines the behaviour of the bandage from being torn	Must be easy to tear by hand
Absorption and wicking	Determines the absorption wicking and comfort	Must possess good absorption and wicking properties
Pressure transference	Determines the pressure distribution capability of bandage	Capable of absorbing high pressure exerted by compression bandage and distribute the pressure uniformly around the leg

Test methods

- Bulk density (calculated from area density and thickness)
- Tear resistance
- Demand absorption and wicking (using an instrument developed at Bolton Institute).
- British Pharmacopoeia absorption method
- Sinking time
- 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 15.13.

Effect of bulk density

Bulk density determines the bulkiness of bandages. It is important to mention that an appropriate bulkiness, say 0.05 g cm^{-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 15.14 that the bulk density of all the commercial padding bandages are within the acceptable limit and PB1, PB3, PB4, PB7 and PB9 registered higher bulk densities.

Table 15.14 Properties of commercial padding bandages [162]

Bandage code	Bulk density	Impact tear
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	10.05	4240

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 15.14) 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 tear strength of 5000 mN or less, tested by using Elmendorf tear instrument, can be torn easily, by hand.

Relationship between demand absorption and wicking

It is a common practice in hospitals that venous leg ulcers are treated by a combination of wound dressing, under cast padding and compression bandage which are either a two-layer or multi-layer system depending on the severity of ulcers. The highly 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.

It is observed 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 of all the bandages is satisfactory except PB3, PB6, PBS 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 the 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.

It is observed that none of the bandages provide uniform pressure distribution up to 60 mmHg. However PB5, PB6 and PB8 did distribute the applied pressure evenly only up to around 7 mmHg and the efficiency of the even pressure distribution degrades thereafter. It is vital that an ideal padding bandage should dissipate the pressure between 30 and 40 mmHg, exerted by high compression bandage, uniformly around the limb.

Adhesive bandages

An adhesive bandage usually has an absorbent pad (often medicated with antiseptic) covered by woven fabric, plastic, or latex rubber which has an adhesive. The plaster is applied such that the pad covers the wound (but does not stick to the wound), and the fabric or plastic sticks to the surrounding skin to hold the dressing in place and prevent dirt from entering the wound. Some newer plasters also contain woven strands of silver fibre, used to speed healing and minimize scarring. Adhesive bandages are generally applied to provide support rather than compression. The adhesive coating helps to ensure that the bandages do not slip or become displaced. These bandages are commonly used for strapping purposes and to provide support or compression in the treatment of sprains and strains. Diachylon adhesive bandage, more commonly known as Lestreflex, is often used in place of bandages coated with a zinc oxide adhesive where skin sensitivity reactions are present or suspected [163].

Adhesive bandages are characterized by their construction of two basic components, the adhesive coated backing material and the wound covering pad material. While such bandages are effective and desirable products, the assembly of the component materials during production results in increased manufacturing and inventory costs. In addition, the packaging of individual bandages requires additional handling and materials which further increases manufacturing costs. The bandage material is preferably

a heat-bondable, absorbent, nonwoven fabric which provides loft and absorbency in the pad area, while the single thickness wing portions of the bandage and the wrapper portion are heat calendered to provide a dense, sheet-like material. The bandage material is preferably a low density, highly absorbent, thermal bonded nonwoven fabric comprising absorbent fibres and staple length polyester-polyethylene conjugate fibres. These nonwoven fabrics are produced by a process which includes producing a web comprising absorbent fibres and staple length polyester/polyethylene conjugate fibres; subjecting the web to a temperature sufficient to fuse the lower melting component of the conjugate fibres without fusing the higher melting component while maintaining the web under little or no compression; and cooling the web to resolidify the lower melting component of the conjugate fibres, thereby forming a nonwoven fabric bonded at sites where the conjugate fibres touch each other and adjacent absorbent fibres.

A particularly preferred nonwoven fabric is a laminate comprising a core of a mixture of short-length natural cellulose fibres and staple length polyester/polyethylene conjugate fibres, and a lightweight veneer of heat-fusible fibres on each surface of the core. The composite web is passed through a through-air heater to fuse the lower melting component of the conjugate fibres while maintaining the fibrous integrity of these fibres, and to fuse or soften the surfaces of the heat-fusible fibres in the two outer veneers. As the material emerges from the heater and cools, the fused surfaces of the lower melting component of the conjugate fibres, i.e. the polyethylene, solidify, and bonds form where these surfaces touch each other and other fibres. Absorbent fibres employed in such thermal-bonded, nonwoven fabrics include rayon staple fibres, cotton fibres, short length natural cellulose fibres such as wood pulp fibres and cotton linters, and mixtures thereof [163].

Light support bandages

Light support bandages are also called short or minimal stretch bandages. They include the familiar crepe-type products of the British Pharmacopoeia together with numerous ‘non-official’ variations of these bandages, which are manufactured from cotton or cotton and viscose, and which show considerable variability in performance. They are used to prevent the formation of oedema and give support in the management of mild sprains and strains. Compared with the compression bandages, light support or minimal stretch bandages have limited extensibility and elasticity, and tend to ‘lock out’ at relatively low levels of extension. This feature enables them to be applied firmly over a joint to give support without generating significant levels of pressure. Short stretch bandages have also been used for the

treatment of venous leg ulcers. When applied at full extension, they form an inelastic covering to the leg, which tends to resist any change in the geometry of the calf muscle during exercise, thereby increasing surface pressure in a cyclical fashion and enhancing the action of the calf muscle pump [164].

Similarly, when an individual moves from a supine to a standing position or sits with the legs dependent, blood collects in the vessels and sinuses of the lower leg under the influence of gravity, causing the volume of the leg to increase. If this is associated with the formation of oedema, leg volume will increase still further. A short stretch bandage applied at full stretch, with the legs elevated, will tend to resist a change in volume as the legs are placed in a dependent position. This restriction will result in a significant rise in sub-bandage pressure, the degree of which will be determined by whether the subject is sitting or standing. Because short stretch bandages have limited elasticity, they are likely to be less effective than high compression bandages at reducing existing oedema as they lack the ability to 'follow in' as a limb reduces in circumference. They may, however, offer some advantages in the treatment of venous ulcers where a degree of arterial impairment is known or suspected as the low residual pressures will be less likely to compromise arterial inflow. Examples of light support bandages (including short stretch bandages) include Elastocrepe, Leukocrepe, Lenkelast and Comprilan.

Retention bandages

Retention bandages are used to retain dressings or other wound contact materials in position. They should not be used to apply pressure and are therefore totally unsuited for use in the management of leg ulcers or for the control of oedema. A number of different types of retention bandages are available. The first 'retention bandage' was White Open Wove (WOW), a rigid fabric with extremely limited conformability that is available in a range of widths. Because of the poor performance characteristics of WOW two softer more retentive bandages were introduced. These are Kling and Crinx, the cotton bandages of the British Pharmacopoiea. These lightweight cotton products have very little elasticity but are sufficiently extensible to give them a useful degree of conformability.

The ideal retention bandage should have a long shallow extensibility curve so that small changes in limb circumference will not significantly increase sub-bandage pressure, which in any event should not normally exceed a few millimetres of mercury. More recently lightweight woven and knitted bandages have been introduced which contain elastomeric yarns. These bandages, sometimes called 'contour' or 'conforming stretch' bandages, are often cheaper than the original cotton products and are said to

be easier to use. Many different types are available which include Slinky, Stayform, Tensofix, J Form and J Fast [164].

A new film dressing called Omiderm consists of a thin, flexible, transparent membrane of 40 microns thick. It is manufactured from polyurethane which has been chemically modified by the addition of hydrophilic monomers such as acrylamide and hydroxyethyl methacrylate. In the dry state the film is relatively inelastic but when brought into contact with wound exudates or aqueous solutions, it absorbs water and changes its physical properties, becoming highly conformable and elastic. Unlike traditional semi-permeable film dressings such as Opsite, Tegaderm and Bioclusive, Omiderm is not coated with adhesive but nevertheless will adhere to a moist wound without the need for additional fixative agents or sutures. The film is easily removed without causing pain or trauma but if left undisturbed it will separate spontaneously from a healed wound once epithelial cover is achieved. The film itself is highly permeable to moisture vapour, at least 20 times more permeable than the traditional film dressings, and is thus able to cope with the exudates produced from all but the most heavily exuding wounds. Omiderm is also significantly more permeable to oxygen than standard polyurethane film dressings. However the permeability of the film is not limited to water and oxygen. Antimicrobial agents such as silver sulphadiazine, povidone iodine and chlorhexidine gluconate can pass through the film onto the wound beneath if applied to the outer surface of the dressing in the form of a cream or as an aqueous solution absorbed on several layers of gauze. It has been suggested that this technique may be used to administer topical antimicrobial agents to wounds dressed with Omiderm to prevent infection or lower the bacterial count. Omiderm is recommended for the treatment of donor sites, dermabrasions and partial thickness burns and may also be used as a temporary dressing on full thickness wounds at the discretion of the medical officer in charge. It is not currently recommended for use on infected or dirty wounds [165].

15.3 Textiles for hygiene products

An increasing improvement in qualitative standards of human lifestyles has brought a greater sense of comfort and cleanliness. People are more and more looking for fresh public living surroundings and a higher level of hygiene in home areas. A wide class of micro-organisms coexists in a natural equilibrium with human body and living environments, but a rapid and uncontrolled multiplication of microbes can seriously compromise the hygienic and healthy personal standards. Because of their capillary spread in human living spaces, textiles have been involved in this research on improving the quality of hygienic living conditions. Many efforts have been

performed by the textile industry with two goals: the protection of the living environments and the textile fibres from an uncontrolled proliferation of microorganisms like bacteria [166]. Fabric treatments imparting bactericide characteristics are highly desired by apparel, home, furnishing, and medical textiles. However, conventional processes used to impart such characteristics have a major drawback. That is, these effects are not permanent and the properties of the material may be altered. This problem has resulted in research efforts to develop durable treatments.

15.3.1 Antimicrobial textiles

Antimicrobial agents can be applied to the textile substrates by exhaust, pad-dry-cure, coating, spray and foam techniques. The substances can also be applied by directly adding into the fibre spinning dope. It is claimed that the commercial agents can be applied online during dyeing and finishing operations. The fibres derived from synthetic with built-in antimicrobial properties are listed in Table 15.15. We will discuss the following processes: blending, coating, finishing, chemical modification and grafting to improve the antimicrobial property of the polyester.

Blending

Incorporation of bioactive agents including antimicrobial agents into polymers by blending has been commercially applied in surgical implants and other biomedical devices. This is a pretreatment technology, where the antimicrobial agent is introduced during the processing stages. For this, the additive characteristics have to be compatible with blending conditions, e.g. particle diameter, heat stability, chemical stability and effect on fibre quality [166].

Table 15.15 Antimicrobial fibre on the basis of synthetic polymers [167]

Polymer	Company	Brand
Polyester	Trevira, Montefibre, Brilen	Trevira Bioactive, Terital SANIWEAR, Bacterbril
Polyacryl	Accordis, Sterling	Amicor, Biofresh
Polyamide	Kaneba, R-STAT, Nylstar	Livefresh, R-STAT, Meryl Skinlife
Polypropylene	Asota	Asota AM Sanitary
Polyvinyl chloride	Rhovyl	Rhovyl's as Antimicrobial
Regenerated cellulose	Zimmer AG	Sea Cell Activated

Table 15.16 Antimicrobial effect of polyester cloth containing Zeomic [171]

Tested bacteria	Test samples	Number of bacteria per cloth after contact	
		0 hr	6 hr
Escherichia coli	1	3.6×10^5	10 or less
	2	3.6×10^5	6.5×10^4
	Control	3.6×10^5	2.4×10^5
Pseudomonas aeruginosa	1	1.3×10^5	10 or less
	2	1.3×10^5	1.9×10^4
	Control	1.3×10^5	4.8×10^4
MRSA	1	9.8×10^4	10 or less
	2	9.8×10^4	1.1×10^5
	Control	9.8×10^4	1.1×10^5
MRSE	1	1.8×10^4	10 or less
	2	1.8×10^4	8.7×10^3
	Control	1.8×10^4	1.8×10^4
Trichophyton mentagrophytes	1	3.5×10^4	6.9×10^2
	2	3.5×10^4	4.8×10^4
	Control	3.5×10^4	9.6×10^4

Silver–zirconium based antimicrobial agents have also been widely used for imparting long lasting antimicrobial properties [168, 169]. Wash fast antibacterial synthetic fibres like polyester were prepared by mixing metal ion supported inorganic compounds with fibre forming polymers. Polyethylene terephthalate and 2% Ag ion supported zirconium phosphate were melt spun to give antibacterial fibres exhibiting *Pneumonia bacilli* extinction to about 99% and 88% after 10 and 250 washings, respectively [170]. In another method, silver ions containing Zeomic show antimicrobial effects against a wider spectrum of microorganisms including Gram-negative bacteria such as *Escherichia coli* and *Pseudomonas aeruginosa*; Gram-positive bacteria such as *Staphylococcus aureus* and MRSA; and fungi such as *Aspergillus niger* and *Penicillium nigricans* (Table 15.16) [171].

Different bactericides like Cu, Ag, pyridine chloride, ethonium rivanol and kinamycin monosulphate have been used in polyester fibres where Ag and kinamycin monosulphate were observed to be active against gram-positive and gram-negative bacteria [172].

Coating

In post-processing technology, the most common approach for applying the antibacterial agent is the coating. Antimicrobial agents that cannot

tolerate the temperature during polymer processing are often coated onto the material after fabrication. The antimicrobial agents are linked to the surface through physical bonds or anchored by cross-linking on the fibre. Since most of these antimicrobial agents are water soluble, they are weakly anchored onto the fibre surface so that it has to be constantly reapplied [172].

An approach for antimicrobial coating of polyester is by using silk sericin. Silk sericin is a natural macromolecular protein derived from silkworm, *Bombyx mori*. Sericin protein can be cross-linked, copolymerized, and blended with other macromolecular materials, especially artificial polymers, to produce materials with improved properties. The protein is also used as an improving reagent or a coating material for natural and artificial fibres, fabrics, and articles. Polyester fibres have micro-pores of 0.001–10 mm diameter. The sericin molecule can be introduced into these micropores and cross-linked. Sericin-modified polyester fibre is obtained by cross-linking with glyceryl polyglycidyl ether and diethylene triamine. The sericin-modified polyester fibre can be more than five times as hygroscopic as untreated polyesters and more than 85% of initial hygroscopicity remains after 50 washes [173].

Finishing

The following requirements need to be satisfied to obtain maximum benefits out of the finish:

- Durability to washing, dry cleaning and hot pressing
- Selective activity to undesirable microorganisms
- Should not produce harmful effects to the manufacturer, user and the environment
- Compatibility with the chemical processes
- Easy method of application
- No deterioration of fabric quality
- Resistant to body fluids
- Resistant to disinfections/sterilization.

Hydrolyzed PET treated with 10% w/v seed extract (without any cross-linking agent) showed antimicrobial activity of 89% and 32% even after one washing against *Bacillus subtilis* and *Protues vulgaris* respectively. This is may be due to more physical and hydrophobic interaction between the hydrolyzed PET and the neem seed extract. The lesser antimicrobial activity of neem seed extract against gram-negative bacteria is again proved here.

From the Table 15.17, it is observed that antimicrobial activity of 84% has been obtained after one washing using 10% neemazal technical (seed

Table 15.17 Antibacterial activity of neem seed extract (10%) treated PET fabric against *Bacillus subtilis* [174]

Samples	Tested bacteria			
	Temperature (°C)		*Bacillus subtilis*	
	Drying	Curing	Colony forming units (cfu)/ml	Antibacterial activity (%)
Original PET (Control-I)	–	–	335×10^5	–
PET hydrolysed by 20% NaOH (Control-II)	–	–	340×10^5	–
PET hydrolysed by 20% NaOH + C/L (citric acid $NaH_2PO_2H_2O_2$), 1 washed (Control-III)	85	180	300×10^5	10
PET hydrolysed by 20% NaOH + C/L (citric acid $NaH_2PO_2H_2O_2$), 1 washed	85	180	55×10^5	84
PET hydrolysed by 20% NaOH, unwashed	85	–	15×10^5	95.5
PET hydrolysed by 20% NaOH, 1 washed	85	–	$37 \times 10\ 5$	89

extract) along with citric acid as a cross-linking agent. But one remarkable observation was that the fabric becomes yellowish to some extent when using citric acid as crosslinking agent [174]. Table 15.18 shows the bacterial reduction against *S. aureus* after 30 minutes of cultivation. Researchers calculated the average bacterial reductions of each silver size. Average bacterial reductions of silver colloids explain why smaller sized colloidal silver has a better antibacterial efficacy than the others. Accordingly, 11.6 nm sized silver colloids had the best bacteriostasis, 99.9%. The growth of bacterial colonies was absolutely inhibited by only 10 ppm colloidal silver when the mean diameter of silver was 2–5 nm instead of 11.6 nm. Consequently, the smaller particle sizes had better antibacterial effects on silver-padded nonwoven fabrics. Higher concentrations of silver colloids have better bacteriostasis because bacterial reductions decreased when the silver concentrations in the pad bath decreased. These nonwoven fabrics are used for air filters or medical clothes [175].

Table 15.18 Bacterial reductions of nanosilver colloids against *S. aureus* after 30 minutes of cultivation [175]

Concentration ppm	Number of bacterial colonies /ml and % bacterial reduction			
	11.6 nm	30 nm	70 nm	150 nm
70	<10	1.3×10^4	1.5×10^4	1.7×10^4
	99.9%	82.1%	79.4%	77.7%
100	<10	3.0×10^2	1.0×10^3	1.8×10^3
	99.9%	99.6%	98.7%	97.6%
150	<10	1.5×10^3	5.0×10^2	1.6×10^3
	99.9%	98.0%	99.3%	97.8%
Average	99.9%	93.2%	92.5%	91.0%

Chemical treatments

A new class of *N*-halamine polymers has been synthesized. These polymers can be emulsified in water to produce coatings which, once chlorinated, act as contact disinfectants. The term '*N*-halamine' herein signifies a molecule containing a nitrogen–halogen bond prepared by halogenations of an imide, amide or amine [176]. *N*-halamines were proven to be the suitable biocides that could provide desired antibacterial functions without causing much environmental concern [177]. The surfaces inactivate bacterial organisms efficiently, requiring relatively brief contact times of several minutes. The latexes can be formed by copolymerization of an *N*-halamine precursor monomer with other monomers in water with the aid of a surfactant, or by chemically grafting the *N*-halamine precursor monomer onto an emulsified polymer backbone, followed by chlorination. These coatings, once chlorinated, are effective at inactivating both Gram-negative and gram-positive bacterial organisms in relatively short contact times [176].

Antibiotics such as ciprofloxacin (Cipro), a quinolone antibiotic, can be directly incorporated onto the polymer using textile-dyeing technology, resulting in a sustained release of antibiotic over a period of time. Ethylenediamine (EDA) was used to bifunctionalize the Dacron material. Cipro covers a majority of the Gram-positive and negative bacteria that are encountered in a typical biomaterial infection, specifically *Staphylococcus aureus*.

A combination of specific surface characteristics can be incorporated into a single biomaterial. Functional groups are created with woven Dacron (Control) material via exposure to ethylenediamine (C-EDA). The antibiotic ciprofloxacin (Cipro) is then applied to the C-EDA material using

pad/autoclave technique (C-EDA-AB) followed by surface immobilization of the coagulation cascade enzyme thrombin (C-EDA-AB-Thrombin). Antimicrobial activity by the C-EDA-AB surface has been observed to persist for five days compared with control and dipped controls. Thrombin surfaces had very high surface thrombin activity compared to nonspecifically bound thrombin and Cipro-dyed surfaces, respectively. Surface thrombus formation *ex vivo* was evident after 1 min of exposure, with thrombus organization evident by 2.5 min. In contrast, C-EDA-AB and Control segments showed only blood protein adsorption on the fibres [178, 179].

Surface modification

A variety of techniques are useful for chemical modification of polyester surfaces. These techniques include acid etching, X-ray irradiation, ultraviolet irradiation, electron beam bombardment, ozone treatment, and corona discharge and plasma treatments. A variety of polar groups are generated on the polymer surface as a result of these treatments. The generated peroxides and hydroxyl peroxides, in particular, are capable of initiating radical polymerization of vinyl monomers, resulting in surface grafted polymer chains [106].

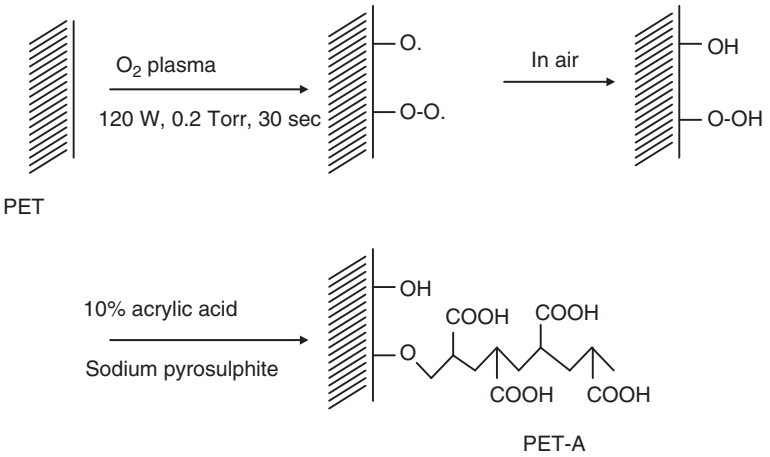
Plasma grafting

As in the case of plasma polymerization, plasma grafting began in the 1960s. In the 1960s and later in the 1970s, grafting experiments were mainly performed with acrylic acid and acrylic amide, preferably on fibres and textiles to enhance their wetability and receptivity for dyes. In the 1980s, especially with the work of Hirotsu, there was an increasing amount of interest in plasma grafting as it is desirable to modify polymers selectively for specific applications without losing much in terms of inherent characteristics [180]. The better the retention of the bulk properties, the more appropriate is the modification approach. In this respect, graft copolymers offer novel materials where the inherent polymer is represented by the backbone and the branches are formed by the grafted monomer with respective functionalities (Table 15.19) [181].

Chitosan possesses a good antibacterial property against various bacteria and fungi through ionic interaction at a cell surface, which eventually kills the cell [182]. PET texture was exposed to oxygen plasma glow discharge to produce peroxides on its surfaces. These peroxides were then used for the polymerization of acrylic acid (AA) in order to prepare a PET with carboxylic acid group (PET-A). Chitosan and quaternized chitosan (QC) were then coupled with the carboxyl groups on the PET-A to obtain

Table 15.19 Functionalities imparted by monomers used in grafting [181]

Monomer used in grafting	Functionality imparted
Acrylic acid	Soil proofing, Antistatic properties, Hydrophilicity
Maleic anhydride	Hydrophilicity Adhesivity
Acrylamide	Antistatic properties
Polyethylene glycols (PEG)	Improving blood compatibility

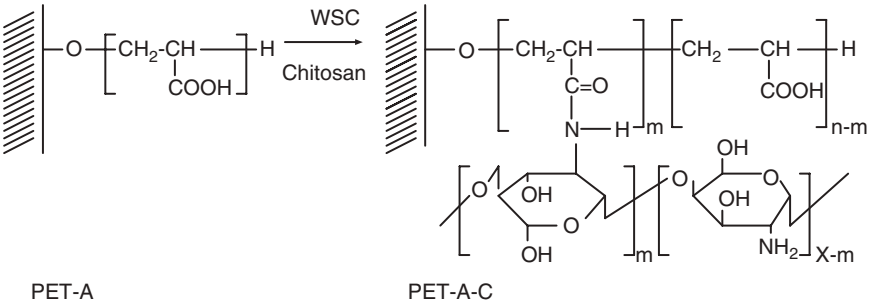


15.11 Oxygen plasma treatment of PET and graft polymerization of acrylic acid (AA) on PET [183].

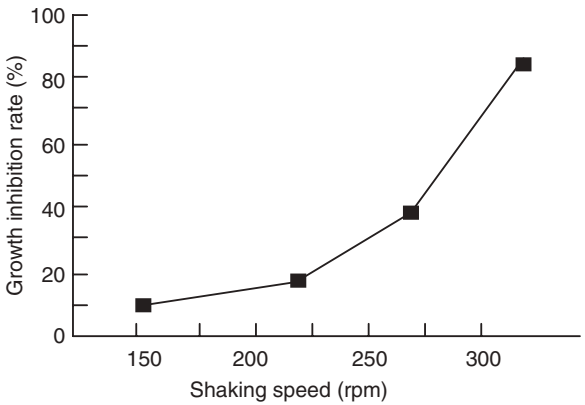
chitosan-grafted PET (PET-A-C) and QC-grafted PET (PET-A-QC), respectively (Figures 15.11 and 15.12).

The growth of *S. aureus* was not much influenced by contact with PET or AA-grafted PET. However, the growth of bacteria was significantly inhibited by contact with chitosan-grafted PET (62% in PET-A^--Cl^+, 39% in PET-A-C, 59% in PET-A-QC). After 6 h of shaking the growth of bacteria was markedly inhibited by PET with ionically (86%) and covalently (75%) grafted chitosan and covalently grafted QC (83%). The PET-A^--Cl^+ (86%) showed higher antibacterial activity than PET-A-C (75%). The high growth inhibition by PET-A-QC seems to be attributed to the quaternary ammonium ions of the grafted chitosan [183].

Nonwoven PET was activated by argon gas plasma. The plasma-activated substrate was immersed in the acrylamide (AAm) solution, which was sealed in a glass tube [184]. The antibacterial nonwoven PET can be

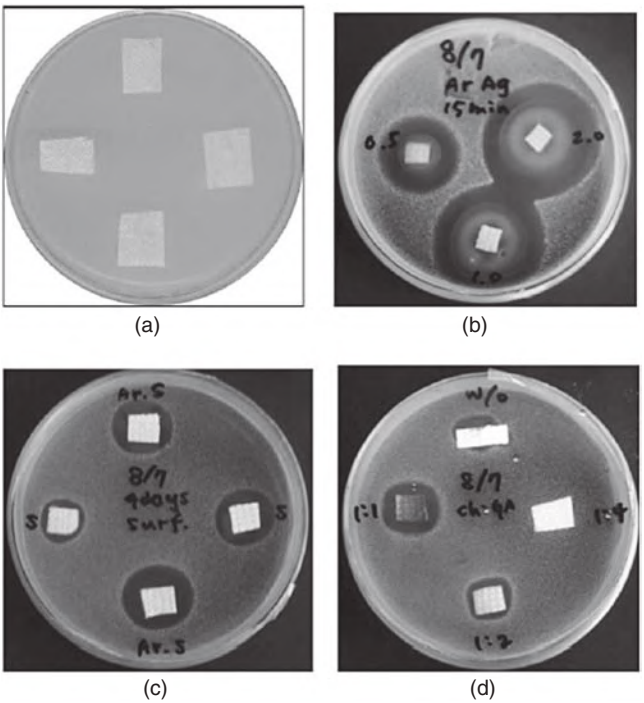


15.12 Schematic diagram showing the formation of chitosan-grafted poly (ethylene terephthalate) (PET-A-C) [183].

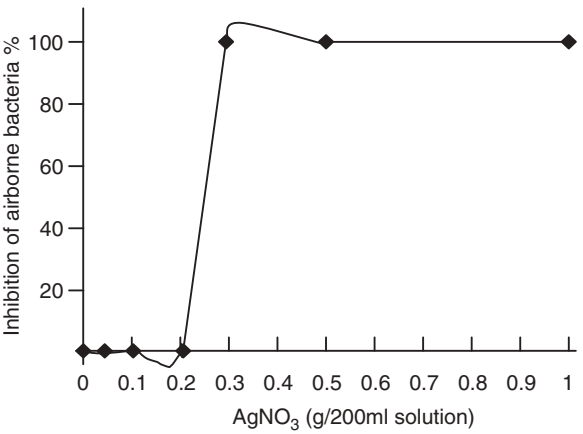


15.13 The effect of the shaking speed on bacteria growth inhibition in a flask [183].

fabricated by the following methods. Method one is performed by immersing the AAm-grafted nonwoven substrate in $AgNO_3$ solution (concentration: 0.034–20.0 wt. %). Method two is to UV graft-polymerize the argon-plasma-activated substrate in the VQAS monomer aqueous solution (concentration: 10, 30, 50 wt. %). Method three is to immobilize the chitosan solution (solvent: 0.1 M acetic acid, chitosan concentration: 2 wt. %) with the glutaradehyde (GA) cross linking agent ($CHO(CH_2)_3CHO$, concentration: 1 wt. % GA/chitosan = 1:1) on the AAm-grafted substrate. The Ag^+ ion treatment exhibits the best biocidal properties for the as-treated specimen shown in Figure 15.14. The preparation of the polyester–polyamide Ag-loaded textiles was carried out by RF-plasma and vacuum-UV (V-UV) surface activation followed by chemical reduction of silver salts. The rate of bacterial inactivation by the silver loaded textile was tested on *Escherichia coli* K-12 and showed long lasting residual effect (Figure 15.15).



15.14 Antibacterial results of PET nonwoven treated by different biocides: (a) original; (b) Ag^+ ions; (c) VQAS; (d) chitosan [184].



15.15 Inhibition of airborne bacterial growth by textile fabrics activated by RF-plasma as a function of the Ag loading [185].

Another approach for antimicrobial activity of nonwoven PET is to treat the plasma activation with argon and the subsequent UV-induced grafting polymerization of *N*-vinyl-2-pyrrolidone (NVP) to modify its surface hydrophilicity (NVP-*g*-PET nonwoven) [186]. The preliminary antibacterial assessment was determined qualitatively from the area from which *S. aureus* had been eradicated. The eradicated area was transparent. In comparison with the as-received nonwoven cloth, these three additive factor treatments improved the antibacterial properties of the PET nonwoven. The untreated PET nonwoven could not be anti-*S. aureus* growth; 28(b–d) could be anti-*S. aureus* growth because NVP integrating an iodine molecule acted as a biocidal agent. The improvement increased with an increase in the grafted amount of NVP on the surface of the PET nonwoven. It is apparent that NVP (additive AP and/or MBAAm) gave the best biocidal results [186].

γ-radiation

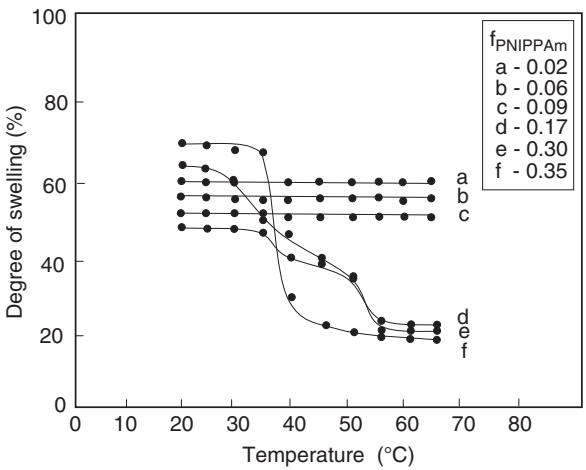
Similar to plasma activation, γ-radiation also produces sufficient activation of the textile materials. Poly (ethylene terephthalate) fibers were treated with ^{60}Co-γ-ray and grafted with acrylic acid (AA), followed by binding with chitosan (CS) *via* esterification. Afterwards, these CS-grafted fibres were immobilized with chondroitin-6-sulphate (ChS). The blood compatibility of PET was reduced by grafting with CS, while improved by immobilizing with ChS. The antibacterial activity of CS against *Staphylococcus aureus*, and *Pseudomonas aeruginosa* was retained after ChS-immobilization. After immobilizing ChS, the L929 fibroblasts cell proliferation was higher than CS-grafting PET fibres. The results indicate that by grafting with CS and immobilizing with ChS, PET fibres exhibit antibacterial activity and also improve the cell proliferation for fibroblast activity [187].

15.4 Intelligent textiles

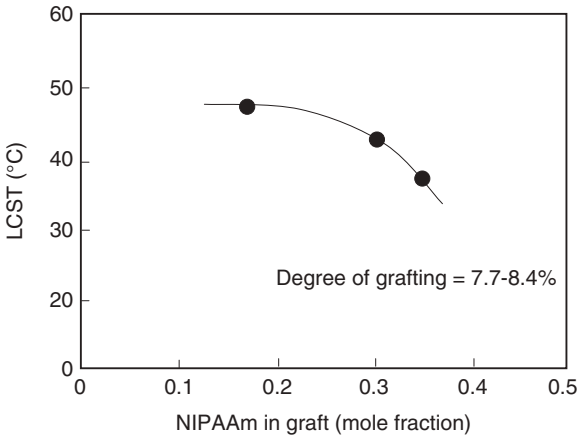
The discovery of shape memory materials in the 1960s and intelligent polymeric gels in the 1970s was generally accepted as the birth of real smart materials. It was not before the late 1990s that intelligent materials were introduced in textiles. The first textile material that, in retroaction, was labelled as a smart textile was silk thread having a shape memory. Smart textiles can be described as textiles that are able to sense stimuli from the environment, to react to them and adapt to them by integration of functionalities in the textile structure. The stimulus as well as the response can have an electrical, thermal, chemical, magnetic or other origin [188].

In a recent report, thermosensitive material was prepared by radiation-induced graft copolymerization of monomers on PET fabrics. A binary mixture of *N*-isopropylacrylamide (NIPAAm) and acrylic acid (AA) was grafted on polyester fabric as a base material to introduce thermosensitive poly (*N*-isopropylacrylamide) chains having LCST close to 37°C in the membrane. The thermosensitive nature of the fabric was monitored by swelling at different temperature. The immobilization of tetracycline hydrochloride one model drug and its release characterictics at different temperatures were monitored.

The temperature sensitivity of equilibrium swelling in grafted samples was examined to determine their temperature dependent swelling and collapse process. No change in the swelling was observed for samples a, b and c since the mole fraction of NIPAAm grafted is very small as compared to AA. As a result, these samples don't have a thermosensitive character. As the NIPAAm content in the copolymer increases, grafted samples start showing phase transition at specific temperatures. The first visible sign of the phase transition is noticed at 0.17 mole fraction of NIPAAm in the grafts. The LCST of the composition was 47.5°C. This temperature is known as lower critical solution temperature (LCST). The LCST of the graft copolymer decreases as mole fraction of NIPAAm increases (Figure 15.16). It is interesting to see that LCST of the fabric reaches 37.5°C for the NIPAAM fraction of 0.35 with grafted component. It may be mentioned that the grafting of pure NIPAAM exhibits LCST of 32.5°C as measured by DSC thermogram [189]. It may be stated that this composition of modified fabric may be useful for the drug delivery applications.



15.16 Variation of the equilibrium swelling with the temperature with degree of grafting (a) 9.6%, (b) 9.2%, (c) 8.6%, (d) 8.4%, (e) 8.4%, and (f) 7.7%.



15.17 Variation of LCST with mole fraction of NiPAAM in graft.

One of the most attractive uses of PNIPAAm based copolymers is as drug carriers in which intelligent properties or auto-adjustables adjust to external temperature changes. It is important and practical to examine the T-HCl release data from the grafted samples having LCST (37.5°C) close to body temperature (37°C). The controlled release of T-HCl from PET fabric at different temperatures 20°C, 33°C and 37.5°C is shown in Figure 15.17. The drug loaded samples swelled at temperatures <LCST and deswelled at 37.5°C, in deionized water. Because the hygrogels shrink at 37.5°C, the T-HCl in the gels will be released due to the driving force of the volume change and concentration gradient of the drug. Hence, the amount released in the initial 10 minutes is highest at 37.5°C. Although at all the temperatures, samples exhibited very similar release profiles, their release rates and extents are different. The cumulative drug release during the 8 h study was 54% at 37.5°C, 14% at 33°C and 5% at 20°C. The observed initial burst release is possibly due to the drugs that were located near the graft copolymer surface. Since the concentration gradient is the driving force for the drug diffusion, a high drug concentration gradient between the copolymer surface and the release medium during the very early stage of contact leads to higher initial burst and fast release rate. Those drugs located near and at the surface could be released immediately from the graft copolymer to the surrounding medium as soon as the sample was placed into the distilled water [190].

A novel method of preparation of easily stripped off temporary wound dressing material is disclosed. In this process, the-N-isopropyl acrylamide (NIPAAm) monomer is successfully grafted on the non-woven polyester fabric by copolymerization. It is initiated by gamma-ray irradiation to activate the surface of the non-woven cloth. NIPAAm is then grafted onto

the surface of the non-woven cloth. The free radical or peroxide is produced by Co-60 gamma-ray, then grafted on the non-woven cloths. The lower critical solution temperature (LCST) in thermoresponsive poly-N-isopropylacrylamide (NIPAAm) is still retained after grafting. This will make the dressing cloth strip off easily without hurting the tissue. The material process is very simple and has medically applicable value [191].

15.5 Conclusion

Textile materials continue to serve an important function in the development of a wide range of medical and surgical products. Medical textiles are the products and constructions used as healthcare systems for example for first aid, clinical, hygiene implants and sutures for the huge medical market. The demands of the biomedical textile market have been growing worldwide at an annual rate of 4.6% because of their innovative features. Textile materials offer porosity and compliance which are often not exerted by other polymeric materials. Textile materials and products that have been engineered to meet particular needs are suitable for any medical and surgical application where a combination of strength, flexibility, and sometimes moisture and air permeability are required. Different forms of textile materials are used which include monofilament and multifilament yarns, woven, knitted, non-woven fabrics, and composite structures. The numbers of applications are huge and diverse, ranging from a single thread suture to the complex composite structures for bone replacement, and from the simple cleaning wipe to the advanced barrier fabrics used in operating theatres. Textile structures are particularly attractive to tissue engineering because of their ability to tailor a broad spectrum of scaffolds with a wide range of properties. There is no universal scaffold that meets the requirements of the various tissues of the human body. Further systematic study is necessary to design an optimal scaffold for each tissue application. Recent advances include the development of polylactic acid and polyglycolic acid fibres as structures for cell growth, temporary bioresorbable textile supports for growing human organic tissue such as bladder reconstruction, tissue engineering of vascular grafts, etc, and the development of smart fibres, based on naturally occurring polymers and also on non-animal-based protein fibres and structures for the treatment of wounds and ulcers.

Surgical implantation of these materials is encountered with both thrombosis and inflammation at the site of injury. These processes are related and both contribute to the healing of tissue into and around the material. Therefore, the main requirement of the textile material is bioreceptivity and biocompatibility at the application site in human beings. For this

requirement, it is necessary to modify the materials before using them in biomedical engineering. The various approaches to develop functional biotextiles are blending, coating, chemical treatments, and graft polymerization for making the surface bioreceptive and biocompatible. The introduction of new materials, the improvement in production techniques and fiber properties, and the use of more accurate and comprehensive testing have all had significant influence on advancing fibres and fabrics for medical applications. As more is understood about medical textiles, there is every reason to believe that a host of valuable and innovative products will emerge in the future with multidirectional growth in human healthcare systems.

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16

Sports applications

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16.1 Introduction

This chapter looks at the technical, textile driven, design development of performance sportswear as a prime example of innovative applications for polyester and polyamide fibres. It considers the technical, aesthetic and cultural demands of the identified end-user as the starting point in informing the selection and positioning of specific textile assemblies, and trims, within an ergonomically designed clothing system. It looks at the sports 'layering system', traditionally tried and tested in military combat wear, as an inter-dependent combination of base-layer, mid-insulation layer and outer layer.

Until the emergence of man-made fibres, sports practitioners were often weighed down by military surplus clothing as well as by their heavy boots and accessories. The cut of early woven man-made fibre outer garments was necessarily voluminous, to provide ventilation prior to the introduction of breathable coatings, and to accommodate extreme movement. The silhouette of functional sportswear began to change in the late 1960s and 1970s, with the emergence of elastomeric yarns and waterproof, breathable fabric assemblies. Styling has become increasingly streamlined and sympathetic to the ergonomics of movement and the predominant posture for a given sport.

The needs of the body, in relation to the demands of the sport, provide a focus for the selection of an appropriate mix of fibre and yarn properties, woven, knitted and non-woven fabric constructions, assemblies and finishes. The characteristics of the textiles directly influence the cut, fit, and handle related to the specification of garment detail and construction methods to address protection, movement and posture for a breadth of different activities. The participation level and the varying degrees of expertise of the wearers, as well as the duration of the activity, or sequence of events, will influence the textile specification. Environmental and seasonal aspects of a sport, often taking place in extreme conditions, impact directly on the textile selection.

Modern sports clothing offers maximum performance, balanced with minimum weight, without sacrificing durability or comfort. Nylon and polyester fibres contribute to protective outerwear, insulating mid-layers, base layer and underwear as well as footwear and accessories. Sophisticated sportswear ranges demand design co-ordination throughout the clothing system with regard to colour, styling, proportion and trim. In the performance sportswear market textile fibres and innovative fabrics are invariably branded, or co-branded with apparel products, and often endorsed by internationally recognised, sponsored, sports 'heroes', such as Tiger Woods promoting Nike products.[1]

16.1.1 The emergence of the sports 'layering system'

The sports 'layering system' has evolved from military combat dress to address the selection of appropriate combinations of technical textiles in clothing to protect the body for a range of activities in contrasting environmental and climatic conditions. The clothing system is normally made up of an inner 'base layer', insulating 'mid-layer' and a protective 'outer layer' or 'hard shell'. A new hybrid category has come into usage, that combines outer and mid-layer functionality promoted as the 'soft shell'. In addition intimate apparel demands technical textile assemblies to offer support and to move with the body without chaffing. Personal protective garments or inserts, for contact sports or for extreme sports in hazardous environments, are also incorporated into the layering system.

Intimate apparel

Intimate apparel has been an early adopter of technical textiles and novel garment manufacturing processes since the introduction of Spandex for corsets in the 1960s. To achieve comfort, good fit and support, for both sport and fashion, lingerie and corsetry uses a breadth of woven, warp and weft knit, lace and non-woven materials in a range of fibre and yarn combinations. Weft knits offer more stretch around the body while warp knits are more stable in providing support. Warp knits are also used for swimwear. A variety of garment construction methods rely on a high percentage of synthetic fibres, predominantly nylon and polyester, in combination with elastomers, for the moulding of components and for their suitability in relation to the replacement of traditional garment sewing with new joining and finishing techniques. These processes include bonding, ultrasonic and laser welding, digital embroidery, engineered knits and seam free knit technology. Integrated textile sensors are now emerging in sports bras for monitoring health and performance, for example the Numetrex product range.

Base layer

The term 'second skin' is often used for base layer garments worn closest to the body. These garments are normally made of knitted textiles and made both by traditional 'cut and sew' garment construction methods and by circular knit construction. Lightweight warp and weft knitted fabrics are usually selected for ease of movement, providing stretch in their stitch construction to fit like a second skin. Base layer fabrics for sport are made from fibres and yarn combinations that wick perspiration away from the skin to prevent chilling, especially when stationary and in extremely cold conditions. Synthetic fibres promote moisture management and dry much quicker than cotton. Polyester has good wicking and fast drying properties, while nylon is more abrasion resistant. 'Added value' may be provided through a range of fibres and finishes that offer anti-microbial and anti-ultraviolet (UV) protection.

Mid-layer

The mid-'insulation layer' may be varied in thickness or bulk, to alter its ability to trap 'still air', or 'dead air', depending on the demands of the range of likely conditions. This layer should have compatible cut and styling, with that of the base and outer layer garments, to avoid impeding movement. The insulation layer may be made up of more than one garment; with examples such as jackets, smocks, gilets, traditional knitwear, felted garments and quilted woven textile assemblies incorporating down and synthetic waddings. The most important innovation in insulating textiles for sport, however, has been the development of knit structure fleece fabrics. These fabrics are primarily weft knit and polyester based although nylon adaptations and warp knit structures are also in use. While sophisticated fleece constructions are finely tuned to particular specifications for performance sport, mass-market derivations embrace men's, women's and children's wear ranges in the high street for both sport and everyday life. A recent innovation has been based on the concept of the trapping of still air in a garment that can be filled with air, via a network of internal chambers, and the level of insulation regulated via a tube attached to the inside of the vest to keep the wearer warm.[2]

Outer layer

The usual requirement for an outer shell garment is to be super lightweight with minimum bulk for easy storage.[3] The 'shell', or protective layer, is selected to provide the most appropriate balance of windproof and 'waterproofness' versus 'breathability' and protection for the specified range of

activities. The wind chill factor can lower the ambient temperature dramatically and threaten the clothing microclimate. The outer shell, traditionally also known as 'hard shell', is intended to protect and maintain the function the whole 'layering system'. 'Soft shells' provide a relatively new generation of outer layer garments that have emerged as 'all-rounders' for winter and summer.[4] These are softer, bulkier and warmer than hard shell garments and often with stretch for comfort.

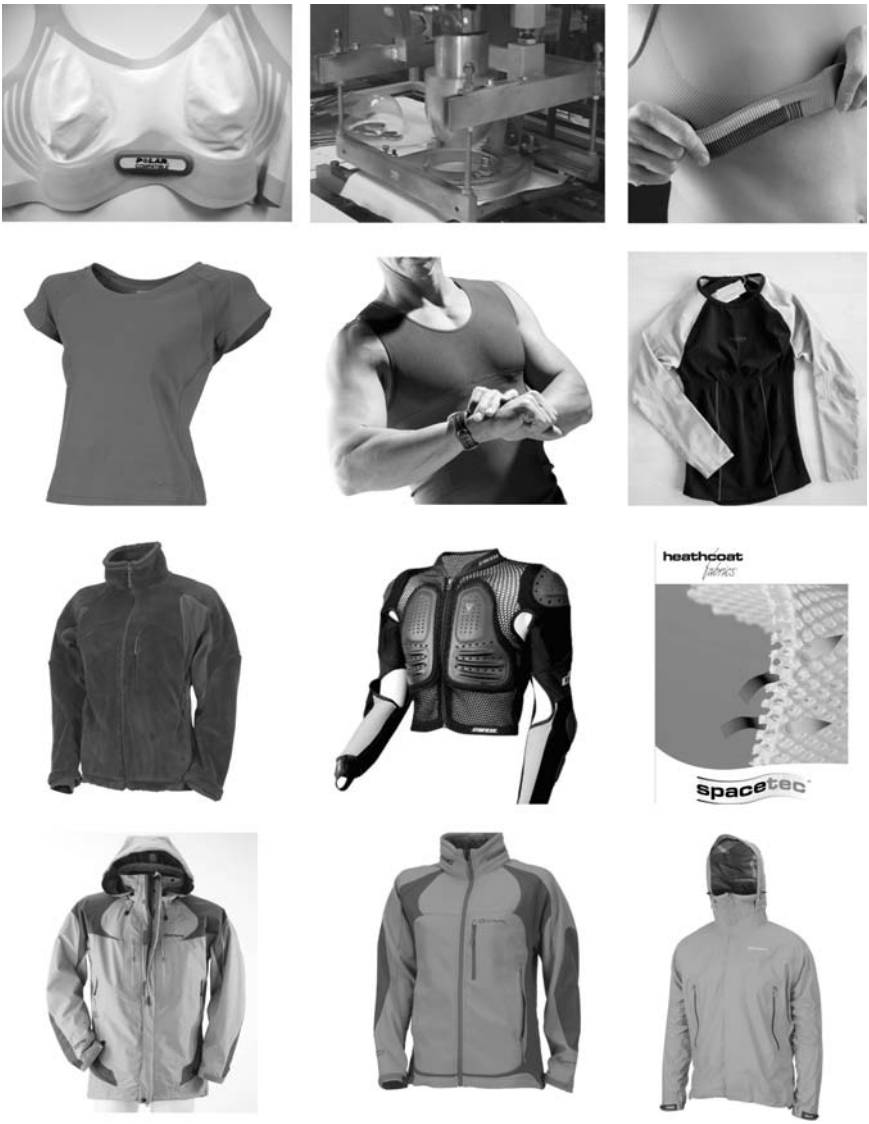
Personal protection

For certain contact sports, or for those carried out in hostile environments, the governing bodies' rules have standard requirements for health and safely that directly impinge on design. For extreme sports, such as motor biking and, more recently, snowboarding, textile fibres are being incorporated into a sophisticated mix of spacer fabrics and heavy meshes in exciting ergonomic designs.

Other market opportunities that have the potential to benefit from lightweight protection and the comfort and easy care attributes of polyester and polyamide fibrous materials include corporate wear, travel wear and inclusive design, with particular relevance in the promotion of health and wellness. A well-designed, versatile, 'layering system', has the potential to address the functional demands of the modern, global, 24-hour society, mixing work, relaxation and everyday activities for an inclusive audience.

16.2 Fibre developments and characteristics

The marketing hype, associated with the branding of fibres, escalated towards the end of the twentieth century with Dupont branding spandex as Lycra in 1960s, W. L. Gore introducing waterproof breathable laminates as Gore-Tex in the late 1970s and ICI re-launching nylon as Tactel in 1983.[5] Performance sportswear is now brought to market through the promotion of internationally recognized brands with clothing products often co-branded through partnerships with fibre and textile producers. Fibres are promoted through a marketing 'story', in a plethora of point of sale (POS) material, often linked to the performance of top athletes. In this new century there is a growing concern for environmental issues associated with the textile chain, as well as an emphasis on textile attributes that can promote health and wellness. Although it is almost impossible to ignore the claims of the brands, with their changing ownership, it is important for designers, and those in the product development team, to have an appropriate level of understanding of generic fibres, their production, properties and characteristics.



16.1 The application of technical fibres and fabrics in the sports layering system.

16.2.1 Fibre and yarn extrusion

In man-made fibre production the fibre is extruded in the form of continuous multifilament flat or straight filaments referred to as continuous multifilament flat yarns. These thermoplastic filaments may be permanently distorted, under the influence of heat, to produce bulky or textured

filament yarns. These yarns may be bulky and elastic or simply bulky. Fibre producers introduce many interesting variations of nylon and polyester fibres in the extrusion process, by altering the shape of the spinneret holes, to produce multi-channel filaments in a range of multilobal shapes. The handle and light reflecting properties of a fibre may be modified by changing the cross-sectional shape, for example trilobal, pentalobal and octalobal filaments. Hollow channels may be introduced into synthetic fibres to increase thermal insulation. Ultra-fine microfibres give enhanced flexibility, wicking and water repellency coupled with water vapour permeability. Moisture wicking may be enhanced by the use of appropriate hydrophilic surface finishes, by the incorporation of 'water attracting' co-polymers. Other finishing techniques such as soil release, flame retardant and anti-microbial attributes are available.

Some examples of well-promoted polyamide and polyester branded fibres, adopted within the sports layering system, are as follows. The nylon fibre Tactel®, originally launched by ICI in 1983, has since passed from DuPont to Invista. A current product, licensed to Nilit, is Tactel® multisoft with a round or trilobal cross-section. AdvanSA's moisture management polyester fibre, Coolmax®, has both four and six channel variations, with an increased surface area to promote moisture wicking. AdvanSA's polyester hollow fibre is marketed as Thermolite® to provide added insulation. Co-polymers may be introduced to give dye variant fibres, with two different colours in one dying process or tone-on-tone effects such as Nilit's proprietary brand Sensil® Duelle or their licensed brand, Tactel® Strata. Fibre properties may be improved through further modifications to the basic man-made fibre extrusion processes. High-tenacity nylon fibre, such as Tactel HT, that is drawn after extrusion, is known to be lighter and more abrasion resistant than other nylon fabrics. The nylon fibre, Cordura® is said to be twice as durable as standard nylon and three times as strong as polyester.

16.2.2 Micro-encapsulation

Micro-encapsulation or impregnation techniques may be used to introduce anti-microbial properties that reduce odour formation and the risk of infection. Antibacterial agents can be added to synthetic fibres in the spinning process. 'Sanitized' silver yarn has permanent bacteriostatic properties due to the incorporation of sanitized silver nano-particles in the PA6 polymer mix before spinning which prevents the proliferation of bacteria and the build up of unpleasant odours in garments – even if washed frequently. Because of its PA6 polymer matrix it will not yellow and takes up dyes exceptionally well'.[6] Another example is the newly launched 'Cocona' fibre, the result of a partnership between Burlington Worldwide and Trap Tek, that has activated carbon particles, from heated coconut husks, per-

manently embedded into polyester fibre. This provides a porous structure that traps odours, promotes the evaporative cooling of perspiration, and offers protection from harmful solar, ultraviolet radiation.

Another example of micro-encapsulation is in Phase Change Materials (PCMs). 'Outlast®', USA, is a branded product, originally developed for the garments of NASA astronauts, that buffers temperature swings, absorbing excess heat when the wearer is active and releasing heat when the wearer begins to cool down. This is described as a 'microencapsulated latent heat storer, based on paraffin wax'. This is 'the phenomenon that occurs when the wax changes from the solid to the liquid state. During this phase transition a large amount of thermal energy (latent heat) is consumed without the temperature of the material itself changing. The innovative, design led knitwear company, Falke, has incorporated Outlast 'Adaptive Comfort' phase change technology into polyamide fabrics for their Autumn/winter 2007/2008 'Ergonomic Sports Underwear Collection' with styles marketed as 'Athletic Warm' and 'Comfort Warm' that aim to provide 'a balanced body climate'.[7]

16.2.3 Fibre blends

All fibres have good, fair and poor characteristics relating to a particular end-use. Pharr Yarns, maintains that 'the market is driven by the properties the end-user wants'. This US spinner steers their clients towards an appropriate blend as 'a yarn made of 100% of any fibre will not accomplish all that a customer wants.'[8] Fibre blending allows manufacturers to combine fibres so that good qualities are emphasised and poor qualities minimised. Blending may be carried out at any stage prior to the spinning operation. The earlier the fibres are blended in processing, the better the blend. Blending may be carried out to give colour effects, to obtain better texture, to alter handle or fabric appearance and to improve performance. Special categories of blended yarn have been developed to exploit particular fibre characteristics. Some yarns have two types of continuous filament intermingled within one continuous filament yarn. Others have two types of polymer within the same filament. A blend of nylon fibre and silver-coated nylon fibre, known as X-static®, is an effective sustained-release antibacterial agent. Composite yarns have two or more elements one of which is a continuous filament. Core spun elastane has a central core of elastane often covered with polyester or nylon wrapping yarns.

16.2.4 Stretch

Ease of movement has become a highly desirable fabric property not only in performance sportswear, but also in everyday clothes. Stretch fabrics

enhance comfort and fit and ease the putting on / taking off of garments and provide good shape retention. High power elastomeric stretch can also provide a valuable supportive function, applying compression to injured limbs, muscular support or support to a bust line. There are three types of stretch yarns. 'Elastomerics' are those where elastic recovery is a fibre property. Although elastomerics may be used bare, they are often covered with a non-elastic yarn such as nylon or polyester. Crepe or 'over spun' yarns are those where the high degree of twist in the spinning process makes the yarn pull back on itself. Texturized yarns are those whereby a false twist is manufactured during the production of synthetic yarns.

Other materials have highly elastic properties, e.g. special polyesters such as polybutylene terephthalate (PBT). These materials are used in swimwear, support garments such as athletics garments, skiwear, leotards and increasingly in comfort stretch general clothing. PBT is less susceptible to degeneration in chlorine or sunlight. An elastic bicomponent polyester fibre, generic name 'elasterell-p', is a hybrid between elastane and textured polyester. It is not too elastic and therefore suitable for fabrics requiring moderate stretch or comfort stretch providing better-fit and good shape retention. With extraordinary tensile strength, it can withstand tough wear, extending garment life.

16.2.5 Sustainability

In the twenty-first century designers, and those involved in the textile related product development teams, should have an awareness of sustainable issues in relation to the selection/specification of textiles from fibre development to textile processing, finishing and after-care. This is particularly relevant for performance sportswear products where the users are normally concerned with health, wellness and care of the environment. As recycling becomes compulsory, so sustainability issues will increase in importance and the 'end of life' for technical garments must be considered. The outdoor clothing company Vaude, and partners, has pioneered 'Eco-log' whereby every component in the clothing system is made of polyester from waterproof weave with Sympatex, polyester based, membrane, to fleece mid-layer and wicking base layer. Polyester zips, studs, threads and trims complete the mix enabling the whole garment layering system to be recycled. The US outdoor company, Patagonia, has used recycled PET (polyethylene terephthalate) fleece fabrics for over a decade, initially from Wellman in the USA and now from Teijin in Japan.

Biodegradable, crop-based, polymers may be produced from corn starch, an abundant natural polymer, cellulose, as an alternative to fossil fuel synthetics. PLA (polylactose acid) fibre is said to 'bridge the gap' between natural polymers and synthetics, offering a unique combination of proper-

ties with the best attributes of natural and synthetic fibres. It is claimed that biodegradable polyester has the easy care properties of real polyester and the right technical credentials to replace polypropylene. Cargill Dow's PLA fibre 'NatureWorks' is now extruded into a high-performance synthetic fibre, branded as Ingeo, claimed to be 'the world's first man-made fibre derived from 100% annually renewable resources'. Yarns are being developed, to include apparel applications, in both pure qualities and innovative blends. Strength and resilience are balanced with comfort, softness, drape and good moisture management characteristics. It may be used as fibre fill for products such as padded outerwear with superior loft that is said to feel more like down than a synthetic imitation.

Marks & Spencer (M&S), the major retail chain, announced 'Plan A' in January 2007, to provide leadership on the issue of sustainability over the subsequent five years and beyond.[9] With regard to textile products, M&S plans to promote the use of sustainable raw materials including PLA and polyester made from recycled PET bottles. 'Plan A' includes the planned opening of a model 'green factory' in collaboration with a supplier. Recycling points will be introduced for packaging and in-store points for the consumer to be able to recycle clothing. The aim is that within five years the consumer will not need to throw away any M&S clothing waste after they have finished with it. There are also plans to start researching alternatives to clothing disposal, including donation, composting and recycling.

16.3 Design considerations

16.3.1 Technical garment design

The adoption of technical textiles in lightweight nylon and polyester fibres has directly driven design innovation in sports clothing in terms of comfort, performance and aesthetics. The demands of the body, for movement, moisture management, thermal regulation and protection may all be addressed through the application of modern technical textile developments with nylon and polyester fibres as major constituents. The versatility of the performance sportswear clothing system enables top athletes and recreational sports enthusiasts to carry out individual or mixed activities, over short or extended durations, without the need for heavy or bulky clothing and accessories that impede movement. In combination with technical performance attributes, polyester and nylon fabrics may provide sophisticated aesthetic appeal.

A slim fitting silhouette is now the norm as a result of innovation in breathable fabrics and stretch properties. This, in combination with ergonomic cut, avoids billowing when moving at speed, with the front hem of a jacket invariably hollowed out and the back lowered, relevant to the

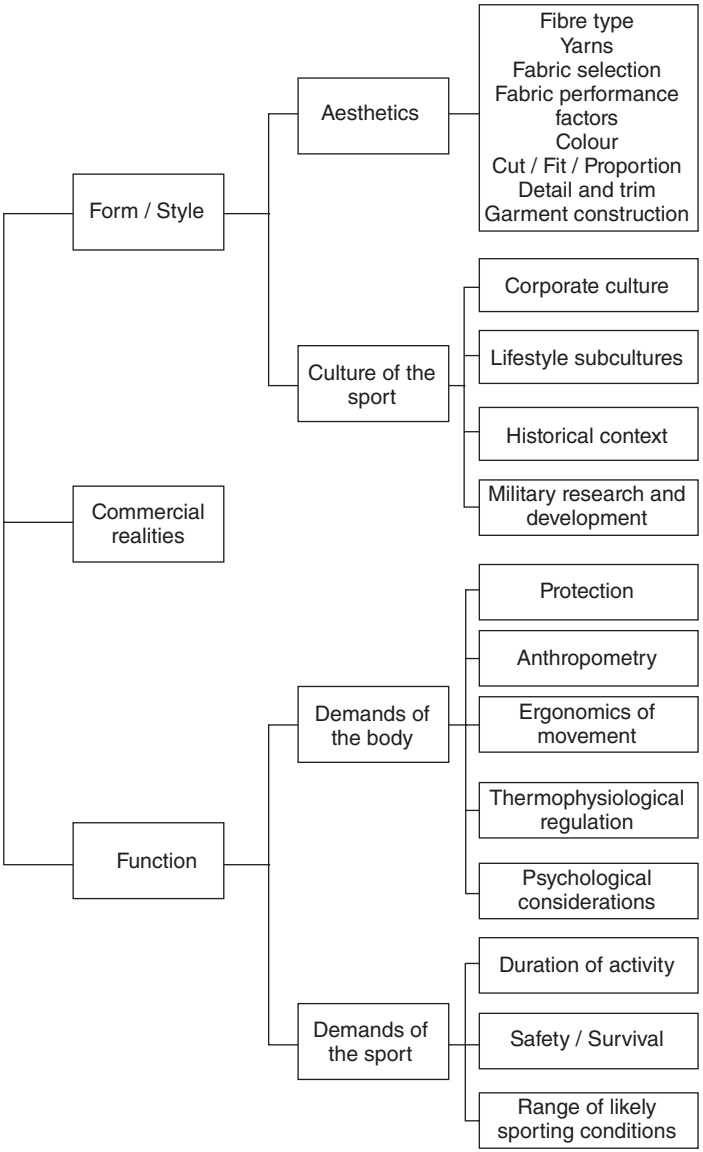
predominant posture desired. For outdoor performance clothing, garments incorporate details such as optional foldaway hoods into collars and pockets for maps, phones and security items. Other garment details, which use a range of nylon and polyester textile constructions, include abrasion resistant articulated elbows, hook and loop cuff adjustment (commonly marketed as Velcro®), zips for closures and ventilation as well as shock cords, fleece facings, garment insulation and protective spacer fabrics.

The potential combinations of nylon and polyester fibres, and blends, in fabric structures for mid- and base-layer garments is infinite in providing a breadth different attributes. Strategic 'zone construction', or the placement of fabrics, in relation to the needs of the body, increases performance with relevance to the end use. Seam free and whole garment knitting technology is integral to the design of garments that adopt these all-in-one production techniques. Mesh structure inserts increase air flow for increased moisture wicking in high sweat areas, mixed fabric weights can be selected to enhance mobility, give protection and can add durability in areas of high abrasion. Traditional garment construction is done in two dimensions on a flat surface while new functional garment construction methods follow the three dimensional contours of the body to provide reduced friction, increased movement and protection and ergonomic shaping. Functional garment construction benefits from features such as gussets that reduce friction in key areas like underarm; raglan sleeves keep the shoulders free from seams that might rub; and articulated construction enables freedom of movement for elbows and knees. Additional shape and protection may be provided in the moulding of garment components, commonplace in intimate apparel garments, and for lightweight body armour.

Leading edge stitch free garment construction techniques are emerging throughout the technical textile driven performance sportswear layering system. Garment bonding and laser welding are stitch free joining technologies used in high end markets to provide clean, streamlined design both for woven and knitted textile constructions without inhibiting stretch. Flat seams with clean finishing enhance comfort inside the neck and around sensitive areas. Laser cut edges and pockets with bonded waterproof zips reduce weight in both hard and soft shell garments. Sonic stitching is used primarily for disposable garments such as forensic suits, medical end use and clean room garments. Performance sportswear has been an early adopter of novel manufacturing techniques that are gradually filtering through to mainstream fashion.

16.3.2 Analysing garment characteristics

When designing a performance sportswear 'product' there are many factors to consider. These should be fully explored and identified by starting with



16.2 Design process tree for performance sportswear design.

an analysis of the intended end-use. The design development process should begin with identifying the 'customer' or market sector in relation to the specified sport or range of activities. The range of issues uncovered may then be prioritised to inform the garment design brief and help guide the subsequent product development.

Questions to be addressed may include the following. Is the garment or product intended for individual use or team wear and what is the level of expertise of the wearer(s). Is the garment incorporated in a layering system and, if so, what are the other layers? What are the demands of the likely environmental conditions, or range of locations, that may be potentially hazardous, as well as weather and seasonal considerations? What is the duration of the activity or sequence of events? The predicted life span of the product must be considered and a plan for its disposal. Will the material selection influence the type of garment construction?

Is the product to be in contact with the skin and what are the demands of the workload? Is the activity a contact or non-contact sport in terms of body protection? The ergonomics of movement is a major consideration in performance sportswear design. Predominant posture and extreme movement varies for different activities but there are generic considerations for performance sportswear that are not commonplace in fashion. For a breadth of sporting activities it is important to have extended arm lift, articulated elbows and knees and a lack of restriction across the back and in the leg-wear crotch area. Movement may be enhanced through the garment cut but also in the selection of appropriate fabric constructions, making use of bias cut and through the incorporation of elastomeric fibres and yarns.

The garment characteristics required, from both technical and aesthetic perspectives, will inform the drafting of a clear and effective design brief to guide decision making with regard to the most appropriate textile fibres, fabric structures and finishing choices for the chosen 'customer' or market. Nylon and polyester fibres are prevalent in a range of products throughout the sourcing and selection of functional fabrics, trims and components, from linings and laminates to knits, weaves, cords and zips, that enhance the comfort, functionality and appearance of highly detailed performance sportswear outer garments.

16.4 Textile selection

Nylon and polyester fibres constitute a breadth of different structures and assemblies for performance sportswear applications that include wovens, non-wovens, weft and warp knits, nets, meshes and narrow fabrics. Woven fabrics are generally strong, relatively rigid and hardwearing and tend to be used for outer layer sports garments. Woven constructions are also used for back-pack fabrics and their webbings and trims. Lightweight weaves and nets may be used as linings. Non-woven textiles are found in protective laminates and insulating waddings. Knitted textiles provide highly flexible structures throughout the clothing 'layering system' from base-layer, or 'second skin', to mid-insulation layers and to both the linings and main

substrate of many protective outer layer garments. Textile structures, with their branded fibres, may be loosely categorized within the different layers of the generic sports clothing system. The base layer is primarily concerned with moisture management, the mid-layer with insulation, and the outer layer with protection.

16.4.1 Textiles for moisture management

It is important to move moisture away from the skin and to maintain a dry microclimate as damp base layer garments can cool rapidly, be uncomfortable, and may cause post-exercise chill. This is vital in high activity winter sports which take place in cold climates by comparison with hot dry desert conditions where cooling is desirable. 'During intensive training, an athlete's clothing has to transport around 1.5 to 2.5 litres of moisture per hour.'[10] The breathability, heat and moisture management of textiles play a crucial role in supporting the physical and mental performance of the wearer.

Double face 'denier gradient' fabrics use a plaited technique that joins two different constructions to manage moisture through push-pull capillary action. The body's heat pushes sweat and moisture vapour through the larger gradient fabric, next to the skin, towards the outer surface (face), and the micro-yarns on the face pull the moisture to the surface, absorbing and spreading it quickly to evaporate and leave a dry surface next to the skin. A dry inner surface feels more comfortable and reduces chaffing. AdvanSA and Lenzing have launched a new range of fabrics that have polyester Coolmax® to be worn against the skin, and absorbent, cellulosic Tencel fibre, with a natural touch, on the outer face of the fabric.[11]

A close body fit enables faster moisture absorption to speed the wicking process. When close fitting garments are required, lightweight weft knits give maximum stretch around the body. Weft knitted fabrics have more stretch in the course, or horizontal direction of the fabric, than in the wale, or vertical direction, which has minimal stretch. Weft knit fabrics are relatively bulky and open in construction being air and water permeable providing good insulating properties as well as breathability. Weft knits are used in intimate apparel, base layer garments, swim wear, cycling wear, team wear as well as in open mesh garments/linings and fleeces. Fabric elasticity may be enhanced by the use of elastomeric fibres. Garment fit, for a breadth of figure types, is a key consideration for the embedding of wearable technologies in base layer garments to monitor the wearer's performance for sport as well as general health and wellness.

Circular weft knit innovation is being led by the machine makers, such as Santoni and Stoll. Santoni 'seamfree' technology can be used to

engineer seamless structures to create garment fit and the placing of controlled 'zones' of different knit constructions, with jacquard patterning, surface dimensionality and the selection of different colours and yarn properties.[12] Areas can be incorporated with three dimensional and open mesh stretch support to create shaping with very little sewing required. Engineered customization can be realized by integrating other technologies, such as a body scanner and performance yarns.

At the major sports trade fair, ISPO, Spring 2007, the Swedish company, Craft, presented seamfree 'Pro Warm' base layers that use 'very lightweight hollow polyamide fibres, polyester and elastane in a complex 3D knit with seamlessly integrated climate zones. While the hollow fibres and spaces in between trap air, thus providing the insulation, the climate zones are said to guarantee excellent temperature management, keeping the body warm where it is needed, yet preventing overheating. It is also said to be super soft, providing a high level of moisture management, good fit and freedom of movement.'[6]

16.4.2 Textiles for insulation

Weft knitted fabrics in different variations of weight and bulk are prevalent in 'mid-layer' garments. They tend to be more extensible and elastic than woven fabrics. Fibre and fabric mixes for insulation require bulk and include fleece, or brushed pile fabric, fibre pile or sliver knit, sometimes known as fake fur, and other three-dimensional knitted spacer constructions. Insulating fibres may be shaped and/or hollow and often made from polyester to prevent absorption of moisture. 'The invention of fleece changed the entire apparel, sports and outdoor market. It is even considered to be one of the top one hundred inventions of the 20th century.'[13] It is now worn as much in everyday wear, and for corporate workwear, as it is for performance sport for all age groups.

Mountain Hardware's 'Euro Stretch' is a dense bi-elastic two sided fleece fabric that can be worn either way, allowing a smooth outside and plush inside, used in their 'Expedition reversible T'.[13] Some warp knitted constructions also have one smooth face and one textured loop or brushed face, so that, worn one way, garments trap air and offer extra warmth in cold conditions and when reversed offer cooling comfort. This reversible technology was developed by Nikwax, UK's Paramo range, in their 'Parameta S' shirts.

As with base layer garments, knitted mid-layer fleece developments can be engineered to embrace different 'zones' of insulation in relation to the ergonomic design of the product and the requirement for protection, thermal regulation and moisture management relevant to the demands of different areas of the body. Seamless garment construction reduces any

chaffing as traditional joining is eliminated. The US outdoor company, Patagonia, developed a variable knit fleece with Malden Mills, the originators of 'Polartec' fabrics.

In addition to insulation in mid-layer garments, other technologies have been discussed that address thermal regulation such as phase change materials, that retain or release heat depending on workload. Outlast® molecules can be incorporated through fibre micro-encapsulation but also incorporated into the garment system as a laminate. Wearable electronics can be embedded in mid layers for products, such as fleeces, with battery-driven heating providing warmth to the kidney area.

16.4.3 Textiles for protection

Outer layer garments are generally made of woven constructions with coatings or laminates incorporated into two or three layer assemblies. These are also treated with water repellent finishes on the outer face. Hard shell outer fabrics are normally of lightweight nylon or polyester. Nylon fibre is used for its strength and abrasion resistance for more extreme end-use while polyester is selected for a softer handle and is more suited to recreational sport. Garments may have enhanced protection with areas of abrasion resistant fabrics such as nylon Cordura. These placements are often on the elbows or knees, across the shoulders or to reinforce an area that has regular use such as the side of a garment if carrying a snowboard. Lightweight nylon weaves can be strengthened with rip-stop weave structures. Polyester weaves may have enhanced softness and drape through sanded or emerised finishing.

There are various descriptors for protective outwear garments categorised by their fabric assembly. Within the 'Hard Shell' category, 'two-layer' garments are made from fabric that has an exposed coating or laminate on the inside, normally protected by a loose mesh lining, and 'three layer' garments have a 'sandwich construction' with an outer woven fabric, a laminate and a backing to protect the laminate, such as a fine single jersey or mesh. The outer shell design must incorporate appropriate ventilation as few textile assemblies cope with the moisture produced from extreme workload.

The new class of outerwear garment, the Soft shell, normally incorporates stretch for added comfort. Soft shells are often of a 'sandwich' construction of stretch woven outer, a laminate, and a fleece or brushed mesh inner backing. Some 'soft shells' have additional anti-abrasion 'hard shell' laminates on outer areas that need greater protection and reinforcement. Outer fabrics are often of nylon fibre for strength and inner fabrics are often polyester for softness. Successful designs combine a mix of material compositions and constructions, placed in positions appropriate to the

demands of the body, to achieve maximum comfort and performance. Sports companies adopt their own terminology in developing garments using garment construction techniques. 'Body mapping' is the terminology used by W. L. Gore to address the placement of textiles with a range of attributes to address the needs of different zones of the body, that may require extra padding, moisture absorption or heat insulation. For personal protection a stable warp knit structure is used to produce three-dimensional spacer fabrics in a two-layer 'sandwich' construction. Monofilament connecting yarns maintain the space between the layers.

Waterproofness and breathability continue to be major requirements for sports outerwear garments. The branded waterproof breathable laminate, 'Sympatex', is a polyester based membrane. Promotional material from the company claims that their product 'Reflexion 111' is a 'membrane with optimised heat management providing efficient insulation in cold temperatures while also offering breathability in a light weight form. The compact hydrophilic membrane is thinner, lighter and more flexible (300% bi-stretch) than other membrane systems as well as being waterproof, windproof and recyclable. The non-porous surface is plasma treated and aluminised in a 4000 degree vacuum environment using an extremely thin 50-nanometre layer of aluminium. The laminate can be sewn, seam sealed or bonded.'[6] Fine continuous filament flat yarn warp knitted fabrics are normally used to protect the inner layer of laminates. Woven linings are used for more tailored elements and warp knit mesh fabrics are widely used for loose linings and pocket bags.

16.5 Future trends

Innovation in performance sportswear design continues to be driven by technical textiles, in particular the attributes of lightness in weight, stretch, moisture management, thermal regulation and protection. Increasing sophistication in garment cut and fit, enhancing movement and protection, is directly related to advances in synthetic fibre developments within novel textile structures, in tandem with new garment construction. We are now at the beginning of a new revolution in the textile and clothing industries as the disparate areas of technical textiles and performance clothing merge with the electronics industry and related sectors such as communications and health.

The embedding of smart attributes and electronics in textiles further enhances the comfort of clothing through the protection and maintenance of the clothing microclimate. Functionalities that include phase change and shape memory polymers, sensors that measure human vital signs, positioning and performance, heated textiles and self-cleaning nano finishes are being brought to market in sectors such as corporate workwear, health and

wellness products and in performance sportswear. Many of these textile innovations, for performance sports end-use, are embedded in textile assemblies that are largely constituted from polyester and polyamide fibres.

16.5.1 Biomimicry

Many examples of innovations in modern fibres and textile structures have resulted from the principles of biomimicry. Textile applications that improve functionality in sportswear, have drawn inspiration from lotus leaves, mimicked in self cleaning fabrics, and gecko feet mimicked in closures. Fir cones were one of the earliest examples cited as 'a flexible response to moisture and adaptation to temperature change. When the weather is cold or wet they close up and when dry they open again.' In Schoeller's 'C-change' technology, a hydrophilic membrane is set to a particular temperature range and, as soon as higher temperatures or body warmth result in greater moisture being produced, the flexible polymer structure adjusts to allow water vapour to escape quickly to the outside air. When the body produces less heat energy and therefore less moisture, the polymer structure returns to its original condition.

16.5.2 Shape memory polymers

'Shape memory polymers (SMPs) are smart materials that, as a result of external stimulus such as temperature, can change from a temporary deformed shape back to an original shape.'[14] Shape memory polymers offer flexible lightweight impact protection for extreme sports. Dow Corning has an 'Active Protective System' described as '3-D spacer textile treated with special silicone coating which remains soft and flexible under normal use but hardens instantly upon impact'. This foam-based material immediately reverts back to being pliable material once the pressure is lifted.

An alternative protective technology is described as 'Rate Sensitive Material'. The product 'd3o', is made up of free flowing molecules that provide a soft pliable material which reacts the moment impact occurs. Once the impact is over, the material immediately becomes flexible again. The molecules lock together to provide a shock absorbing system that may provide removable protectors in areas such as shoulders and elbows and knees. This product is also used in the relatively thin and stylish Reusch 'Unshok glove'. This material both absorbs and distributes impact force with the reaction starting sooner and lasting longer than in rigid systems.

16.5.3 Wearable electronics

Conductive fibres are of particular interest in relation to smart textile applications and wearable technology, both in terms of the elimination of static, and also as conductive pathways for the connection of electronic components. Conductive materials include metal fibres as well as inherently conducting polymers (ICPs) and carbon fibres already being used in many applications for occupational work wear such as antistatic working, EMI (Electromagnetic Interference) shielding, heating and the transport of electrical signals. Some sportswear companies have already had great marketing success with wearable electronics from the simplest applications to complex systems. Smart textiles, with embedded technology, are emerging in a rapidly growing range of applications that include heat conductive textiles, textile switches and vital signs and performance monitoring devices.

Several UK-based companies have integrated electronics into sports clothing and textile based accessories.[15] Companies, including Eleksen, EXO^2, Fibretronic and Peratech, have designed products that interface with software from Microsoft and iPod music players from Apple. Products are being developed with internationally recognised sports brands such as Berghaus, Burton, Nike, O'Neill, Quiksilver, Reusch, Rohan, Schoeffel, Spyder and The North Face. One of the most prominent technology providers in the sportswear market has been Eleksen who specialised in touch-sensitive interactive textiles for electronics interfaces. The core technology is the use of an electro-conductive fabric touch pad, ElekTex, for the creation of flexible, durable and rugged fabric touch screen interfaces. This technology has been employed in products that include interactive sports apparel, bags, back packs and communications controls and in textile computer keyboards that can be rolled up into a compact space.

The UK outdoor clothing brand, Berghaus has developed the 'Heatcell Gilet', a fleece containing the EXO^2 with a 'Thermomesh' heating system, edged with conductive tinned copper braiding, encapsulated in a nylon envelope, that spreads warmth around the torso for up to six hours.[16] This type of climate control system is also used in the 'StormRider' heated vest for professional motorcyclists. Many of the well-known sports and outdoor brands are now employing technology and electronics specialists. Andreas Roepert, of Interactive Wear AG, advises that 'Attention to the differences in the design and production processes, a joint project plan and timely cooperation between wearables and textile partners helps to fashion the design successfully and to optimise costs' and that 'well thought out production directives save some surprises'.[17]

16.6 Sources of further information and advice

Sports clothing and equipment trade events

ISPO, Munich, Germany, winter and summer and other global fairs. (www.ispo.com)
European OutDoor Fair, Germany, annual fairs. (www.european-outdoor.de)
Outdoor Retailer, USA. winter and summer fairs. (www.outdoorretailer.com)

Sports related technical textile trade events

Avantex / Techtextil, Frankfurt, Bi-annual.
Premiere Vision, Paris, Annual, Spring and Autumn.

Journals and publications

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Future Materials, World Textile Publications Ltd., Perkin House, 1 Longlands Street, Bradford, West Yorkshire, BD1 2TP, UK.
Textiles Intelligence Ltd., 'Performance apparel markets: Business and market analysis of worldwide trends in high performance activewear and corporate apparel'. 10 Beech Lane, Wilmslow, Cheshire, SK9 5ER, UK.
Textiles: The Quarterly Magazine of The Textile Institute (www.textileinstitute.org).
Zoom: The Magazine of Schoeller Textile AG, Banhoffstrasse 17, CH-9475 Sevelen

Websites

http://www.schoeller-textiles.com/
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