Elsner P, Hatch K, Wigger-Alberti W (eds): Textiles and the Skin.
Curr Probl Dermatol. Basel, Karger, 2003, vol 31, pp 82–97

Functional Textiles in Prevention of Chronic Wounds, Wound Healing and Tissue Engineering

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The use of textiles in medicine has a long tradition. An important field of application is wound care and prevention of chronic wounds, in particular pressure sores. Among the long list of textile materials, bandages and wound dressings gained great popularity. The use of textile materials was supported by availability, prices and re-usability. Woven textiles are mostly used. Despite the fact that traditional textiles fulfilled primary quality approaches like biocompatibility, flexibility, strength, etc. there is an increasing need for specified functions. Along with the technological development of functional textiles, their use in wound healing and prevention of chronic wounds has reached a new quality of interactivity between biological tissues and textiles [1].

Use of Spacer Fabrics in Prevention of Chronic Wounds

Spacer fabrics are interesting textile technological solutions for a medical condition. The basic principle is a combination of textile sheets with distance fibers. An overview on fibers used is given in table 1 and figure 1. Monofilar polyester fibers have a marked stiffness providing a higher pressure resistance of the spacer fabric. Monofils, however, are not suitable to encourage a directed fluid transport in contrast to capillary fibers composed of single fibers and fixed by heat. The higher the fixation temperature, the higher the crystallinity of filaments is. Surface modification as in profiled Coolmax® fibers supports the fluid transport. By optimization of materials and technologies a directed transport of fluids and heat becomes possible. Constructions of synthetic fibers with

Table 1. Some properties of synthetic and cellulosic fibers used in spacer fabrics

Fiber	Fiber type	Density g/cm^3	Elasticity % dry/wet	Specific electric resistance, Ω/cm	Melting point, °C	Water sorption (mass percentage)	Water holding, %
Polyamide 6	Filaments	1.14	20–45/105–125	10^{9}–10^{11}	215–220	3.5–4.5	10–15
Polyamide 6.6	Filaments	1.14	20–40/105–125	10^{9}–10^{11}	255–260	3.5–4.5	10–15
Polyester	Filaments	1.36–1.41	20–30/100–105	10^{11}–10^{14}	250–260	0.2–0.5	3–5
Viscose	Filaments	1.52	10–30/100–130	10^{6}–10^{7}	175–190[a]	12–14	85–120
Cotton	Fibers	1.52–1.55	20–50/100–120	Low	From 180[a]	7–18	42–53

[a] Decomposition.

cellulosic fibers, combinations of synthetic fibers and different densities of fiber connections with the textile sheets have been used to ensure a directed fluid transport [2] (fig. 2).

Another important property of spacer fabrics is pressure resistance which is dependent on pol-fiber material, pol-fiber angle and stitch density. The mechanical and microclimatological qualities (table 2) ensure their use for medical textiles such as compression bandages, supports for beds and the operation theater to ensure decubitus prophylaxis [cf. 3, 4].

Spacer fabrics based bandages have been used in a clinical trial for patients with lymphedema of the leg. In primary lymphedema the mean microlymphatic pressure is raised from 7.9 mm Hg (healthy controls) to 15.0 mm Hg. Thereby the microlymphatic pressure reaches the range of the interstitial pressure. The lymphatic flux becomes inhibited [5]. An analogous mechanism develops in secondary lymphedema, e.g. in combination with chronic venous insufficiency or after lymph node dissection and/or radiation. Physical treatment with lymphatic massage and special compression bandaging is a cornerstone of modern therapy. Spacer fabric-based compression bandages have been shown to be as effective as classical bandaging but much more comfortable, since there is the need of only one layer bandaging. By microclimatic quality of spacer fabrics, sweating and overheating of skin is prevented [6]. The same principle can be used to decrease pressure peaks in bed coverings, for shoes, textiles for the operation table or wheel chairs [7]. Spacer fabrics have also been employed in biosurgery as carriers of living maggots used for wound debridement and stimulation of healing.

Embroidery Technology for Medical Applications

Advanced composite materials are reinforced by textile preforms for primary structural applications. The close control over fiber architecture offered

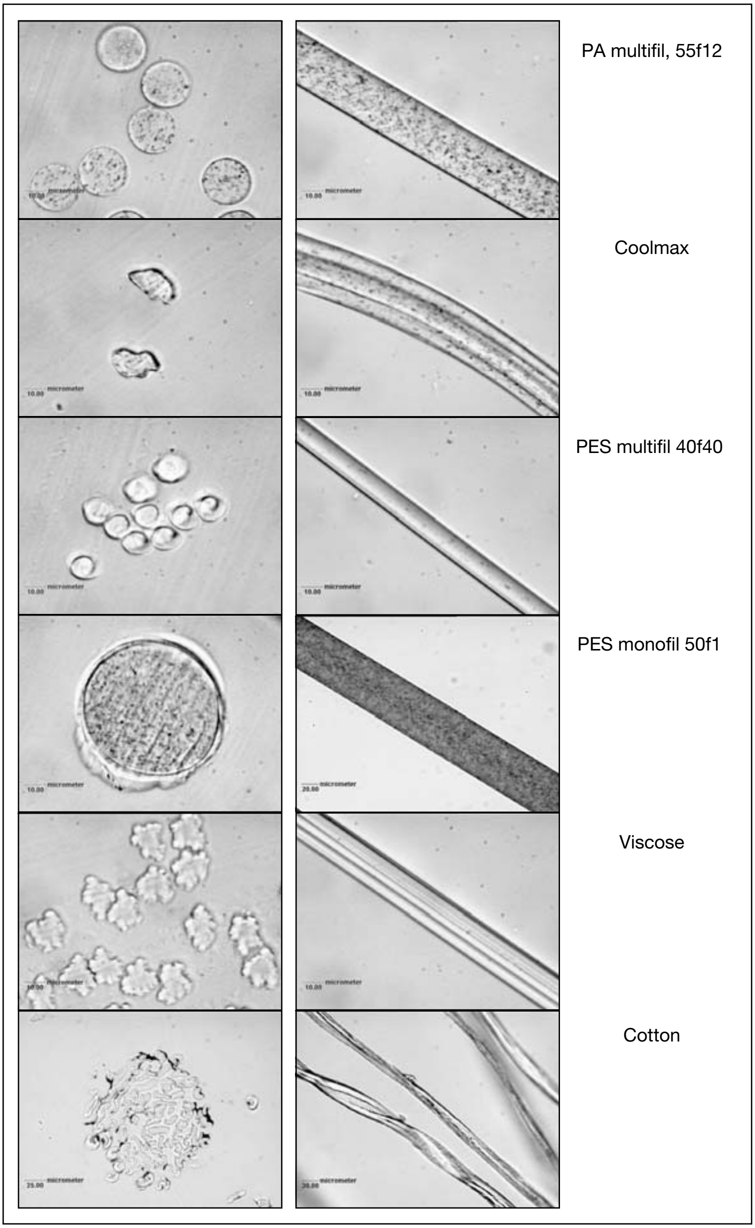

Fig. 1. Microscopy of synthetic and cellulosic fibers.

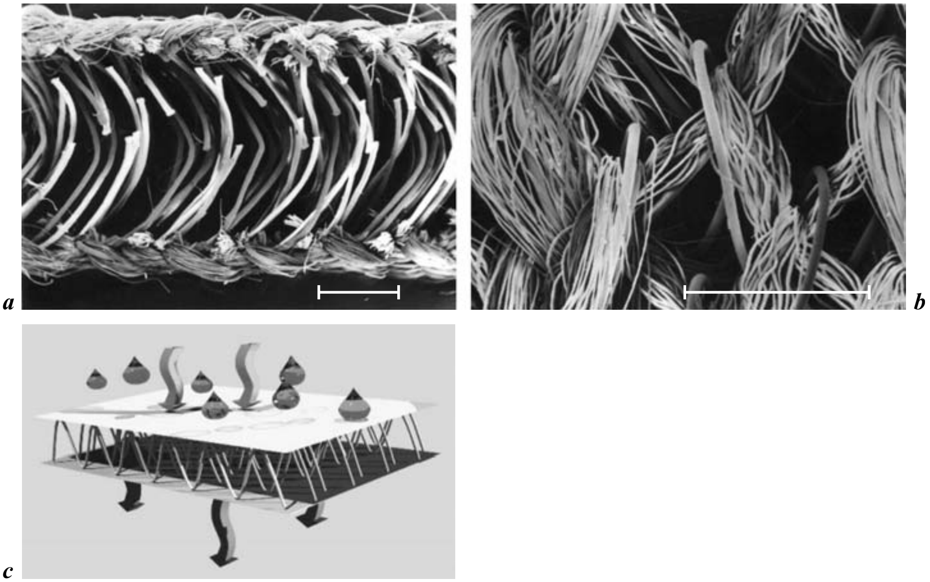

Fig. 2. Spacer fabrics – two textile areas are interconnected by pol filaments encouraging a directed liquid and heat transport. ***a*** Scanning microscopy of spacer fabrics demonstrating the monofil filaments interconnecting the textile areas. ***b*** Details of the pol filament construction. ***c*** Schematic presentation.

by embroidery is of potential interest for highly loaded structures, enabling fibers to be placed in the position and with orientations necessary to optimize strength and stiffness locally. Hernia patches, implants for intervertebral disc repair and a graft stent for the repair of aortic aneurysm have been designed [8]. Karamuk et al. [9] developed a textile wound dressing based upon this technique. The embroidered textile has a three-dimensional architecture that combines different kinds of pores and holes for directed angiogenesis with stiff elements for a local mechanical stimulation of the wound bed. First clinical trials focused on the treatment of pressure sores and venous leg ulcers.

Absorbing Textile Devices

Incontinence is a major problem in small children and elderly people. The avoidance of skin irritation by enzymes in feces and urine is mandatory in pressure sore and napkin dermatitis prophylaxis [10, 11]. The fluid-handling capacity of incontinence devices is realized by introduction of superabsorber. The textile

Table 2. Microclimate parameters of spacer fabrics

Parameter	Mean quality of spacer fabrics with liquid-transporting pol filaments (spacer fabrics with one-sided cotton sheath)	Mean qualities of spacer fabrics without fluid-transporting pol filaments (100% synthetic fibers)
Water steam diffusion resistance, m^2·Pa/W[a]	8.0–10.2	11.2–12.1
Fluid sorption %[a]	197.5–292	0.4–64.2
Buffer effect from the steam phase (Buffer score 'Feuchteausgleichskennzahl Fd')[b]	0.36–0.47	0.25–0.36
Buffer effect from the liquid phase (Buffer score 'Pufferkennzahl Kf')[b]	0.89–0.99	0.73–0.75
Liquid permeability, g/m^2·h mbar[b]	16.3–17.8	10.7–13.5
Water sorption, g[b]	7.0–8.9	5.6–7.1
Heat capacity $\frac{(W\cdot\sqrt{s})}{m^2\cdot K^b}$	40–55	34–37

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surface of these devices, however, is also of importance for comfort and prevention of mechanical irritation. A smooth surface is better to avoid irritation.

Technically the most important compound for the production of superabsorbers is acrylic acid. The monomer acrylic acid is polymerized with the support of compounds like tri-allylamine. Co-polymerization allows the coating of cellulosic fibers like viscose or lyocell [12]. Such products are used for napkins and other hygienic devices. For both fields of application voluminous nonwovens are a significant supplement and a functional improvement (fig. 3). By application of the compound methods, multilayer products can be produced in which several layers fulfill different functions. The monolayers were created by several techniques, such as stitch bonding and needle punching (Kunit, Malivlies, needle-vlies). The assembly of the monolayers was realized by multiknit or Kunit layer compound procedures (KSB) [13, 14]. Soaking pads of modified nonwoven voluminous material with knitted fibers have been developed and used successfully for acute (split skin donor sites) and chronic (leg ulcers) wounds. In the field of pressure, sore prophylaxis special devices such as covers are under investigation.

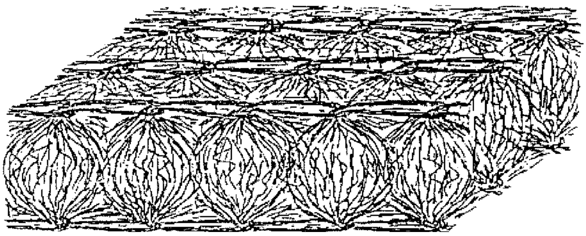

Fig. 3. Modified nonwoven with mixed knitted fibers for absorbing pads or incontinence devices.

Antibacterial Textiles

Textiles are carriers of bacteria and fungi. Controlling bacterial or fungal growth on fabric can be achieved by (a) finishing using resins to fix the antibacterial/antifungal agents to the textile surface or (b) grafting antimicrobials/antifungal agents on the cellulosic chain, i.e. viscose, lyocell etc.

Antibacterial activity is closely related to soil-repellent and soil-release qualities of textiles. Fluoropolymers represent the class of polymers usually used in anti-soil finishes. They consist of perfluorinated hydrocarbon units and fluorine-free polymer structures, which are linked together by spacers containing perfluorinated groups. These spacers can also act as bifunctional polymer linkage and can be polymerized and co-polymerized through unsaturated groups.

Extenders containing fluorine-free substances with isocyanate or other reactive groups serve to reduce application quantity of fluorine products and optimize the hydrophobic and oleophobic effects. Surfactants necessary for dispersion also contribute to anti-soil effects. Polymers with a polar structure exhibit good soil-release capabilities with high durability during washing. In recent years, combinations of fluoropolymers with siloxanes have been developed to improve anti-soil properties [15].

Recently, Kawoll®, a homogenous mixture of kapok hollow fibers and wool fibers, has been applied for bed covers. It has a positive effect on microclimate by moisture-absorbing capacity and an unusually high content of air. The kapok fiber also shows antimicrobial activity [16].

The most important criteria for the selection of additives are (a) their extremely low solubility in water, alkali and acid, (b) their chemical stability against strong acids, bases, and oxidants, and (c) their thermal stability. Additives should have no negative influences on the spinning process and fiber properties. They must have a migration capability from the fiber interior to its surface and should have excellent toxicologic and environmental properties.

Antibacterial activity of small ions like silver, zinc, copper and quaternary ammonium compounds is well documented. Silver impregnated textiles are used as wound dressings for infected wounds or wounds at high risk of infection. Whereas linkages between biocidal moieties and cellulose are covalently formed on reactive hydroxyl groups, polyamides, polypropylene and polyester lack such reactive sites. Quaternary ammonium salts have a positively charged nitrogen ion that can interact with the negatively charged groups of anionic dyes. These intermolecular interactions inside fibers serve as binding forces to enhance the durability of the biocidal agents once attached. Dye molecules can be used as bridges to bind functional antimicrobial groups to chemically stable synthetic polymers. Quantitative antimicrobial evaluations of treated fabrics reveal that there are significant reductions in bacterial load on surface contact [17].

Ofloxacin, penicillin and other antibiotics have been applied to polyester grafts. A collagen coating was used for binding chloramphenicol and rifampicin. A fibrin sealant was employed to bind gentamycin. More recently, ciprofloxacin and ofloxacin were used unmodified as dyes for polyester fibers. Pad heating was employed as well. The preliminary data were encouraging enough to conduct in vitro testing in rabbits. The best results were obtained with pad heating of a mixture of both antibiotics [18].

Another technique is the use of antibacterial agents in the spinning process of viscose fibers. Modal fibers are obtained by adding the antibacterial agent to the spinning dope. The viscose is pressed through the holes of the spinnerets into the generation bath where filaments are formed and drawn off at high speed. By the incorporation technique a homogenous distribution of the additive within the cellulose matrix of the fiber can be achieved. The hydrophilic and porous structure of the fiber enhances the diffusion of the agent onto the surface. This is also supported by a humid environment (i.e. due to sweating) [19].

The use of small molecules to prepare textiles is of hygienic interest, i.e. impregnation of towels, bed covers, underwear, etc. [20, 21]. In addition, antimicrobial activity can also reduce odor, which is of interest for wound dressing in the treatment of chronic wounds as well as for clothes [22].

Halamine-modified cotton has been used for protection textiles in workers exposed to pesticides. Halamine-modified cotton is also capable of suppressing a great variety of microorganisms including *Staphylococcus aureus*, a leading cause of infections in hospitals, or Salmonella species. Since body odors largely depend on the skin flora, halamine-modified cotton may also be used for odor control [22].

A principle for the development of functional textiles is based on permanent fixation of supramolecular compounds on textile surfaces [23]. These compounds are ligands with specific three-dimensional structures allowing the enclosure of certain chemical compounds. There is a molecular process of identification between ligands (host) and the complexed compound (guest) which in some respects resembles enzyme substrate relationship.

Among others, cyclodextrins have been used successfully as supramolecular compounds. The ring-like carbohydrates are nontoxic and nonallergic. They have a hydrophilic surface and can combine with hydrophobic unpolar organic molecules. The complex formation changes the physicochemical qualities of both the ‘host’ and the ‘guest’ [24]. In pharmacy, cyclodextrins have been employed to increase bioavailability and prolong efficacy of agents [25]. Cyclodextrins are of interest in the optimization of textile technologies as well. They have been used to remove surfactants from the goods or to deactivate in the liquid phase to enhance activity of enzymatic processes in finishing processes like degumming, desizing, or felt-free finishing of wool [26]. Cyclodextrin-prepared textiles can be used within transdermal therapeutic systems [27]. Another application is their use as transdermal collector systems in toxicology monitoring of personnel at high risk, to diminish bacterial contamination of sweat gland-rich skin areas (odor-defending textiles), and as antibacterial textiles [23].

Chitosan is a β-(1–4)-linked natural polysaccharide of 2-amino-2-deoxy-β-*D*-glucopyranose residues. The compound is highly biocompatible. Chitosan as well as its natural source, chitin, has gained increasing attention due to antimicrobial activity. Newly prepared derivates synthesized by N-selective introduction of quaternary ammonium-type side chains show low electric resistance making these materials as promising biocompatible antistatic materials [28]. Chitosan-based material has been used successfully as a wound dressing for burns and chronic wounds like leg ulcers and burns (fig. 4). Chitosan fibers or fibers covered with chitosan support local blood coagulation. They can be modified using functional groups comparable to the supramolecular approach. Other natural polymers of interest are pectins, alginates, bacterial cellulose and sulfated carbohydrates like carrageenan [29, 30].

Recently, cotton gauze dressings have been manufactured that are capable of binding elastase, which is overexpressed in chronic wounds and is thought to be responsible for delayed healing. Another attempt is to graft onto cotton fibers inhibitors of elastase that would be released into the wound over time. A third attempt is to modify gauze surfaces that would sequester both elastase and the appropriate mixture of metalloproteinases found in chronic wounds [31].

Cellulose is a component of modern wound dressings such as hydrocolloids. It has been demonstrated that carboxymethylcellulosis is capable of stimulating keratinocyte proliferation in vitro [Wollina et al., unpubl. data].

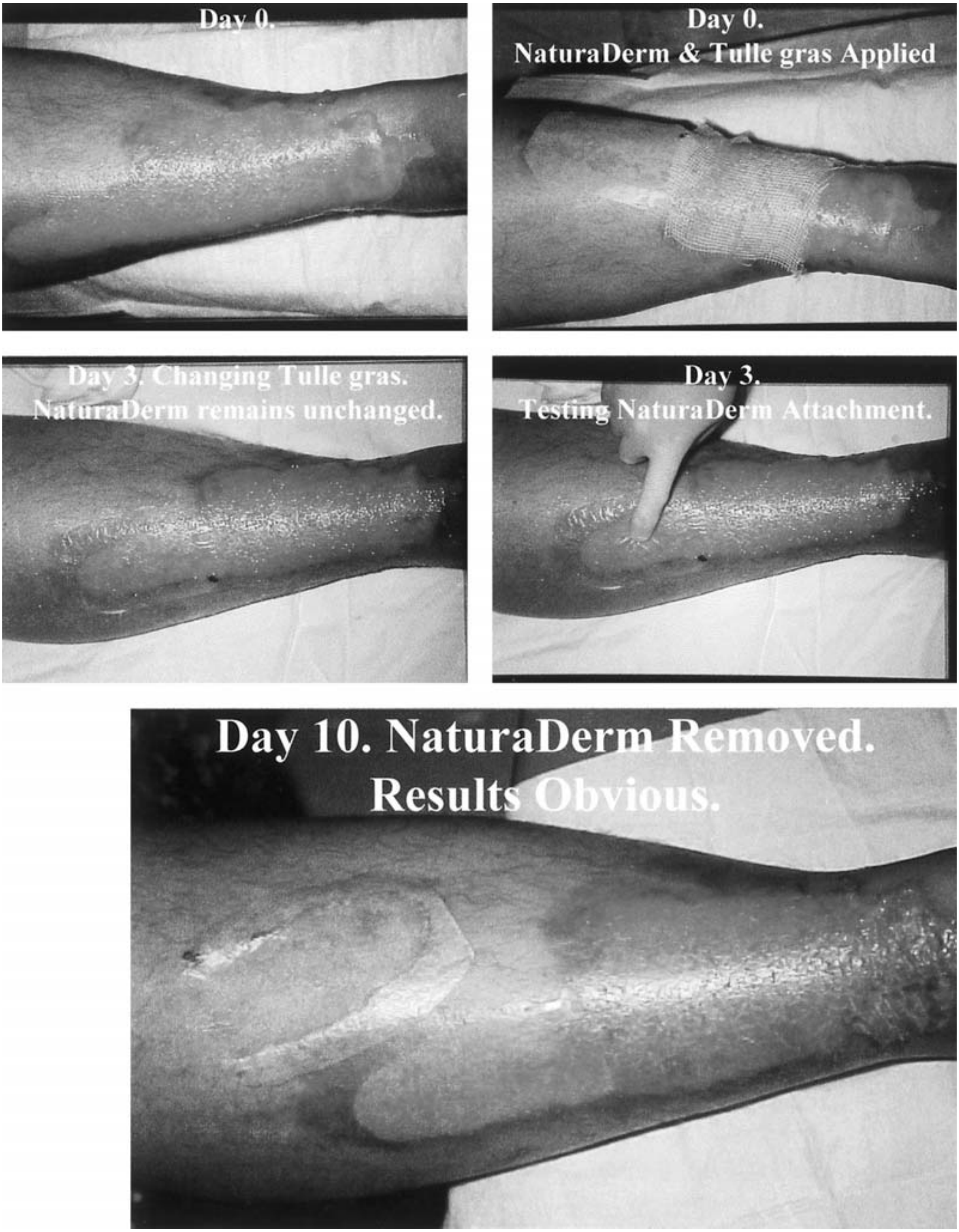

Fig. 4. Chitosan-based Naturaderm® on a burn wound.

Table 3. Basic properties of barrier textiles

Abrasion resistance
Blocking resistance
Flex cracking resistance
Puncture resistance
Tensile strength
Burst resistance
Trapezoidal tear resistance
Resistance to permeation by liquids
Resistance to penetration by particles
Resistance to ignition
Seam strength
Suit

Textile-Ceramic Composites

The sol-gel technique allows one to develop thin ceramic layers on different surfaces including textile fibers [32]. Hereby, three-dimensional structures with variable porosity can be prepared. This provides textiles a shelter against chemical or bacterial attack. In addition, fluid binding can be changed by ceramic surfaces. The porosity allows their use as drug carriers in transdermal therapeutic devices or collector systems as well. The coating can be used as a grinding aid for pharmaceutical formulations, as a stabilizing agent against temperature-humidity degradation of organic fibers, etc. [33, 34].

Ceramic matrix composites are of medical interest, i.e. in dentistry, orthopedics and surgery. The technology of textile structural composites has gained increasing technological importance. Two- and three-dimensional textile preforms have been used successfully for reinforcing ceramic-based composites. The potential of near-net-shape manufacturing of composites based upon textile preforms is very attractive [35–37].

Barrier Textiles

Barrier textiles are necessary in cases of high risk of contamination by infectious or toxic material. They are widely used in the operation theatre not only to protect the staff but the patient as well. Barrier textiles are of major importance in the hygienic regimen of surgical procedures and to prevent infections in the hospital. Table 3 provides a summary of basic properties of barrier textiles.

The protective function is obtained by the construction of fabric and product which shield the user from fine particulate matter or liquids. A basic quality of these textiles is the filtration of medically relevant media, like blood, sweat, urine, etc. Medical laminates are used for such purposes, which are composed of porous membranes, tissues and absorber. The fluid exchange is limited by capillary flow. Microfiber textiles were found suitable for re-usable protecting clothes [38, 39]. A critical structure is the seam area. Lapped seams provide a better barrier function, but other techniques such as polyurethane adhesives provide improved qualities. For medical applications like surgical gowns, sheets or mattress covers, polyurethane adhesives or hot melts have been used in different laminated materials. Chemical resistance, resistance against body fluids, laundry and sterilization are some of the demands for adhesives in this field [40]. Encasings are a special application of barrier systems for mattress and pillow covers. The barrier must be equally effective for airborne particles as well as mechanically transported particles. Again the seam areas and the fastening parts are critical in this respect. Since barrier retention capacity and particle transport are determined by the electrostatic behavior of the complex system 'bed', the electrostatic properties of the encasings and their wash-dependent variability have to be taken into account when considering barrier effects [41].

The most protective materials are the nonporous membranes. However, in practice a compromise has to be made between barrier function and comfort [42]. Another problem of conventional textiles in the operation theatre is the particle release, especially in the case of re-usable woven textiles for abdominal surgery. Knitted cotton dramatically diminishes particle release even after repeated washing-drying and disinfection cycles [43].

Use of Textiles for Organ Replacement, Grafting and Tissue Engineering

Braided fabrics can be used in textile composites. Textile composites are produced by impregnating matrix materials into their dry performs to hold the multidirectional yarns together. This is generally done by using liquid-molding techniques such as resin transfer molding, structural reaction injection molding, and resin film infusion. 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. However, braided fabrics exhibit poor stability under an axial compression in the yarn system direction [44].

Plain tubular braids may be used as prostheses for the replacement of injured ligaments in joints, like the human knee joint [45]. 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 behavior of the prosthesis, which should be adapted to the individual situation within the joint as well as to the intended implantation position [46]. In the future, braided lubricated packing of biocompatible lubricants may offer their use for other tendons as well.

Prosthetic arterial grafts have been developed on the base of knitted polyester (Dacron®) or polytetrafluoroethylene (Goretex®). They are available in a diameter range from 4 to 13 mm and length from 20 to 900 mm. A major problem of arterial grafts (as with other vascular grafts as well) 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. Preclotting has been found useful in delaying or preventing thrombosis. Albumin has been cross-linked around the graft and deposited by soaking the graft. Heparin has been used as a cationic surfactant. Binding of hirudin and thrombomodulin to albumin-coated surfaces provided promising results. None of these methods is completely successful. Recent investigations have tried to covalently bond a glycoprotein specific for endothelial cells to the surface attracting endothelial cells from surrounding vessels. Another attempt is to covalently bind anticlotting proteins to the graft like nonylphenol-9-ethylene oxide [18].

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 mold and by subsequent thermal gelatination, followed by 7-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 [47].

Polyester meshes are employed in hernia repair in the concept of open, tension-free hernioplasty. Among other materials, textile meshes are made either from bioresorbable polymers such as polyglycolic acid and polyglycolide lactide or nonresorbable polymers such as polyester, nylon, polypropylene and carbon [48]. Biocompatibility and stability are major qualities of such meshes. In vitro studies in piglets suggest that a fluoropassivated polyester-knit mesh offers advantages in sense of greater mechanical reinforcement, and tissue development versus a polypropylene mesh. The healing performance of the fluoro passivated mesh was attributed to a more intense chronic inflammation, which stimulated greater tissue ingrowth and integration [49].

Polyglactin filaments added to a propylene mesh reduces the number of macrophages and granulocytes as measures of acute inflammation. The scar reaction is limited merely to the perifilamentary region. The abdominal wall compliance, on the other hand, remains unchanged. Coating of polypropylene with polyglactin favors the development of a connective tissue capsule around the mesh, which seems to hinder its incorporation [50].

Despite all the efforts made in textile technology for prostheses, tissue engineering has become available in wound healing. Tissue engineering seeks to create functional substitutes for damaged tissues by combining engineering principles with life sciences. Different approaches were made for artificial skin, chimeric skin substitutes and hybrid technology using living and nonliving components to substitute lost organ functions [cf. overview: 51, 52].

Textiles are interesting for biodegradable tissue engineering scaffolds. The cellular components will generate new tissue through production of extracellular matrix, while the scaffold material provides structural integrity and mechanical stability in the mean time. 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 [53].

Composite scaffolds combining textile superstructures and biomimetic glycopolymers have been developed for the engineering of organotypic liver tissue in vitro. Woven polyethylene terephthalate (PET) fabrics were coated on one side with a thin biodegradable polymer film of poly[*D*,*L*-lactic-coglycolic acid] (PLGA) in order to obtain a polar structure. The composite structure ensured the stability of the membrane during degradation of the membrane polymer. For hepatocyte culturing studies, the scaffolds were coated with an artificial glycopolymer, poly[N-*p*-vinylbenzyl-*D*-lactoamide] (PLVA) to improve cell attachment. The addition of epidermal growth factor and the use of a large mesh size offered the optimal conditions for liver cell culturing in vitro [54, 55].

Textiles show two classes of porosity which can be controlled selectively: pores between the yarn filaments and pores defined by the interloop space. The very nature of textile processing is their high periodicity. Spacer fabrics have been used for scaffolding of human and rodent cells like keratinocytes or hepatocytes [6] (fig. 5). Embroidery technology, on the other hand, allows to control material, porosity and mechanical properties locally in a given textile geometry without any periodicity. Polyglycolic acid yarn was used in embroidery technology in vitro stitched either on a nonwoven polyvinyl alcohol tissue or onto a basic polyester structure. The stitching technique is investigated for local drug delivery from a textile implant and for the development of composite textiles with locally different degradation rates to favor tissue ingrowth with improved mechanical properties [9].

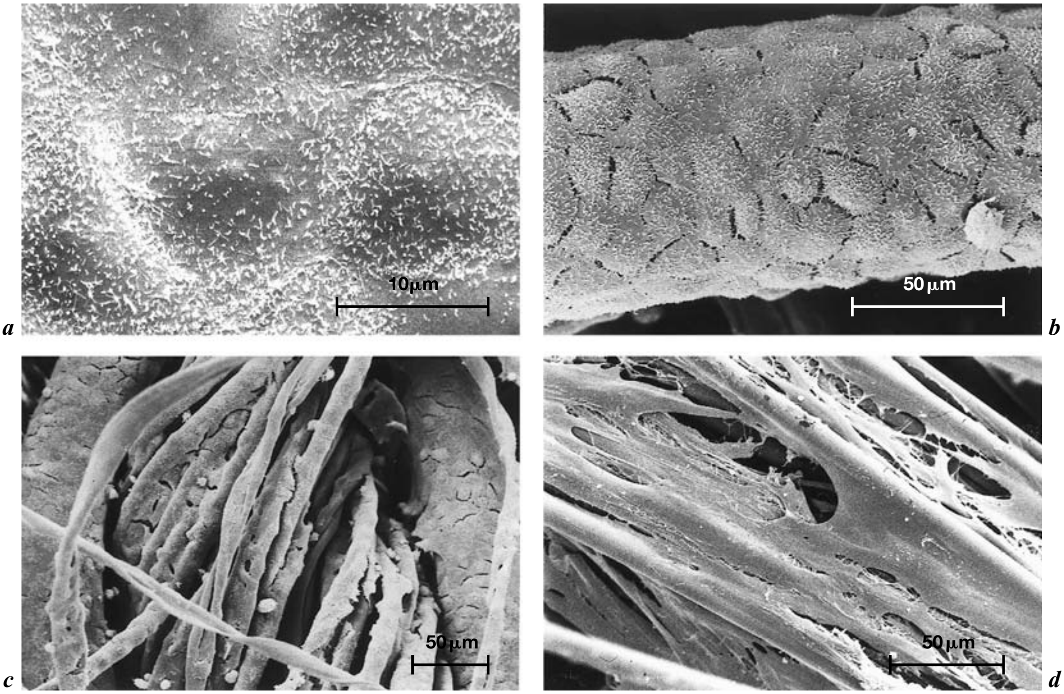

Fig. 5. The use of spacer fabrics in tissue engineering. Scanning electron microscopy of rat liver cells, 9 days of culture, on (***a***) sulfated polystyrol (tissue culture chamber) and polyester-based spacer fabrics (***b***, ***c***). Note the confluent growth of cells on these filaments. (***d***) Skin fibroblasts on polyester-based spacer fabrics, 6 days of culture.

Acknowledgements

The authors gratefully acknowledge helpful support and discussions by Dr. R. Teichmann (Saxonian Textile Research Institute, Chemnitz, Germany), H.-J. Goeser and E. Gründig (C.B. Göldner GmbH & Co. KG, Werdau, Germany), and Dr. G. Neupert (Institute of Pathology, Friedrich Schiller University, Jena, Germany).

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