An Introduction to HEALTHCARE *and* MEDICAL TEXTILES

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To
my father (Liangming Zhong)
my mother (Feifei Yin)
my husband (Malcolm Xing)
and my children (Harvey and Max)

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Preface

For eight years at University of Manitoba I've been teaching two courses related to what I am writing about: *Textiles for the Healthcare Sectors* and *Advanced Textiles for the Healthcare Sectors.* All these years, I've tried in vain to find for my students a textbook that is commercially available. Dealing with an interdisciplinary topic, I've been trying to accommodate the needs of students for such varied areas as materials (including textiles) science and engineering, biomedical engineering, and health studies. On the one hand, students with a background in materials science and engineering may have difficulties understanding the basic mechanisms of the interaction between biotextiles and host cells/tissues; on the other hand, students without the background in textiles may get confused with the various textile structures, including wovens, knits and different types of nonwovens. Similarly, when I am approached by graduate students or professionals in the areas of Materials Science or Biomedicine for a book that will give them some background knowledge about fibers and textiles and how their structures and properties influence their biomedical applications, I've had similar difficulties recommending sources that are tailored to their needs. Such experience has caused me to believe that it is a good idea to write a book of this nature.

The text of this book is organized into two parts besides the first introductory chapter. Four chapters dealing with the basics of what is involved in the area of healthcare textiles comprise Part I. The six-chapter Part II addresses the various applications of healthcare/medical textiles.

Introductory in nature, this is a textbook for students but, since it also includes the latest developments in the related areas, it also suits the needs of professionals who happen to want to learn the basics of fibers and textile structures that can be used in the healthcare sectors, as well as information on design and product development in medical and healthcare textiles. To that end, I have tried to connect the basics of textile engineering and related concepts to the design and development of textile materials and structures for medical end uses. The text of the book is prepared in such a way as to accommodate readers with different backgrounds and intentions, and those who wish to get deeper into a related subject discussed in the book can refer themselves to the abundant literature at the end of each chapter. Specifically, this book is intended to benefit:

1. Senior undergraduate students or graduate students in the disciplines of Textile Sciences, Materials Science and Engineering, or Biomedical Engineering who need a textbook or reference book;
2. Professionals in medical/healthcare textile product development who may find a handbook of this nature useful; and
3. Other professionals (in Materials Science and Engineering, Biomedical Engineering, or Biomedicine) who now and again need to know something about textiles.

At the close of my endeavor, I wish to extend my appreciation to the individuals and parties that have made this book possible. The book would never have been written or be like what it is now had it not been for the opportunity provided by Faculty of Human Ecology, University of Manitoba, an opportunity that has involved me in an interdisciplinary field, provided me valuable interactions and collaborations with researchers in the many related areas, and thus had me well prepared. I also wish to extend thanks to undergraduate and graduate students that I have been working with in the past seven years in my courses about medical textiles. They have had to deal with a situation where the essential *textbook* is so miserably lacking that they have had to learn their lessons depending on handouts and copies of reading materials from various sources, never making a complaint. Instead, their inputs and suggestions have been valuable for the improvement of the courses, and have certainly functioned as a pat on my back during my efforts to teach and write. I also wish to say a word of thanks to faculty colleagues who have reviewed my book in such a way as to be in a position to help eliminate errors and suggest improvement; they are, especially, Drs. & Professors Lena Horne and Michael Eskin.

Special thanks are due to my family—people who have provided any type of support I need. Among them, my father, Professor Liangming Zhong, has been the first reader of my draft book and has tried to make sure that this book can be understood by those who are totally outside of the field; my husband and collaborator, Dr. Mengqiu (Malcolm) Xing, a professional of Biomaterials and Regenerative Medicine, has provided insights as such.

Finally I wish to express my appreciation to *you,* readers of the book, who are the ones most likely and able to offer comments and suggestions essential for improvement to be made in the future, which will benefit all who will use the book, including my students and me as a teacher. So let me know such comments and suggestions, please. Please contact me at zhong@cc.umanitoba.ca.

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WEN ZHONG

CHAPTER 1

Introduction

WHAT are healthcare and medical textiles? It is the first question that must be answered in this book. The Textile Institute (UK) defines *medical textiles* as “a general term which describes a textile structure which has been designed and produced for use in any of a variety of medical applications, including implantable applications” (Denton, 2002). Following the same line of thinking, we can define *healthcare textiles* as textile structures designed and produced for use in the various healthcare sectors. Although there are slightly different implications between the practices of medicine and healthcare, the two terms, medical textiles and healthcare textiles, are often used together or interchangeably, and will be treated as such in this textbook.

Healthcare and medical textiles are a major growth area within the scope of *technical textiles,* which is defined as “textile materials and products manufactured primarily for their technical performance and functional properties rather than their aesthetic or decoration characteristics” (Denton, 2002). Technical textiles include, in addition to healthcare and medical textiles, aerospace, industrial, marine, military, safety and transport textiles and geotextiles (Horrocks and Anand, 2000; Denton, 2002). Over the last few decades, there have been significant changes in the textile market, where traditional textile products, or the textile products produced primarily for their aesthetic or decoration properties (e.g., *apparel*), account for an increasingly smaller portion, while technical textile products constitute an increasingly larger portion.

According to the end use survey reports on the use of fiber quantities (manufactured and natural fibers) released by the U.S. Fiber Economics Bureau, the market share of apparel dropped dramatically from 35% to 15% between 1999 and 2010. Home textiles also showed sizable shrinkage in the market, from 16% to 8%. On the contrary, floor cover-

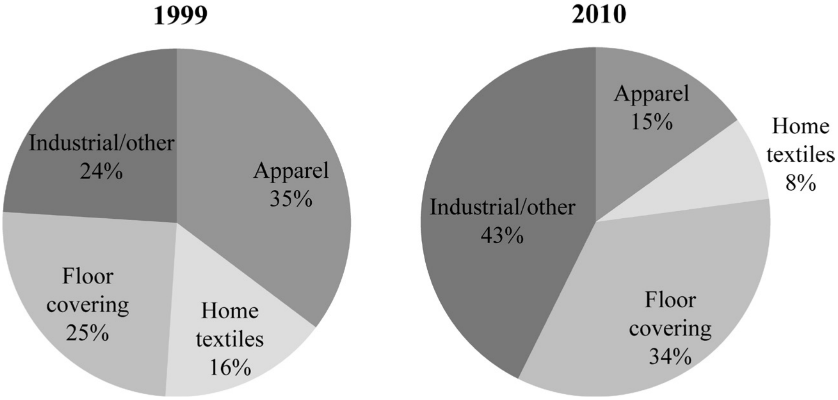

FIGURE 1.1. Market shares of end use categories.

ing increased its share from 25% to 34%, and industrial and other consumer-type textile products demonstrated the largest increase in market share, from 24% to 43%, as shown in Figure 1.1 (Horn, 2011). According to U.S. Fiber Economics Bureau, the category of industrial and other consumer-type textile products overlap a major portion of technical textile products, including narrow fabrics, medical, surgical and sanitary products (excluding sutures), transportation fabrics, tires, hose, belting, electrical applications and reinforced plastics, felts, filtration, sewing thread (including medical sutures), rope, cordage and fishline, bags and bagging, coated and protective fabrics, paper and tape reinforcing, fiberfill, stuffing and flock, and unallocated nonwovens. Figure

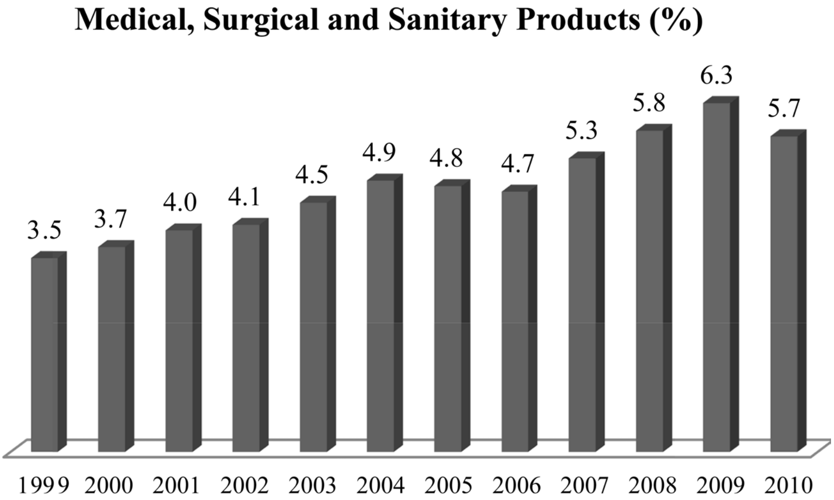

FIGURE 1.2. Market share of medical, surgical and sanitary products (sutures not included).

1.2 also shows a steady increase of market share of medical, surgical and sanitary products (excluding sutures) in the last decade.

1.1. MATERIALS FOR HEALTHCARE AND MEDICAL TEXTILES

Traditionally, a textile product starts from such raw materials as natural or synthetic fibers. Fibers are spun into yarns and then woven or knitted into fabrics. After the dyeing and/or finishing processes, the fabrics can be further turned into a product like apparel, bed sheets or curtains.

The last century witnessed the creation and commercialization of a number of synthetic fibers, which helped bring about the mass production of textile fibers with better performances and specific functional attributes, including better mechanical strength, thermal/chemical resistance, and UV/microorganism resistance. These advantages expanded the end uses of textile materials, especially of technical textile products.

With the progress of materials science and related research work in the last few decades, new fibrous materials (created or as a result of modifications on existing fiber materials) are now available and are being applied in a vast variety of end uses. A striking example is the application of new biocompatible and biodegradable polymer and fiber materials in surgical implants. Modifications on existing fiber materials, both physical and chemical, allow end products to perform such important functions as absorption or cause them to be antibacterial, flame retardant or antistatic.

New fabrication methods have also been developed to create fibrous structures other than woven and knit. For example, nonwoven technology has enabled the manufacturing of fabrics without the yarn spinning process, which not only substantially reduces production cost but also causes the end products to have porous and highly absorbent structures to meet the requirement of hygiene products. The technology of electrospinning allows the production of ultrafine fibers in the size of nanometers, which is way beyond the capacity of traditional fiber spinning technology. Combination of a fibrous material and another material such as polymer, metal or ceramic helps produce various kinds of composite materials that will bring about a synergy between two dissimilar materials.

Due to these new technologies, a much wider range of textile materials, structures and processing techniques are now available for the design and development of advanced products for many purposes, including healthcare and medical applications. As a result, readers of this book will be exposed to a vast variety of materials and structures that are not used for traditional textile products, or for other technical textile products, but are especially suitable for medical and healthcare purposes. Readers will also learn that design principles and evaluation criteria for these special-purpose textile materials differ significantly from those for other applications. To facilitate such understanding, Part I of the book will be devoted to the discussion of such basics for the healthcare and medical textiles: Chapter 2 briefly introduces the fundamentals of textile materials and structures, and how these textile components may be used in the design and development of healthcare and medical products; Chapter 3 discusses medical and healthcare nanofibers, which are not produced via traditional textile processing methods but are of importance in the development of a variety of biomedical textile products. The following two chapters focus on important design criteria for healthcare and medical textiles. Chapter 4 emphasizes textile-related comfort issues and healthcare problems, which are essential for the design and development of medical and healthcare textiles for external end uses; Chapter 5, on the other hand, concentrates on biocompatibility, biostability, and bioresorbability, which are critical criteria for the design of any medical textile product for internal applications.

1.2. APPLICATIONS OF HEALTHCARE AND MEDICAL TEXTILES

Healthcare and medical textiles are found in a wide variety of applications. A non-exhaustive list of these is given here and is discussed in greater detail in Part II of the book.

Hygiene is critical in the practices of healthcare and medicine to prevent diseases and infections and to preserve health. Various textile products are available to facilitate hygiene in both personal life and in healthcare facilities. Highly absorbent products, mostly disposables, have been used to retain body fluids/waste to keep skin surfaces clean and dry. Depending on their end users, they are referred to as *diapers, sanitary napkins* or *incontinent pads*. The development of these products has gone through a long journey; improvements of product performance in terms of absorbency and comfort continue to be made. Since use of these products often has environmental consequences, the discussion will naturally encompass related issues, especially those associated with the so-called *disposables.* For more details about *hygiene textiles,* see Chapter 6.

Since we have extremely tender *skin* as opposed to our audaciously hard surroundings, for many hundred years, we humans have dreamed of having it assisted by something that is as light as cloth but as strong as iron, able to keep us warm and *protect* us as well! Nowadays such wonder clothes/devices are no longer miracles. The last few decades witnessed the development of high performance fibers/fabrics, which, due to their specially-engineered structures or finishes, have rendered a clothing system "protective". Also, depending on the nature of external hazards, different types of protective clothes have been developed to keep us safe from extremely high/low temperatures, mechanical impact, harmful chemicals, microorganisms, insects, UV radiation, and so on, as a result of our having rendered them *fireproof, bulletproof, waterproof, dust-impermeable,* etc. More detailed information on *protective textiles,* especially those used in the medical/healthcare sectors, will be given in Chapter 7.

A large part of the practice of medicine is to aid healing. The treatment of an open wound to facilitate its healing usually involves the use of wound care products like wound dressings. Numerous wound care products are now available on the market to treat wounds of different types and with diverse severity. Many of these are in textile structures. More details about *wound care textiles* can be found in Chapter 8.

Replacement, reparation or regeneration of injured or diseased human tissues or organs has long been a challenge in the practice of medicine. Tremendous progress has been made in the area of tissue or organ transplantations, which save or improve the life of millions of people every year. However, the severe shortage of donors for tissue/organ transplantation makes it critical to develop alternative means. As a result, implantable biomaterials, including *biotextiles* (see Chapter 9), have been developed to be used in a biological environment to replace or repair the damaged human tissues/organs or to assist such repairing processes: sutures are used to close surgical wounds, and vascular grafts, ligament prostheses and hernia repair mesh grafts are also used clinically. However, for most of the grafts made of biotextiles (or other biomaterials)—especially those for permanent implants—their performances are still far from being satisfactory in terms of biocompatibility and biostability. As a promising effort to overcome the drawbacks of current grafts made from biomaterials, tissue engineering approaches aim at developing biological substitutes for the repair or replacement of damaged human tissues or organs. In such a process, appropriate living cells are seeded on a matrix or scaffold and then guided to develop into a new and functional living tissue for implantation. A number of such products, known as *bioengineered grafts,* are already used in clinics. More details about these *tissue engineered grafts* are provided in Chapter 10.

Recent advances in nanotechnology, electronics, materials science and the collaboration among scientists in these fields have resulted in the development of *smart* or *intelligent* textiles that can sense and/or respond to mechanical, light, thermal, chemical, electrical and magnetic stimuli. This is possible because, since these stimuli are able to change the appearances (e.g., color) and/or structures of the smart materials incorporated into the textiles during their fabrication, these changes will emit a warning signal (e.g., a flashing light). Smart textiles may have applications in such end uses as sports/recreation or special work wear for first responders or for use in extreme environments (e.g., space exploration), where early signals of distress would enable timely interventions. More commonly and to the benefit of still more people, they can be used by people whose heartbeat, respiration, blood oxygen saturation, temperature or body motion needs monitoring. Chapter 11 provides a detailed discussion about medical/healthcare *smart textiles*.

1.3. SUMMARY

To a large degree, progress of textile science and technology comes hand in hand with the expanding application of textile materials and structures. Traditional textile products, or those manufactured primarily for their aesthetic or decorative properties, have been shrinking greatly in their market share of fiber usage. On the other hand, interdisciplinary collaboration between textile science and technology and other fields (e.g., engineering, architecture, biology and medicine) have resulted in the creation of technical textiles, covering such sectors as transportation, architecture, sports and medicine.

The future of the textile science and industry lies in the development of new advanced textile materials and structures to meet the demanding needs in the various fields. Among them, medical/healthcare textiles have been one of the most rapidly-growing sectors for a number of years. Born from the marriage of textile science and medicine, these new textiles help prevent and cure diseases or injuries. Aimed at the promotion of human health, the research and development of medical/healthcare textiles have attracted enormous attention and effort. This book will give a description, as comprehensive as possible, of the wide variety of textiles for medical and healthcare end uses.

1.4. REFERENCES

Denton, M.J. (2002). Textile terms and definitions, 11th Ed. Manchester, UK: Textile Institute.

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Part I
Basics

CHAPTER 2

Textile Materials and Structures

THIS chapter contains the basics of textile materials and structures, especially those used in healthcare and medical textiles. They are reinforced by discussions of the contribution of the characteristics of these textile materials and structures to the functionality of the products and their special end uses.

2.1. MATERIALS AND STRUCTURES USED FOR HEALTHCARE AND MEDICAL TEXTILE PRODUCTS

Textile is defined as "a general term for fibers, yarn intermediates, yarns, fabrics, and products that retain all the strength, flexibility, and other typical properties of the original fiber or filaments" (ASTM, 2008). In other words, textiles are made from the basic elements of fibers. However, to develop healthcare and medical textiles, materials other than textiles have to be included. This makes it necessary, at the very beginning, to list related materials and structures that comprise healthcare and medical textiles. In Figure 2.1, they are shown in such a way that each lower-level constituent component (i.e., *raw material*) is related by an arrow to a higher-level component (i.e., *transformation,* or *product*) that is composed of the lower one. If a component, whatever its rank, is related by several arrows to several higher components, they are each and all composed of that lower one as a constituent component.

Shown also in Figure 2.1 is a chain of traditional textile transformation processes (highlighted in bold text): *fibers* composed of natural or synthetic *polymers* are spun into *yarns,* followed by being woven or knitted into *fabrics* and further fabricated into specific *products,* including *apparel.*

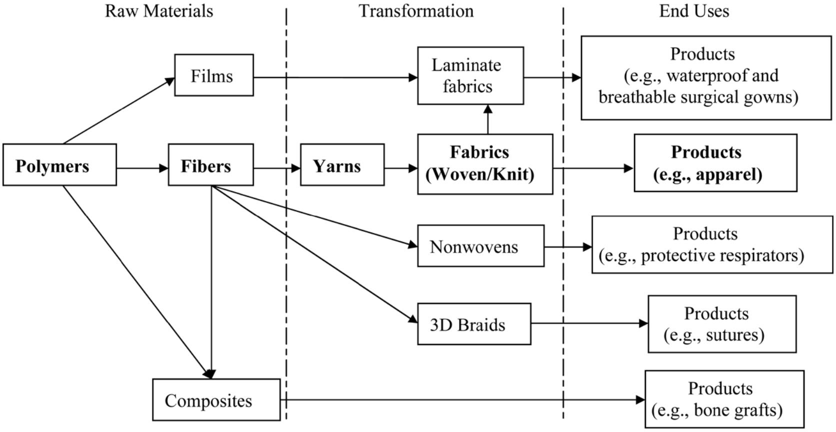


FIGURE 2.1. *Materials and structures used for healthcare and medical textile products.*

Beyond that, there is a variety of structures that are more often used in technical end uses: laminated fabrics can be made by bonding a fabric(s) with a polymeric film(s)/foam(s) by using an adhesive or by the adhesive properties of one of the layers. By controlling the pore sizes in micro-porous films, waterproof but breathable (i.e., water vapor permeable) fabrics can be obtained. Such fabrics are desirable in applications like surgical gowns, where both protection (e.g., against body fluid through which diseases may be transmitted) and comfort are essential. Fibers can also be directly processed into nonwoven fabrics, in which fibers are bonded together via mechanical, thermal or chemical means. Skipping the yarn-spinning procedures, nonwoven fabrics are known for their low cost, making them desirable for applications in disposable hygiene and protective products. Filaments can be braided into 3-dimensional (3D) braids for specific products that require exceptional mechanical properties in the longitudinal direction. Sutures and ligament prostheses are two examples of medical textile products made of braids. Fiber-reinforced composites are another form of structure that can be used for products that require both excellent tensile and compression strength, which can be realized through the synergy effects of the two components that constitute the composite material. Periodontal and bone grafts, for example, can be made of such composite materials.

Although processed through different routes, as listed in Figure 2.1, textile products are entirely or partially composed of fiber materials. In this book, ANY product, device, material or structure that is for medical and healthcare use and is made of fiber materials will be included in the discussion.

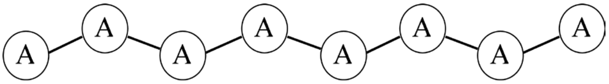
The following sections constitute a discussion of the various components of textiles as listed above, and of their proven or potential applications in the medical and healthcare sectors.

2.2. POLYMERS

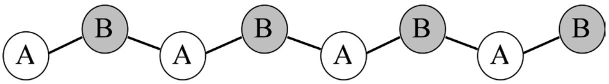
All fibers are made of macromolecules or *polymers* (in which *poly* means "many" while *mer* refers to "repeating units"). A polymer is formed when hundreds or thousands of small molecules (units) are covalently bonded, usually into a linear chain. A repeating unit of a polymer is known as *monomer.* The number of repeating units in a polymer chain is called the *degree of polymerization.*

2.2.1. Types of Polymers

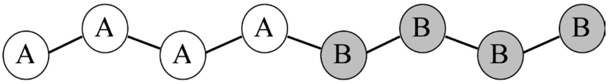
Polymers can be categorized in different ways according to their structures. They can be divided into homopolymers, copolymers or block polymers, as shown in Figure 2.2. A *homopolymer* is composed of one monomer [as represented by the symbol A in Figure 2.2(a)] that repeats itself throughout the polymer chain. Most of the general-use fibers, including cotton, rayon, wool, silk, polyester, nylon, and polypropylene fibers, are composed of homopolymers. A *copolymer* usually contains two or more monomers [e.g., symbols A and B represent two different monomers in Figure 2.2(b)] that appear alternatively along the polymer chain. Acrylic fibers are composed of copolymers. A *block polymer* has two or more repeating blocks or segments along the polymer chain, each of which is a homopolymer, as shown in Figure 2.2(c). Spandex fibers are made of block polymers.



(a) Homopolymer



(b) Copolymer



(c) Block polymer

FIGURE 2.2. *Polymers of different structures.*

Polymers can be either thermoplastic or non-thermoplastic polymers. *Thermoplastic polymers* will soften and melt when heated and harden when allowed to cool down, with their polymeric structure remaining intact if the temperature is below that for their decomposition. Polyester, nylon and polypropylene fibers are composed of thermoplastic polymers. Cellulosic, acrylic and aramid fibers, on the other hand, are made of *non-thermoplastic polymers,* and will not soften or melt before irreversible decomposition occurs. These thermal properties may determine the way in which the manufactured fibers can be produced. Thermoplastic polymers can be spun into fibers via *melt spinning,* whereby a molten polymer is extruded through the holes in a spinneret, and then solidifies while traveling in the cool air to form fibers. Non-thermoplastic polymers cannot be processed by melt spinning. They are usually dissolved in appropriate solvents. The polymer solution will be extruded through the spinneret into a hot air or liquid bath, so that the solvents will be evaporated in the hot air (in the case of *dry spinning*) or extracted by the liquid bath (*wet spinning*) to yield fibers.

2.2.2. Structures and Properties of Fiber Polymers

The performance of fibrous materials originates from the structures and properties of their constituent polymers. The backbone of most polymers for textile fibers contains covalently bonded carbon atoms (C). Other atoms such as oxygen (O) and nitrogen (N) may also appear in the polymer backbone and be covalently bonded to carbon atoms. The atoms in the backbone can be covalently bonded to hydrogen atoms (H) and other side groups.

Polymer chains are arranged in certain ways to form a fiber. In a linear polymer structure, the degree of parallelism of the chain molecules to the fiber axis is referred to as *degree of orientation.* On the other hand, a polymer chain may run through different regions in a fiber with different packing density (Figure 2.3). Polymer chains pack tightly in an orderly fashion in the so-called *crystalline regions,* while distributing loosely in a disordered pattern in the *amorphous regions.* The highly packed crystalline regions contribute to the mechanical strength of the fiber, while the loosely packed amorphous regions allow the uptake of water molecules or other chemicals that may be incorporated into the textile products (e.g., dyes, finishing agents). As a result, a high degree of orientation and crystallinity usually contribute to high mechanical strength, low elasticity, and low absorbency.

Various interactions are involved within a polymer chain and between the polymer chains that constitute a fiber. The atoms within a polymer chain are mostly linked by the *covalent bond,* in which the

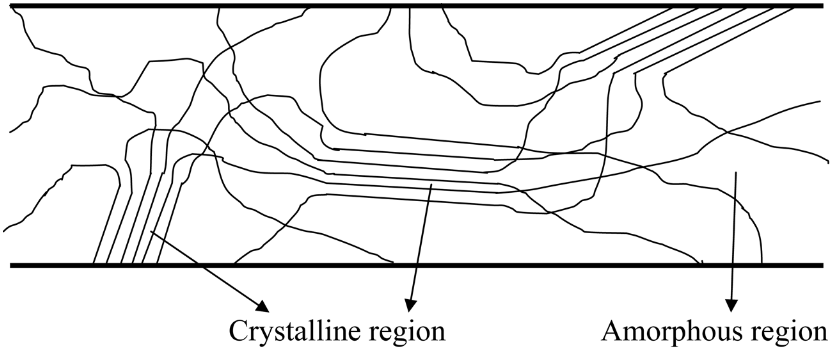


FIGURE 2.3. *Crystalline and amorphous regions within a fiber.*

electrons that are shared by two atoms shift away from the center or stay unchanged due to the difference between the capacities of the two atoms to attract electrons. The tendency for an atom to attract electrons is known as *electronegativity*. The more one atom attracts electrons, the more electronegative it is. O and N are atoms that are very electronegative; O has even higher electronegativity than N. These atoms can pull electrons from atoms with less electronegativity (e.g., C and H) when forming covalent bonds. A covalent bond formed between two atoms with similar electronegativity is referred to as *non-polar covalent bonds,* such as those between two carbon atoms (including single C–C bond in which one pair of electrons are shared between the two atoms, double C=C bond in which two pairs of electrons are shared, and triple C≡C bond in which three pairs of electrons are shared) and between carbon and a hydrogen atoms (C–H). On the other hand, a covalent bond formed between two atoms with different electronegativity is called a polar covalent bond, like C–O, C=O, C–N, O–H.

A molecule or a chemical group (i.e., two or more atoms that are bonded together as a single unit to appear as a part of a molecule) is usually composed of one of more covalent bonds; it may be regarded as a polar or non-polar molecule (or group) as a result of the arrangement of the bonds. In the simplest case, the polarity of a molecule or group containing only one covalent bond can be determined by the polarity of the bond; for example, carbon monoxide (CO), hydroxyl (–OH) and nitrile (–C≡N) groups are known as polar molecule/groups. For a molecule or group with more than one covalent bond, its polarity depends on the distribution of the bonds: Non-polar molecules or groups may be composed of exclusively non-polar bonds. Examples are polypropylene (Figure 2.10) and methyl groups ($-CH_3$). On the other hand, a molecule or group containing polar bonds is most likely a polar molecule/group (e.g., –COOH carboxyl group), unless the polar bonds are arranged in an asymmetric manner to balance out the polar effect (e.g., CO_2 carbon dioxide).

The polarity of a polymer or its side groups can affect the properties of the polymer. Non-polar groups are usually less reactive than polar groups. Polar groups, such as hydroxyl (–OH), have better affinity to water molecules via the *hydrogen bonds,* which occur between a hydrogen attached to an electronegative atom (e.g., oxygen, nitrogen) of the molecule and an electronegative atom of a different molecule. Hydrogen bonds are the strongest intermolecular forces. Figure 2.4 shows a hydrogen bond between a water molecule (H_2O) and a hydroxyl group in a polymer (e.g., cotton). The high electronegativity of the oxygen renders the oxygen atoms (in both the water molecule and hydroxyl group) slightly negatively charged (δ–) and the hydrogen atoms slightly positively charged (δ+). The oxygen in the water molecule, which has two additional lone electron pairs, may utilize one pair to attract the hydrogen in the hydroxyl group to form a hydrogen bond, and may use the other pair to attract the hydrogen in a second water molecule to form another hydrogen bond. This explains why fibers with polar groups tend to attract water molecules and adhere to them tightly.

Neutral or non-polar molecules attract each other via very weak electrostatic forces, known as *Van der Waals forces,* which is one of the most important long-range forces between macroscopic particles and surfaces. They are general forces that always operate in all materi-

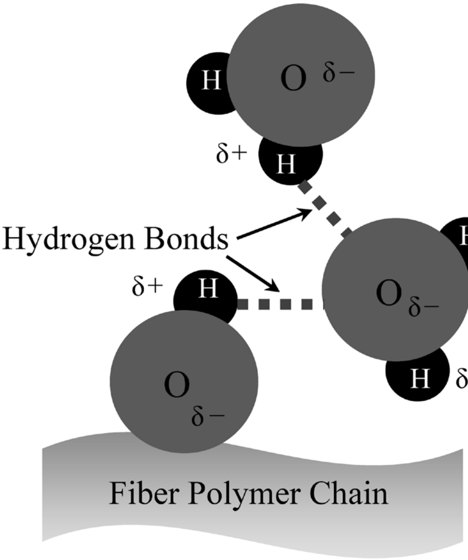


FIGURE 2.4. *Hydrogen bonds.*

als and across interfaces. Van der Waals forces are much weaker than chemical bonds. Random thermal agitation, even at around room temperature, can usually overcome or disrupt them. However, they play an important role in all phenomena involving intermolecular forces, especially those interactions between electrically neutral molecules. Nonpolar polymers, such as polypropylene, attract water to their surfaces via the Van der Waals forces.

2.3. FIBERS

A fiber is the basic, smallest element of a textile material. It is usually long, flexible and extremely thin. Traditionally, a minimum length of 0.5 inch (15 mm) and a length-to-diameter ratio of at least 100 are required for fibers that will be used in spinning and weaving.

The development and introduction of new structures of textiles have made revolutions first in our mind and then in the market, so that nowadays we have, in relation to their origin, *natural* and *man-made* fibers. Natural fibers are derived from plants, animals, or minerals, to be respectively referred to as *cellulosic* fibers, *protein* fibers, and *inorganic* fibers. Man-made fibers are regenerated from natural resources (regenerated fibers) or synthesized from small, organic molecules (synthesized fibers).

2.3.1. Natural Fibers

Natural fiber is defined as "any fiber that exists as such in the natural state" by the Federal Trade Commission (FTC, 1958). Natural fibers include cellulosic fibers and protein fibers. They vary in macroscopic size, length and shape.

2.3.1.1. Cellulosic Fibers

Cellulosic fibers are characteristic of a polymeric structure of linear cellulose, which is composed of β-D-glucose (Figure 2.5). Plenty of hydroxyl groups (–OH) are present in the molecular structure of cellulose. As a result, cellulose fibers are known to be hydrophilic, meaning they are "water-loving", making them absorbent.

Cotton is the most common cellulosic fiber with a white or off-white color. It is a hair of the seed taken from the boll of the cotton plant. Cotton fibers are short or staple fibers with a length in the range of 1/8 to 2.5 inches (0.32–6.35 cm) and a diameter in the range of 16–20 μm (Hatch 1993). Multiple layers exist at a cross section of a cotton fiber, including the outer skin (i.e., the cuticle, which is a thin waxy layer), the

CHAPTER 11

Intelligent Medical and Healthcare Textiles

INTELLIGENCE is a capacity of human beings and some living creatures. The most admirable of such intelligence is man’s ability to “sort of know” something simply according to some “feeling”, without resorting to any extra, material means (a tool, for example), and to respond to that something (regarded as a “stimulus”) by modifying one’s behavior to effect positive outcomes. People have for centuries been dreaming of, and busying themselves with, making tools that also possess that remarkable capacity to know, react and adapt to stimuli.

An even bolder dream is the incorporation of intelligence into materials (metals, textiles, etc.). This dream may have been prompted by the great multiplicity of stimuli (e.g., mechanical, thermal, chemical, electrical and magnetic) that stand in the way (or “the environment”, to use a modern phrase) as inconveniences, obstacles, hazards, etc. This is the classical dream of having an extra “sense” (i.e., one in addition to the corporal “five senses”), a dream for making man abler and stronger.

A word of comfort is that such materials no longer exist only in our dreams. Over the decades, as is the concern of this book, a variety of intelligent textiles and smart products have been used to promote health and quality of life. This chapter will address such textiles and their applications in the medical and healthcare sectors.

11.1. INTELLIGENT MATERIALS

Textiles are the traditional (and the most common) material able to protect us from cold, heat, or other environmental hazards. In order to improve and add to such protective functions, innovations and development implemented in material science and technology have brought about new textile materials and products capable of playing more active roles towards man's better quality of life and increased health and well-being. Related to a rather new field of research and development, *intelligent textiles,* interchangeably termed as *smart* or *active* textiles, refer to textile materials and/or structures that are potentially able to sense, react and/or adapt to environmental stimuli, and therefore can be used in products for performing these functions, as discussed in Section 11.2.

11.1.1. Chromic (Color Changing) Materials

Chromism refers to the phenomenon of color change. Materials that exhibit reversible color change upon the change of external conditions are known as chromic (color changing) materials. They are usually incorporated into textile products in the form of chromic dyes, pigments, or coatings. Chromic textiles that act upon such color change are also known as chameleon textiles. Different kinds of chromism are named after the stimuli that cause color changes (Bamfield, 2001; Langenhove, 2007). They include the photo-, thermo-, electro-, and halochromic materials.

Photochromism is brought about by sunlight or UV light. The chemical structure of a photochromic material can be changed temporarily as a result of UV irradiation. This change in chemical structure leads to a shift in its absorption of electromagnetic waves to the visible part of the spectrum, upon which the color changes from colorless to colored. A reverse change in its chemical structure, and consequently in its electromagnetic waves absorption spectrum, can take place in the absence of UV rays. As a result, the material returns to its original colorless state.

Many photochromic compounds have been identified or developed for different applications. For example, they can be coated on spectacle lenses to have the lenses darken when exposed to strong sunlight while reverse to colorless in dim light. However, most of the inorganic photochromic substances, which are usually based on metals, are not suitable for treating textile materials. Some organic photochromic dyes, therefore, are often used to produce chromic textiles. Photochromic textiles have mostly been used for fashion and decoration purposes since they were commercialized in the 1980s. They are also used for military purposes to provide protection by camouflage.

Thermochromism is brought about by heat. Thermochromic materials change their molecular or supramolecular structure and absorption spectrum as a result of the variation in environmental temperature.

Application of inorganic thermochromic materials in textiles is limited due to the fact that a high temperature and/or a solvent are usually required to induce a change of color. This explains why organic thermochromic compounds are preferable for treating textiles, because their color changing temperatures are often between the ambient and body temperatures. The structural changes of organic thermochromic compounds may include rearrangement of molecules (e.g., cleavage of covalent bonds or changes in spatial configuration of a molecule) and changes in crystalline structures. Thermochromic dyes can be used for decoration and fashion. They are also used as an indicator of temperature or in thermometers (e.g., thermodiagnostics and skin thermometers).

Electrochromism is induced by electrical current. Electrochromic materials may experience a reversible change of color as a result of the gain or loss of electrons, which is an indication of redox reactions (i.e., oxidation and reduction). This process usually involves the passage of a weak electric current or potential at a voltage no more than a few volts. Electrochromic substances include some inorganic metal-based compounds and conductive polymers (e.g., polypyrrole, polyaniline, etc.).

The first commercialized electrochromic devices are self-dimming, anti-glare, rear-view car mirrors. Electrochromic materials have also been used to produce "smart windows" that automatically darken when the sunlight reaches a certain level so as to reduce the heat, and become clear again when the sunlight dims so as to allow more light in.

Halochromism is a color-changing phenomena caused by pH value. Halochromic dyes have been developed and used for textiles, and the resulting halochromic fibers or textiles can be applied in the making of pH sensors. For example, for burn patients, their skin pH values vary during the healing process; incorporation of halochromic molecules into a wound dressing allows the monitoring of the wound recovery process without causing disturbance to the wound bed (Osti, 2008). Halochromic textiles can also be used in geotextiles or protective clothing that provides real time indication of changes in environmental pH values.

Other types of chromism include piezochromism (mechanical pressure), tribochromism (mechanical friction), ionochromism (ions), solvatochromism (solvent polarity) and hygrochromism (moisture).

11.1.2. Phase Changing Materials

Phase (or structure) changing materials are a group of intelligent materials that change their morphology (e.g., shape, porosity, solubility, state, molecular structure) upon predetermined stimuli (e.g., thermal, chemical). Discussed in the following are materials in this group that are used more often: thermal regulation phase changing materials, intelligent hydrogels, and the various shape memory materials.

Typically, phase changing materials (PCM) are remarkable for their capacity to store or release heat upon changes of their states over a narrow range of temperature, and can therefore be used for the purpose of thermal regulation. Specifically, *thermal regulation phase changing materials* absorb latent heat as a result of phase change (e.g., changing from a solid state into a liquid one) during the heating process, a process during which temperature of PCM and their surroundings remains almost constant. Conversely, the materials release the stored latent heat into the environment due to a reverse phase change (e.g., changing from a liquid state into a solid one) during the cooling process, again a process during which the materials and their surroundings undergo almost negligible changes in temperature. Namely, PCM's thermal regulation capacity depends on their ability to absorb or release a large amount of heat with little temperature change.

A good example of natural PCM with high latent heat storage capacity is water, which absorbs a latent heat of about 335J/g upon being heated (i.e., melting) from ice to liquid water, but it will absorb only about 4J/g when it is further heated as a liquid. For that reason, ice can be a theoretically good thermal regulation material when the purpose is to reduce heat (i.e., to have a lot of heat absorbed).

Some PCMs may differ in their phase change temperature ranges and heat storage capacities. The most commonly used PCM are paraffins, which are linear long chain hydrocarbons and a by-product of oil refining with the general formula C_nH_{2n+2}. For instance, hexadecane ($C_{16}H_{34}$) melts at 18.5°C and crystallizes at 16.2°C, with a latent heat storage capacity of 237 J/g, and eicosane ($C_{20}H_{42}$) melts at 36.1°C and crystallizes at 30.6°C, with a heat storage capacity of 247 J/g. The paraffins can be mixed for a desirable phase changing temperature range. In order to prevent loss of PCM during their liquid stage, they are usually encapsulated into microspheres with diameters ranging from 1–20 μm. These PCM-encapsulated microspheres can be further incorporated into textiles via a number of ways: (1) The micro-capsules are embedded into the fibers by mixing the micro-capsules with the spinning solution before spinning; (2) the micro-capsules are mixed into a coating compound which is then applied topically onto a textile substrate; (3) the micro-capsules are mixed into a foaming compound which is then applied topically onto or laminated with a textile substrate; or (4) the micro-capsules are dispersed into the porous structures of a fibrous substrate (e.g., nonwoven) (Langenhove, 2007). Other PCMs include hydrated inorganic salts (e.g., $Na_2SO_4 \cdot 10H_2O$), PEG (polyethylene glycol) and fatty acids (Mondal, 2008).

The incorporation of PCM into textile materials and products was first investigated in the early 1980s by the US National Aeronautics and Space Administration (NASA) as part of the efforts to improve the thermal performance of space suits, which were expected to provide protection against the extreme temperature variations in outer space. A recent trend is the development of PCM-incorporated textiles for consumer apparel products, to meet the demand of those who wish that their clothes would be so smart as to be able to thermally regulate as the environment requires.

Currently, PCM-incorporated textiles have already been used in the healthcare and medical sectors in such products as heating and cooling pads/blankets. Heating and cooling pads are made of a PCM-incorporated polymer matrix embedded in a textile cover. A heating pad can be used for thermal therapy: it can be heated to a desirable temperature in a microwave or oven and, when it is brought into contact with the diseased part of the body, it functions by having the heat stored in the PCM slowly released to help heal that part. On the other hand, a cooling pad can be applied to a body part that is suffering inflammation: the pad absorbs the heat and provides cooling that is gentler than an ice pack, and it does not require refrigeration to regenerate. PCM can also be incorporated into bedding products or surgical protective gowns to enhance their thermal comfort (Langenhove, 2007).

As mentioned in Chapters 6 and 8, hydrogels are made of a water-swollen, three-dimensional network, composed of physically or chemically cross-linked hydrophilic polymers. Environmental stimuli-responsive, *intelligent hydrogels* are usually designed to undergo reversible volume transformation (e.g., expansion or contraction) due to changes of environmental conditions, such as temperature, pH, electrical field, solvent composition, and concentration of certain chemical compounds.

A wide variety of polymers have been developed as intelligent hydrogels capable of responding to different stimuli. Alginate, for example, is a natural, ion-sensitive hydrogel that is responsive to Ca^{2+} or other divalent ions. Cellulose-based electrolyte hydrogel containing NaCMC (sodium carboxymethyl cellulose) is pH sensitive.

A major application of intelligent hydrogels is in controlled drug delivery. For such hydrogels, environmental stimuli (e.g., pH, temperature) trigger the swelling-shrinking transition, which in turn changes the molecular mesh size. A drug or other bioactive molecule can therefore be designed to be either entrapped in (when the hydrogel shrinks) or released from (when the hydrogel swells) its hydrogel matrix (Peppas, 1997).

Shape memory materials have the capacity to “remember” their original shape; for example, they can return to their previous shape upon exposure to a stimulus, such as deformation due to external stress. The most frequently used are thermally-induced, shape memory materials, which are discussed in this section. Certain metal alloys and polymers demonstrate such a smart capacity. A reversible change in the shape of a shape memory material results from a phase transition during the heating process at a certain temperature: for a shape memory alloy (e.g., the Nickel-Titanium alloy), reversible crystal transformation is involved; for a shape memory polymer (SMP), there usually occurs a reversible transformation from a glassy state to a rubbery state (Langenhove, 2007).

SMPs are usually block-copolymers containing both hard and soft segments. The hard segments (e.g., polyurethane) form a crystalline region and determine the permanent shape. The soft segments (e.g., polyether or polyester diol), on the other hand, construct an amorphous region that is responsible for the deformation, retaining the temporary shape, and returning to the original shape upon exposure to the predetermined stimulus.

SMPs have been used for a variety of biomedical applications, including stents, sutures, and surgical gowns, as detailed below.

Introduced in the 1980s, the metallic *vascular stent* is an expandable device to support and prevent the narrowing of a blood vessel. Polymer coatings were later developed to provide drug-eluting stents (DESs), in which the polymer coatings improve biocompatibility and serve as carriers for drugs that reduce thrombosis (O'Brien and Carroll, 2009). Recently, SMPs have found potential applications in vascular stents because of their enhanced biocompatibility, biodegradability, drug loading capacity, compliance and strain recovery capacity as compared to polymer-coated metal. SMP stents are usually programmed to have an activation temperature closely proximate to the body temperature. As a result, such an "intelligent" stent can be inserted into the human body through a small delivery instrumentation so as to ensure minimal invasion, and will then deploy to fit the vessels (Yakacki and Gall, 2010), as shown in Figure 11.1. Both thermoplastic (e.g., polyurethane) (Wache, Tartakowska, *et al.*, 2003) and thermoset (e.g., acrylates) (Gall, Yakacki, *et al.*, 2005) polymers have been developed for this purpose. Research and development work for vascular stents made from SMPs is, however, still in the stage of *in vitro* tests in labs, and performance of such devices have to be justified through further characterization and *in vivo* experiments.

Biocompatible and biodegradable SMPs were first introduced as a potential material for *intelligent sutures,* and as a solution to the well-known challenge in endoscopic surgery: it is very difficult to use normal instruments to form a knot to close an incision with an appropriate stress. That is, if the knot is formed with a force that is too strong, it may cause damage to the surrounding tissue; if the force is too weak, there may be the danger of hernia due to scar tissue that is lower in mechanical strength than healthy tissue. As a result, it is desirable that

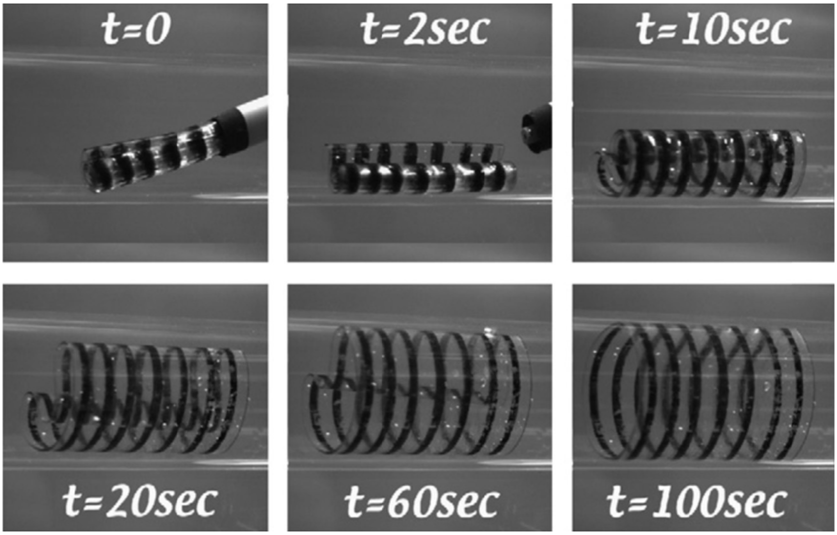


FIGURE 11.1. *The sequence of an SMP stent being deployed: it was delivered via an 18 Fr. catheter and expanded into a 22 mm ID glass tube containing body temperature water at 37ºC. [Reprinted with permission from Yakacki, Shandas et al., 2007. Copyright (2007) Elsevier].*

the suture is so smart that it can be temporarily elongated and applied loosely into the surgical position so that the temperature can be raised above the traditional point, and then the suture will duly shrink and tighten the knot to provide an optimum force. A suitable polymer material for this application can also be made to consist of a hard and a soft segment. For example, a degradable multi-block polymer is reported to contain a hard segment of oligo(*p*-dioxanone)diol and a soft segment of oligo(e-caprolactone)diol, the two segments being coupled with 2,2(4),4-trimethylhexanediisocyanate. *In vitro* and animal model tests have validated its status as an “intelligent” suture, as shown in Figures 11.2 and 11.3 (Lendlein and Langer, 2002).

Piezoelectric materials have a unique property in that they generate an electric voltage when mechanically deformed, and conversely, with the application of an external electric field, it becomes mechanically deformed again. A well-known piezoelectric material in our everyday life is quartz (silica dioxide or SiO_2), its piezoelectric properties allowing it to be used as a frequency standard (quartz clocks or watches). Other piezoelectric materials include crystals, ceramics and polymers. Piezoelectric polymers include polyvinylidene fluoride (PVDF), polyacrilonitrile (PAN) and odd-numbered nylons like nylon-11 and nylon-7.

Piezoresistive materials have characteristics similar to those of piezoelectric materials, but are different in that they change their conductivity/resistivity (instead of producing an electric voltage) upon

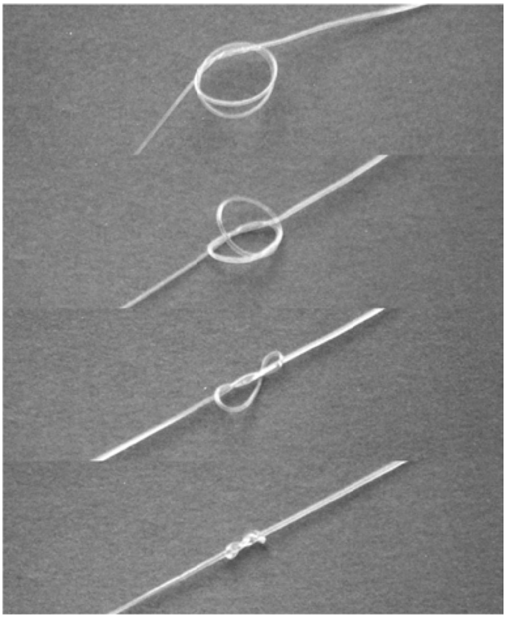


FIGURE 11.2. *A suture of thermoplastic shape-memory polymer, which can be pre-stretched for about 200% before forming a loose knot, with its two ends fixed (the photo series showing, from top to bottom, how the knot tightened in 20 seconds when heated to 40°C. [Reprinted with permission from Lendlein and Langer, 2002. Copyright ©2002, American Association for the Advancement of Science].*

applied mechanical stress. Polymeric piezoresistive materials include conducting polymers (e.g., polypyrrole, polyaniline) and carbon-loaded elastomers (Schwarz, 2010).

Piezoelectric and piezoresistive materials have been used in sensors (e.g., for the measurement of mechanical strength and pressure), resonators, actuators, and so on (Tichý, Erhart, *et al.*, 2010). In the medical or healthcare sectors, they have been studied for their applications in intelligent clothing for healthcare and disease management.

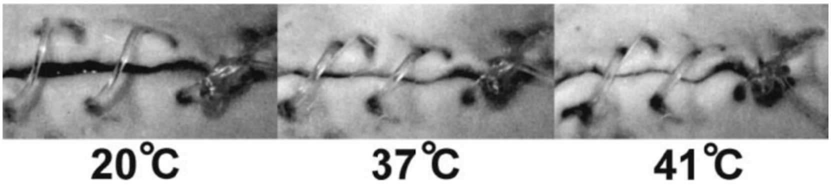


FIGURE 11.3. *A degradable shape-memory suture for wound closure, the photo series from an animal experiment showing (left to right) shrinkage of the suture with increased temperature. [Reprinted with permission from Lendlein and Langer, 2002. Copyright © 2002, American Association for the Advancement of Science].*

11.2. INTELLIGENT TEXTILE PRODUCTS

There is currently a need for intelligent or smart products due to increased recognition of the importance for the elderly and people with chronic diseases or disabilities to live “independently”, obviously a matter of higher life quality for them. To that end, extensive efforts have been made, for example, to promote “active aging”. A major goal of such efforts is to give the elderly the ability to perform activities and functions required in daily life with no or little help from others (WHO, 2002). A promising approach to achieving this goal has been to use intelligent textiles in healthcare products (articles, devices, units, etc.) and therapeutic treatments, often by way of health monitoring and disease management, so that these people may not have to be confined to hospitals for healthcare or treatment.

Smart devices made from intelligent textiles are expected to provide remote monitoring of a patient’s physiological and physical data and signs via non-invasive sensors embedded in clothing materials. These data or signs can be used to support diagnosis and personalized management of chronic diseases like diabetes, arthritis, lung and heart disease, and hypertension. Such technologies allow patients to be treated at home instead of hospitals; they also allow early detection of diseases and timely treatment (Cho and Lee, 2007).

To perform their functions, these smart textile products are often combined into a system, which typically contains the following components: (1) sensors; (2) signal/data processing devices; (3) actuation devices; (4) telecommunication devices; (5) data management devices; and (6) decision support units. Among these, components 1–4 can be integrated on a wearable textile/clothing platform; components 5 and 6 are usually located in the central mentoring unit, in which local healthcare professionals can analyze the data and monitor the health status of the patient, make decisions or be dispatched to offer help in the shortest amount of time. Such a system can be applied in home healthcare for the elderly, people with chronic diseases, or individuals in rehabilitation.

Depending on the functions and behaviors of intelligent textile systems, they can be divided into three categories: (1) a textile system with only a sensing function, referred to as *passive smart textile;* (2) a textile system with both sensing and actuating functions, or an *active smart textile;* and (3) a textile system with an adaptive function (i.e., able to adapt its behavior to the environment), known as a very smart textile system (Tao and Textile Institute, Manchester, England, 2001).

A system of intelligent textile products mimics living creatures (mostly the human being) in the way in which they sense and respond to stimuli, as shown in Figure 11.3: the sensors in the system mimic the nervous system in a human body to detect signals from the outer environment; the signals are analyzed or evaluated by a processor (simulating part of the human brain's function); then the actuators will, upon input of the processor in a pre-determined manner or as guided by the central control unit, act properly in response to the stimuli.

Smart functions of such a system are endowed by the intelligent materials, which are often embedded or incorporated in the fiber, yarn or fabric structures. These materials can be classified according to the types of stimuli, such as the mechanical, light, thermal, chemical, electrical and magnetic. They can also be categorized by the way they respond to these stimuli, such as color change, structural change and shape change (deformation), as discussed in section 11.1.

Application of smart devices made from intelligent textiles can be conveniently discussed under two subtitles: the sensor (a typical, central smart device), and the smart clothing system, which is a typical smart textile system.

11.2.1. The Sensor

Although a wide variety of intelligent functions have been developed for textile products, sensing remains to be the most progressive area for intelligent textiles. A number of healthcare parameters can now be measured by fiber- or textile-based sensors. These parameters include: body temperature, biopotentials (e.g., cardiogram), acoustics (e.g., heart and lung), ultrasound (blood flow), motion (e.g., respiration and motion), pressure (e.g., blood), and mechanical and electric parameters of the skin.

Temperature sensors can be integrated into clothing systems to help monitor body temperature, a basic health parameter. It is important that

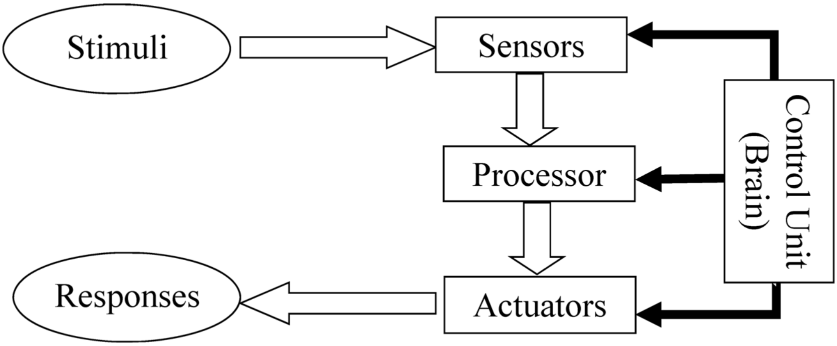


FIGURE 11.4. *A smart textile system.*

these sensors be designed in such a way as to cause minimum disturbance to the wearer. Currently, resistance temperature detectors (RTDs) or resistance temperature sensors are the most popular sensors used for this purpose. Their working mechanism is that the resistance (R) of a conductor increases with the increase in temperature (T):

$$(R - R_0)/R_0 = \alpha(T - T_0) \tag{11.1}$$

where α is the temperature coefficient of resistance, and R_0 the resistance of the material at reference temperature T_0.

Platinum (Pt) thin film is a frequently used material for RTDs. These RTDs, usually in the form of micro temperature-sensing arrays, can be integrated onto a flexible platform via the micro-electronic-mechanical system (MEMS) technology (Xiao, Che, *et al.*, 2007; Kinkeldei, Zysset, *et al.*, 2009). Figure 11.5 shows an example of such a MEMS fabrication process in these steps: (1) as shown in Figure 11.5(a), a flexible polyimide film, Kapton, is pre-treated to achieve a clean surface; (2) a layer of sensing material (usually a metal, e.g., Pt) is then deposited onto the substrate, as demonstrated in Figure 11.5(b); (3) the coated substrate is then attached to a clean glass side with drops of de-ionized water to keep the substrate flat during procedures, as shown in Figure 11.5(c); (4) a thin layer of pre-patterned resist is thereafter deposited on top of the sensing material layer to temporarily shield the selected areas of the sensing material during subsequent procedures, as shown in Figure 11.5(d); (5) the sensing material layer goes through an etching procedure to remove the areas that have not been protected by the resist layer, leaving behind the protected areas with a pre-designed pattern, as shown in Figure 11.5(e); (6) the final product (i.e., a flexible substrate integrated with sensing arrays, is obtained by removing the temporary resist layer and the underlying glass slide, as shown in Figure 11.5(f). Subsequently, the sensor-incorporated substrate is cut into single strips, which can be further inserted into a fabric during the weaving or knitting process (Kinkeldei, Zysset, *et al.*, 2009).

A number of chronic or acute diseases affect the respiration of patients. Respiratory sensors are therefore useful for home care of patients who need long-term respiratory monitoring, as well as athletes who need long-term performance monitoring. A respiratory sensor is usually embedded in a wearable system and placed next to the thorax to detect its expansion during respiration.

Figure 11.6 illustrates one of the designs for a respiratory sensor system, a system based on a capacitive pressure sensor made of multiple layers of fabric with different structures and functions. The core of this

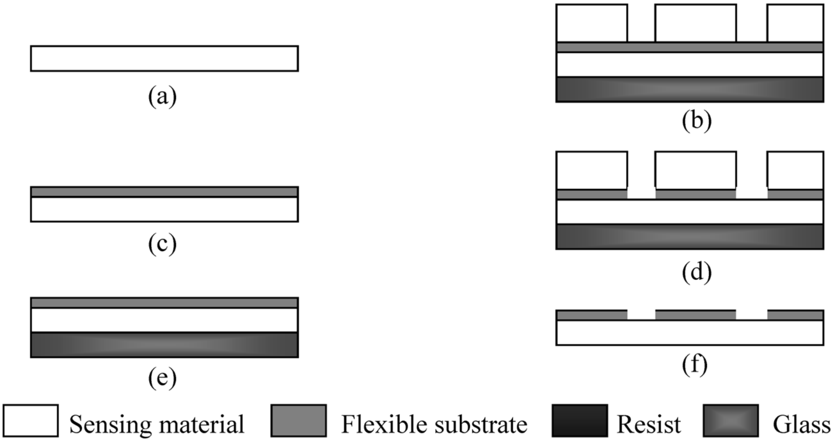


FIGURE 11.5. *A process of fabrication of RTDs on a flexible platform (adapted from Kinkeldei, Zysset, et al., 2009).*

symmetric structure is a 3D spacer fabric that determines the sensitivity of the system to applied force. The 3D spacer fabric is sandwiched between conductive fabrics which serve as the electrode of the plate capacitor. The fabric is endowed with conductivity by the incorporation of silver. Outside each of the conductive fabric layers, a layer of waterproof fabric is added to protect the sensor from being penetrated and affected by moisture. Furthermore, a layer of grounded conductive fabric is mounted on each side to shield the sensor from the external field. Finally, the multilayered sensor is protected by an extra layer of waterproof fabrics on each side. Such a sensor is thus based on the principle of a plate capacitor that is formed by two conductive textiles with a separating distance equal to the thickness of the spacer fabric. An external force (i.e., expansion of the human thorax) can change the thickness (d) of the spacer fabric and consequently the capacitance (C)

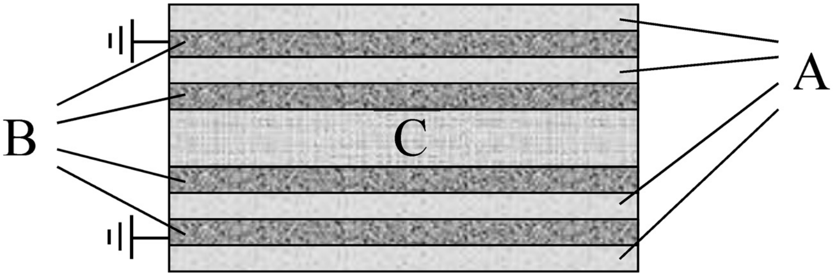


FIGURE 11.6. *A textile capacitive sensor composed of multiple layers at a cross section (A: waterproof fabrics, B: conductive fabrics, C: a 3D spacer fabric) (Hoffmann, Eilebrecht, et al., 2011).*

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