5
High function fiber

5.1 Prospects for high function fiber development

Japan is a forerunner in high function fiber development, although in terms of total output of synthetic fiber, Japan is ranked only fifth in the world. The main direction in the high function fiber development is to utilize biomimetics, namely mimicking the high-order structure of natural fibers such as cotton, wool, and silk. Efforts have been focused on enriching human life by pursuing high function, aesthetic appreciation, and human sensitivity. Such fiber is being applied, not only to clothing, but also to industrial applications. In this chapter, the expected developments for high function fibers and associate textiles are summarized and classified.

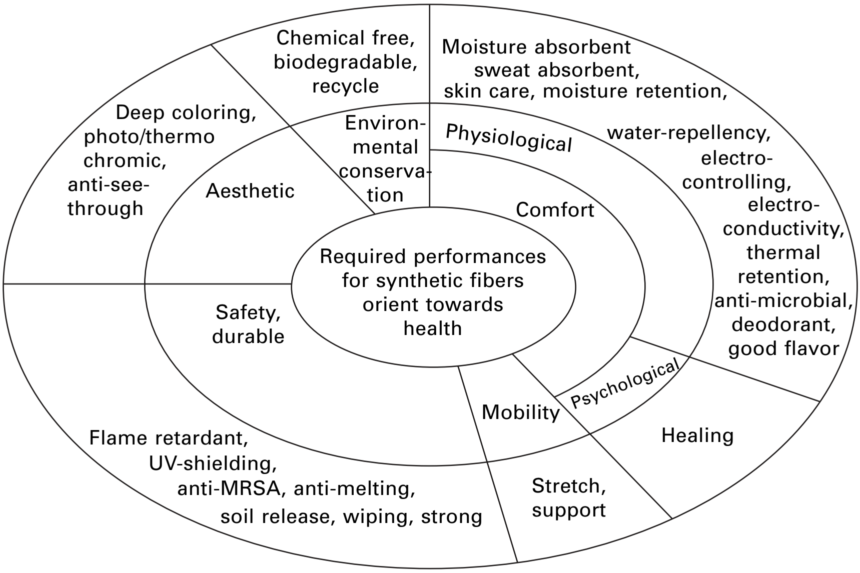
5.1.1 Present status of high function fiber

Functional fibers are developed according to social needs. The function can include health, comfort, and mental satisfaction as summarized in Fig. 5.1.

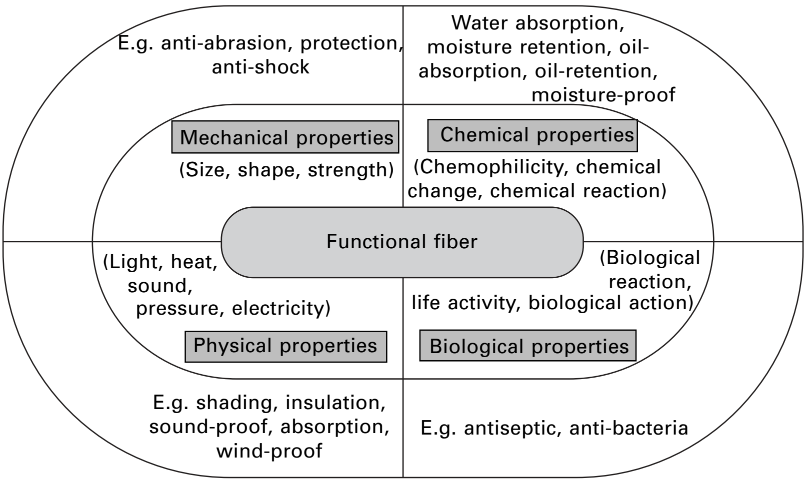
5.1.2 The concept of function will change according to consumer needs

The nature of fiber function can vary in different circumstances and so requires a variety of mechanical, physical, chemical, and biological characteristics, as shown in Fig. 5.2. The broad function can be classified into four categories according to the level of design:

- Basic function fiber (the first order function)
- Higher function fiber (the second order function)
- Super high function fiber (the third order function)
- Intelligent function fiber (the fourth order function)

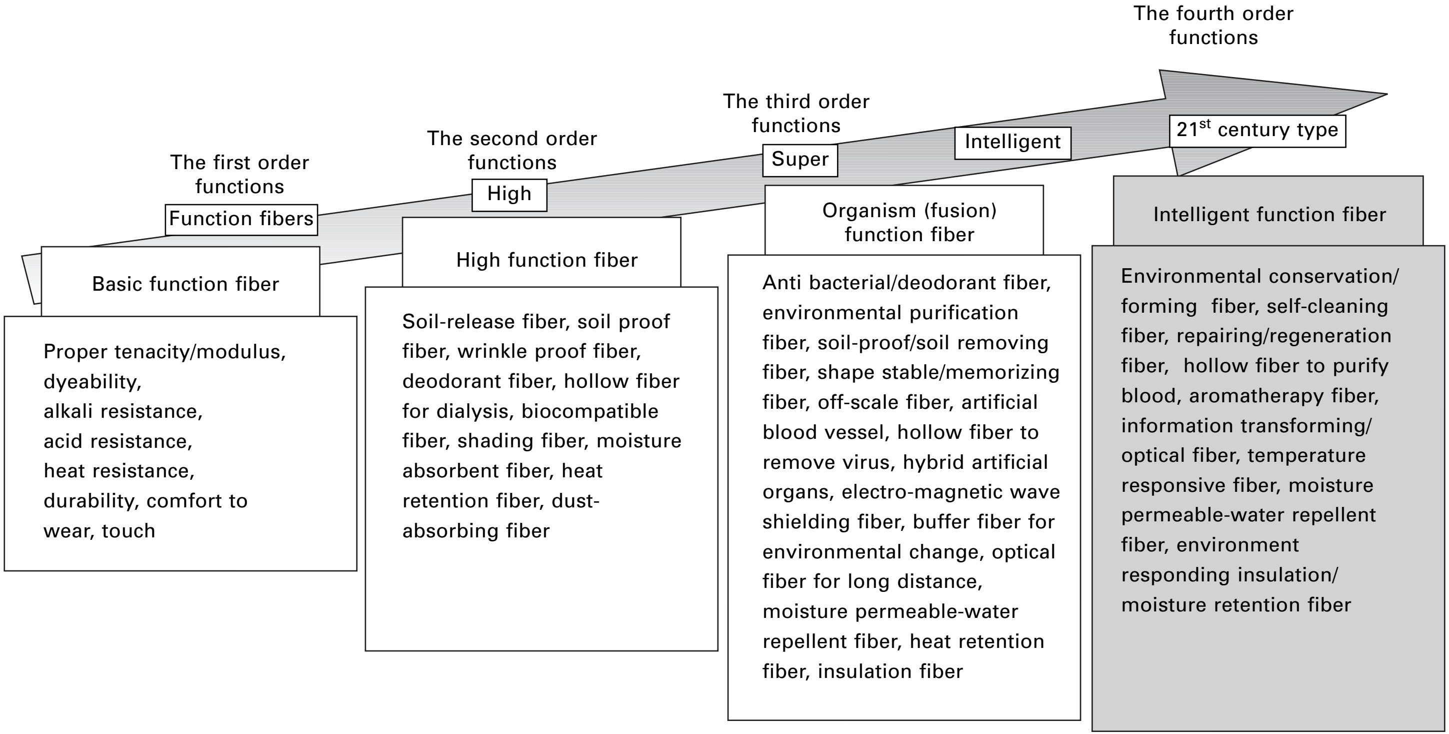


5.1 Present status of high functional fibers.



5.2 Materials for function fibers classified by properties.

Overlapping in multiple fields will be required, as a higher degree of function is structured. The development of fiber functions is summarized in Fig. 5.3 according to these various stages.



5.3 Examples of development of fiber functions.

Basic function fiber (the first order function)

The basic function of fiber is dependent on the long and thin shape of fiber. Thus the basic function is already present, does not require further functionalization, and is thus referred to as a first order function.

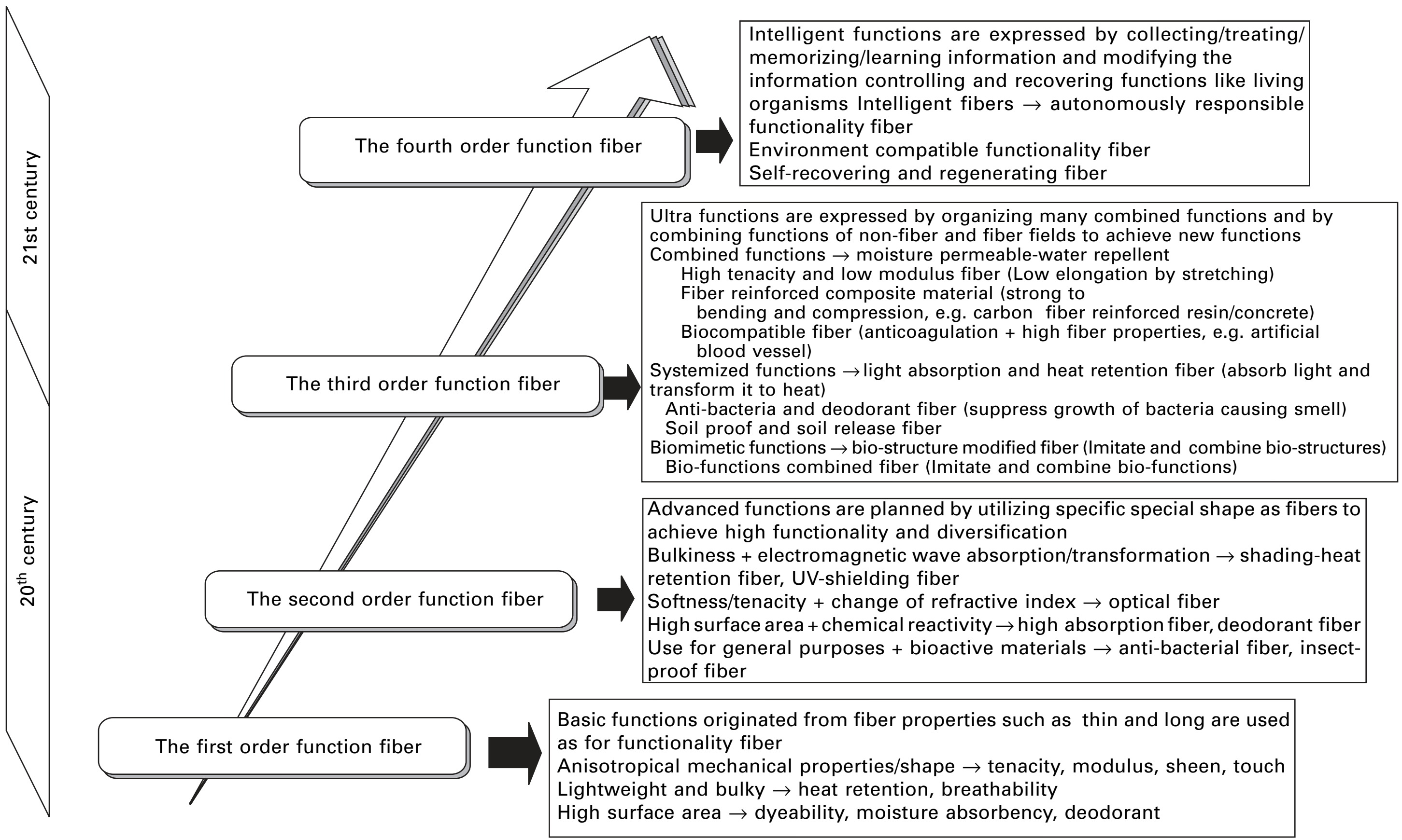
- *Mechanical function*: Typical examples of the basic functions are the tensile strength of fiber, the pressure relaxation by bulkiness, the abrasion resistance and the flexibility. These functions emerge from the chain orientation and crystallization along the fiber axis.
- *Physical function*: The physical function includes the heat resistance, moisture retention, the anti-electrostatic effect, and the transparency. The physical function utilizes the fiber characteristics for thermal, electric, and light stimuli. Conductive fiber is also considered a physical function of fiber. More and more attention is being given to static electricity, which damages computers and contaminates pharmaceutical/food/IC production by collecting dust. Conductive fiber was developed for carpets some twenty years ago in the United States by introducing a metal coating. However, this coating-type is not suitable for clothing and now the carbon composite type is produced by blending high conductive carbon with polyester or nylon.
- *Chemical function*: Chemical functions of natural fibers, such as high moisture absorbency, provide a comfortable in-cloth climate for apparel. Those natural fibers possess high density functional groups on the fiber surface.
- *Biological function*: A weak anti-bacteria effect of silk and wool is a typical example of the biological first order function. Figure 5.4 shows the flow chart of the development of the function fiber towards higher order functions.

Higher function fiber (the second order function)

A new function can be added intentionally by utilizing the characteristic shape of fiber according to the needs. Such second order function for clothing is mainly added by processing, to achieve a comfortable in-cloth climate. However, the second order function for industrial use is introduced into the polymer raw materials by molecular design and can involve mechanical, physical, chemical, and biological functions of fiber.

A second order mechanical function is closely related to the shape of fiber. Examples are suede-type artificial leather with ultra-fine napping and silk-like fiber with a triangular cross-section. Biomimetics is a key concept in such function fibers, where the relatively organized structure of biofibers is mimicked by precision spinning and processing.

A second order physical function is exemplified by a light-absorbing fiber, a moisture-retaining fiber, an UV-cut fiber, or a far infrared radiating



5.4 Flowchart of technical development for function fiber.

fiber. Those functions are incorporated into fiber at the raw polymer stage.

A second order chemical function fiber includes a hollow fiber for artificial dialysis, a membrane fiber for selective permeation, or an active carbon fiber for selective adsorption of toxic substances. Among these chemical function fibers, a hollow fiber is widely applied for clothes as well as for other goods. A catalytic fiber is also available for chemical reactions, where a catalyst is fixed onto fiber.

A second order biological function fiber is mainly developed for medical uses, such as biocompatible fibers for artificial organs and cell-adhesion/cell-supporting fibers for cell cultivation. Biodegradable fiber and biomimetic anti-bacteria fiber from chitosan or hinokitiol are also included in this category.

There are many examples of water treatments using fiber technologies. Here representative water treatments using fiber technologies are given as examples of second order functional fibers. Today, fiber technologies are applied to water treatments such as separation membranes. Traditional water treatments have used activated dirt, coherent precipitation, and sand percolation; however, new techniques are using filters and separation membranes. The new techniques are applied to preparation of useful water, treatment of wastewater, and cleaning of the environment.

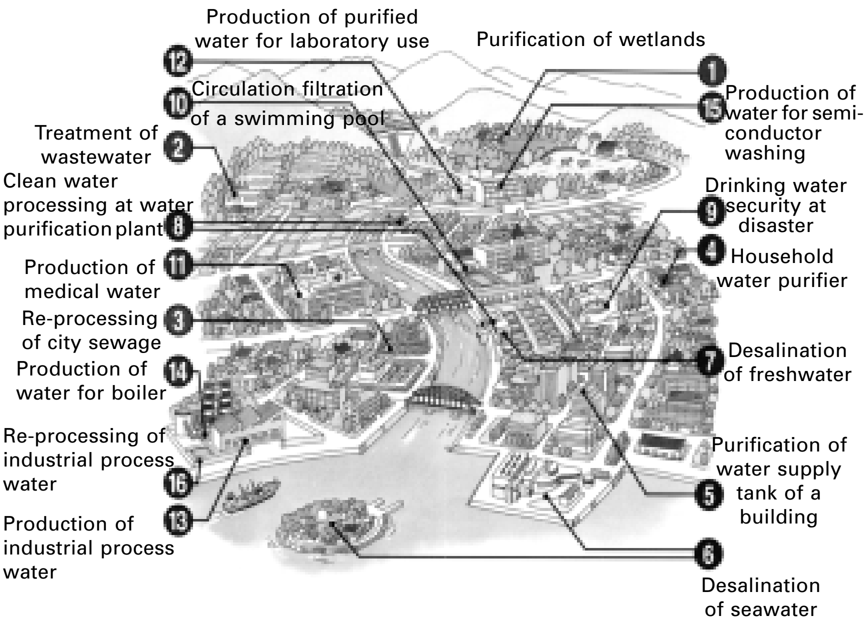
High technology has led to fibers, such as percolation textile made of ultra-fine fibers, ion-exchange fiber using fiber high functionality, hollow fiber membrane technology, dry-and-wet film processes, many hole opening technology using wet film process, and aromatic polyamides as reverse osmosis membrane compound. These have many application fields such as large-scale fresh water preparation from sea water, medium scale of cleaning swimming pool water and small-scale home water purification. Figure 5.5 shows the example of water treatment technologies.

Kinds of separation membranes: Separation membranes are generally categorized by size with the pore diameter determining the distribution achieved. These filters are made from textiles using plane membranes with separation functionalized layers and hollow fiber membrane combined with hole-rich membrane. Separated matter and other water treating technologies are compared in Fig. 5.6.

Decrease in filter hole size leads to microfiltration membrane (MF), ultrafiltration membrane (UF), and reverse osmosis membranes (RO), but pressure required for filtration increases with size decrease and operation costs increase. Therefore the appropriate membrane must be selected according to the nature of the separation necessary.

Ultra-fine fiber membrane cloth, textile filter cloth

Ultra-fine fibers were developed as suede-touch artificial leather. Now a new function of the fiber is its application as a filter cloth for cleaning dirty water.



5.5 Water treating technologies (Toray).

Toray provides the filter cloth Toralome® using ultra-fine polyester fiber.
Requirements for the textile filter cloth are:

- effective filtration of solid particles
- stability in filtration speed
- ease of peel of the cake
- high resistance to tension force (shape stability)
- chemical resistance.

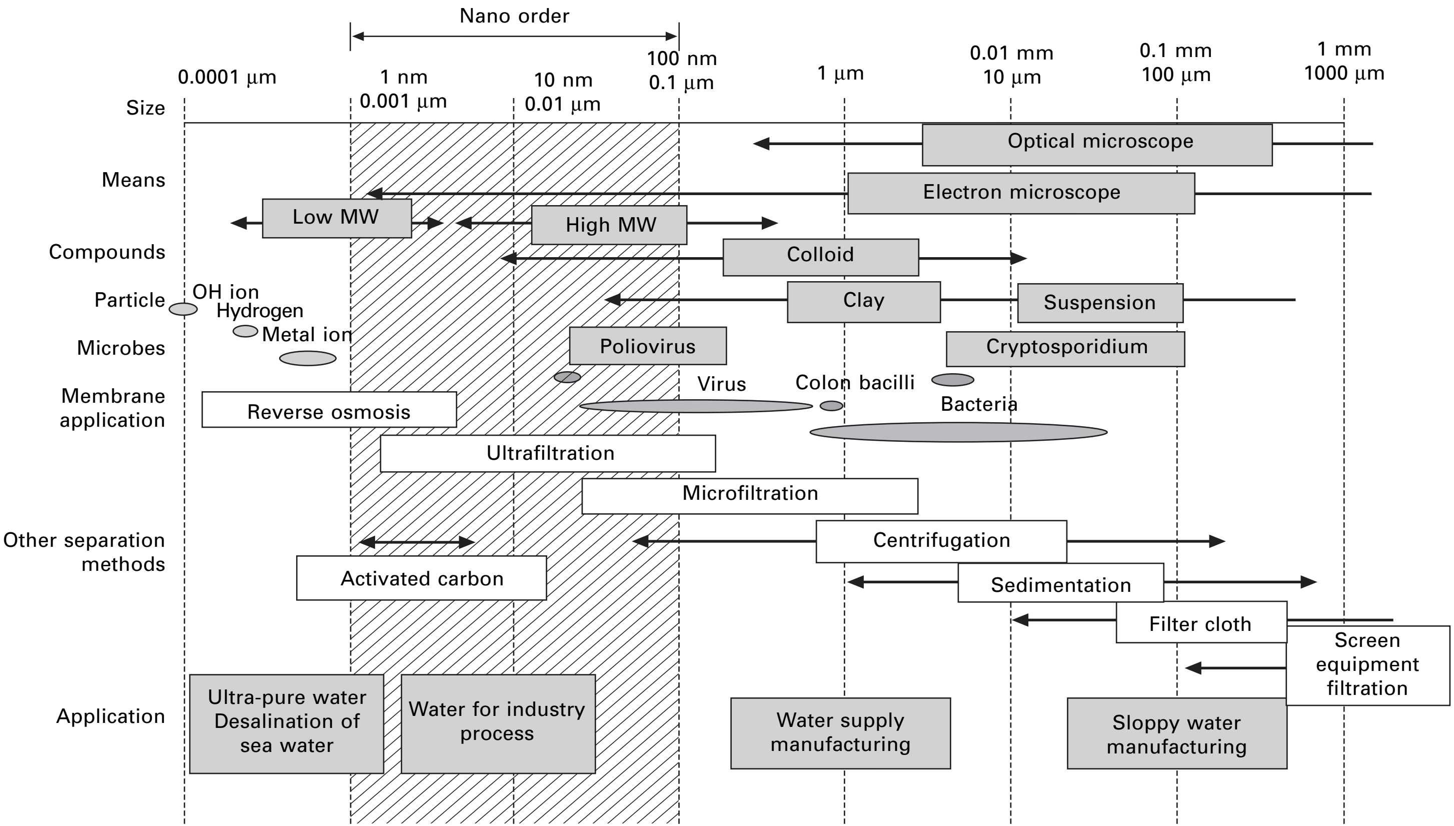
High specification filtration systems require:

- high strength
- long-permanence
- anti-choking
- ability to filter particles with diameter less than a few micrometers.

The cleaned water is recycled possibly as fountains in public locations in towns.

Fine filtration membrane, hollow fiber membrane (microfiltration membrane)

Hollow fiber membrane is the membrane made from macaroni-shaped fibers whose surface has many ultra-fine holes. When water passes on the outside



5.6 Water treatment technologies and separated matters.

of the fiber, impurity included in the water is filtered and the filtered water comes inside the fiber. Thus the diameter of the hole determines the effectiveness of the filtration.

Pore size in the fine filtration membrane is in the order of sub-micro meter. Thus it can filtrate extremely small impurities such as cloud of water, red rust, and bacteria. On the other hand, mineral ions in water such as calcium and magnesium pass through the filter, so the filtered water remains tasty. This fine filtration membrane can be used as a home water purifier, which uses active carbon with the fine filtration membrane. The material of the hollow fiber membrane is polyestersulphone (PSF) which has high strength and high heat resistance.

Ultra-fine filtration membrane

As with microfiltration membrane, the ultrafiltration membrane has ultra-fine holes in the walls. The pore size is 0.01 μm less than the size of germs and viruses. Industrial application began with the filtration of germs from beer in 1968. It has been applied subsequently for small particle filtration, purification of liquids, and now the cleaning of water.

The material used for the ultra-fine filtration membrane requires good longevity for use in the water supply system. Therefore, high molecular weight polyacrylonitrile is used. A capsule packing a bundle of hollow fibers called 'Module' is widely used in water supply systems, and used for cleaning water associated with chemical products. Moreover drink water can be prepared by filtration of industrial water.

Reverse osmosis membrane

A semi-permeable membrane allows water to pass but does not pass salts. When sea water is treated, osmosis induces the sea water to move to the pure water side without the salts, so pure water can be obtained from the sea water. This is reverse osmosis and the membrane used is called the 'reverse osmosis membrane (RO membrane)'.

Spiral type RO membrane, prepared by rolling the seat-shaped RO membrane into a swirl-shape, has good dirt resistance and produces large quantities of pure water. This is the main type of RO membrane for producing drinking water from well-water and sea water and the preparation of ultra-fine clean water used for the semiconductor industry. Aromatic polyamide and amides are used for the RO membranes.

Super high function fiber (the third order function)

A third order function fiber is defined as a super high function fiber designed to possess high multidisciplinary functions. The third function emerged from an unexpected combination of fiber science with electric/electromagnetic science, machinery/structural material engineering or cell biology. The systematic hybridization leads to a multiplicity of effects and functions. Thus super high function fiber can be regarded as a 'multi-function fiber' or 'hybrid-function fiber'. Organic optical fiber is an example of a super high function fiber in the non-clothing field, which emerged by building into the fiber a gradation of refractive index in a radial direction.

In practice, the function can be classified as multiple function, systematized function and biomimetic function. For example, the multiple functions include the water-repellent/vapor permeable fabric (that repels water but allows vapor to permeate) and the high tenacity/low-modulus elastic fiber (that does not stretch). A systematized function is represented by the heat storage fiber (that absorbs light and converts it to heat) and the anti-bacteria/odor-killing fiber (that suppresses bacterial growth and removes bad smells). Morphotex® (developed by Nissan Motor, Teijin and Tanaka Kikinzoku) is a good example of a biomimetic fiber and is composed of multi-layers of polyester and polyamide, and produces color by the interference effect of light (see Fig. 5.7) like the Morpho found in the upper reaches of the Amazon in Brazil. Biomimetic fibers include fiber whose structure is copied from the bioorganisms and whose function mimics that of bioorganisms.

Toray developed a column to treat blood poisoning with endotoxin-absorbing fiber. Infection by bacteria can cause blood poisoning, because endotoxin is produced by the bacteria. Fever, a barrier to blood circulation and a drop in blood pressure can result. Even death can occur.

5.7 Applications of structurally colored fiber, Morphotex®. (Nissan Motor, Teijin and Tanaka Kikinzoku).

The number of patients suffering from blood poisoning is increasing year by year. In the United States, the number of such patients is 430 000 per year. Blood poisoning is the main cause of death in intensive care units. Endotoxin is also known as lipopolysaccharide.

Blood poisoning was once treated by blocking the action of endotoxin. Medicines which combine with endotoxin were given to patients after successful animal trials. However, the medicines did not act efficiently in human clinical trials. So medicines are not now used to remove the toxicity of endotoxin.

Toray developed a treatment to remove the endotoxin by circulating the blood outside of the body using artificial kidney dialysis. In artificial dialysis, hollow fiber is used to remove low molecular weight compounds in the blood and endotoxin can be absorbed.

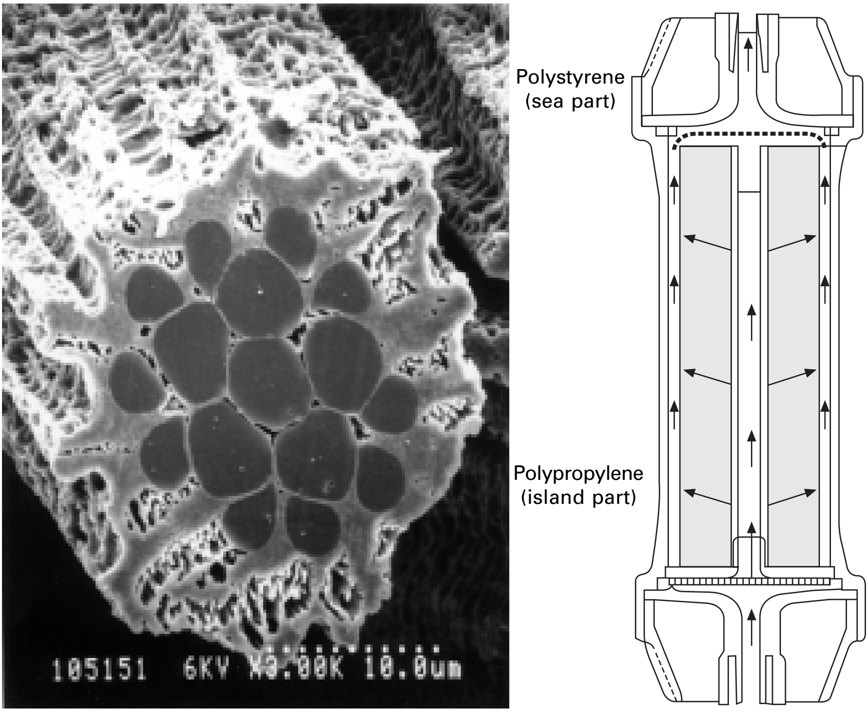
Endotoxin exists in the blood mixed with other essential components, which must not be removed. Only the compounds causing the disease should be absorbed and removed, so that the purified blood can be fed back into the body. The main difference from dialysis is that compounds with high molecular weighs can be removed by absorption. The compound which combines the causative is called a ligand.

Polymyxin, an antibiotic, was selected as the ligand to remove endotoxin as the result of collaborative research with Shiga University of Medical Science. Although it was known that polymyxin combines endotoxin specifically, it can also cause renal dysfunction if too large a dose is used. The solution was to immobilize the polymyxin on to fiber and the fiber packed in a column through which blood circulating outside of the body could flow. The structure of polymyxin-immobilized fiber and a column packed with the fiber are shown in Fig. 5.8.

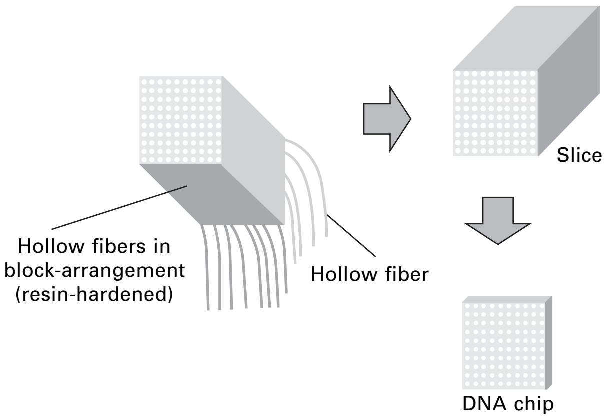
As new outside the body cycling treatments for other diseases are developed the following points should be considered:

- Need to identify/determine filtration targets in the blood such as toxin, excess proteins and cells.
- Devise the ligands which can absorb the targets.
- Optimize a carrier for the ligand. In this way, new medical treatment methods can be developed by studying materials, including fibers, which are effective in eliminating target materials.

Mitsubishi Rayon developed the ‘fibrous-shape DNA chip’ utilizing the technology which had been used for the hollow fiber in the household water purifier. Pieces of DNA are placed in a hollow fiber-like ultra-fine straw. Thousands of these are bundled and fixed into a rod with resin. The chips are obtained by slicing the rod. This technique has the advantage of ease for mass production. The DNA chip reacts with blood of a patient and provides the patient’s genetic information, which assists diagnosis. Figure 5.9 shows the production scheme for the ‘fibrous DNA chip’.



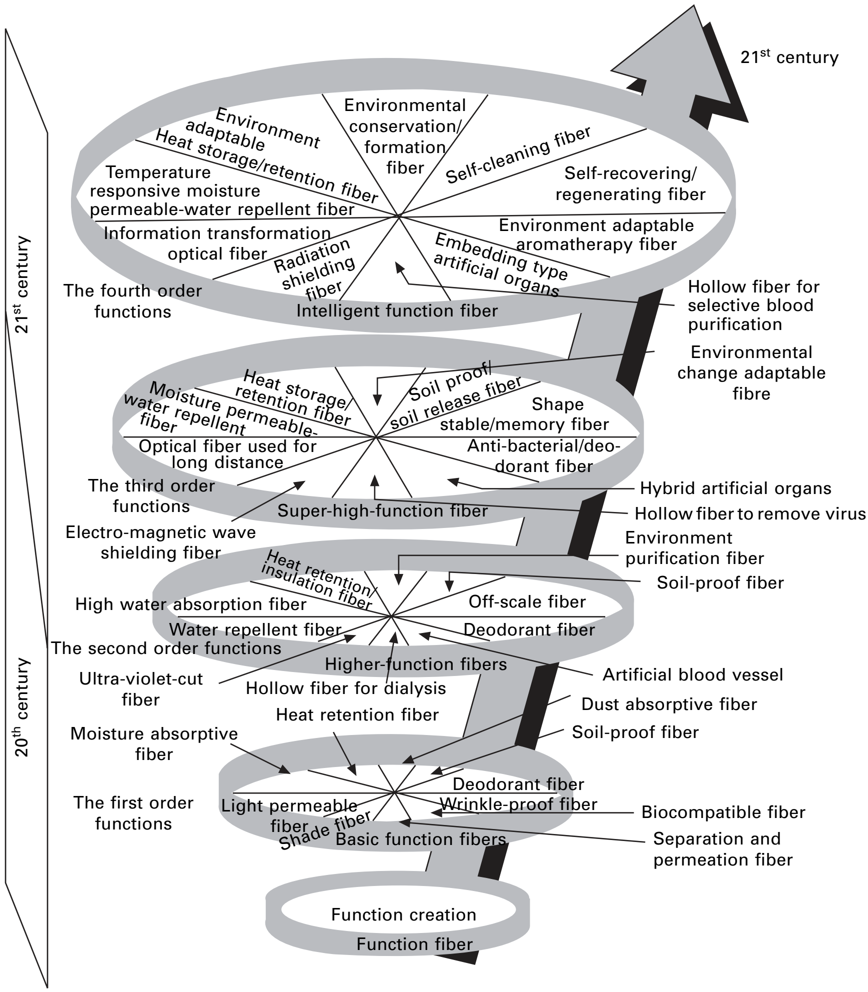
5.8 Structure of polymyxin immobilized fiber and column packed with the fiber (Toray).



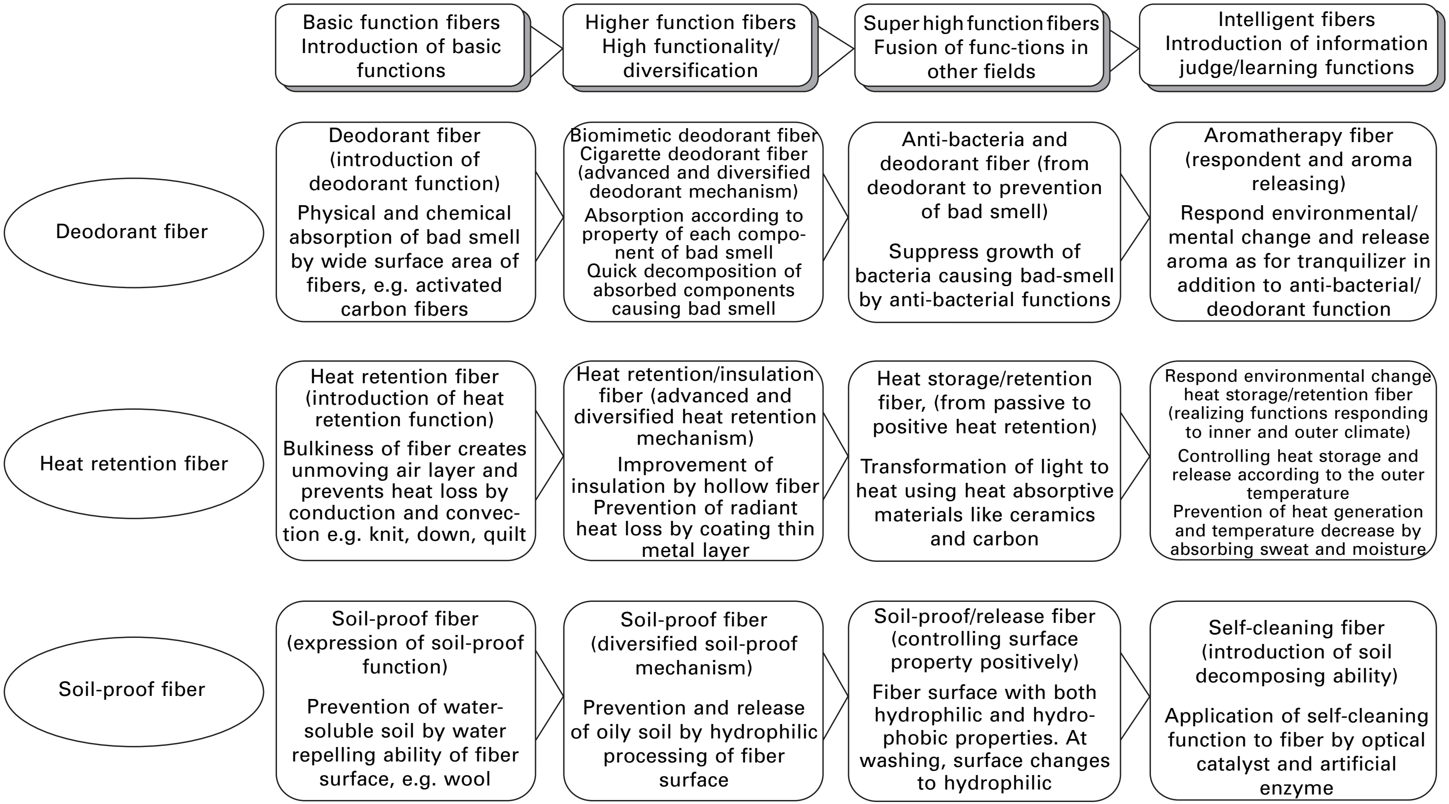
5.9 Production scheme of fibrous DNA chip (Mitsubishi Rayon).

Intelligent function fiber (the fourth order function fiber)

The intelligent fiber can be classified as a fourth order function fiber. The basic concept is to provide the intelligence to reveal a specific function under a specific condition by processing the input information according to the prescribed program. For example, the heat-responsive heat-storage fiber is developed to store heat by converting sunlight, when the light absorption efficiency varies according to the ambient temperature. A typical intelligent fabric in the market is the fabric that opens or closes the texture when hot or cold, respectively. The evolution of the functions in high function fiber is summarized in Figs 5.10 and 5.11.



5.10 Improvement of functions in function fibers (Professor T. Koyama, Shinshu University).



5.11 Examples of improved functions in function fibers (Professor T. Koyama, Shinshu University).

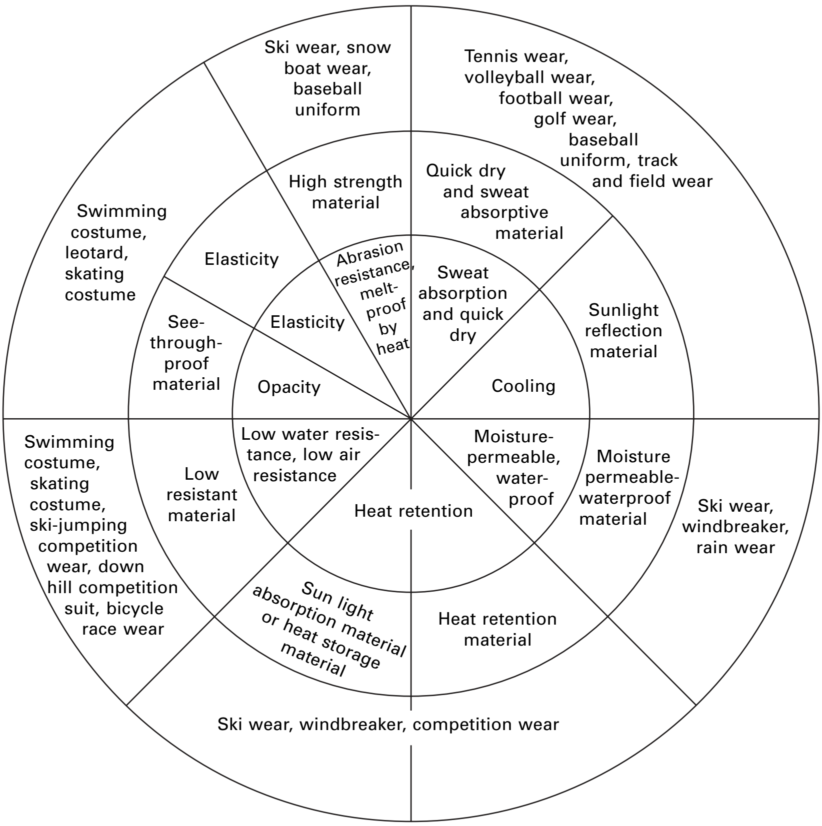
5.2 Sportswear using the high function fiber

Figure 5.12 summarizes the functions and performance required for sportswear, and the required elements are summarized in Table 5.1.

5.2.1 High function sportswear

Although Japan imports increasing amounts of textile products, the export of the fabrics for sportswear has been steadily increasing since 1995. Sportswear needs to have more specialized functions than ordinary clothing. Thus the trends in sportswear will give an indication of new fiber material developments. The recent trend is not towards high performance but comfort. Figure 5.13 shows the position of high touch sportswear.

There is a great demand in high function sports goods. If the performance and function satisfy the consumer, the cost is inconsequential. Golf clubs and fishing rods are two examples of high function sports goods where

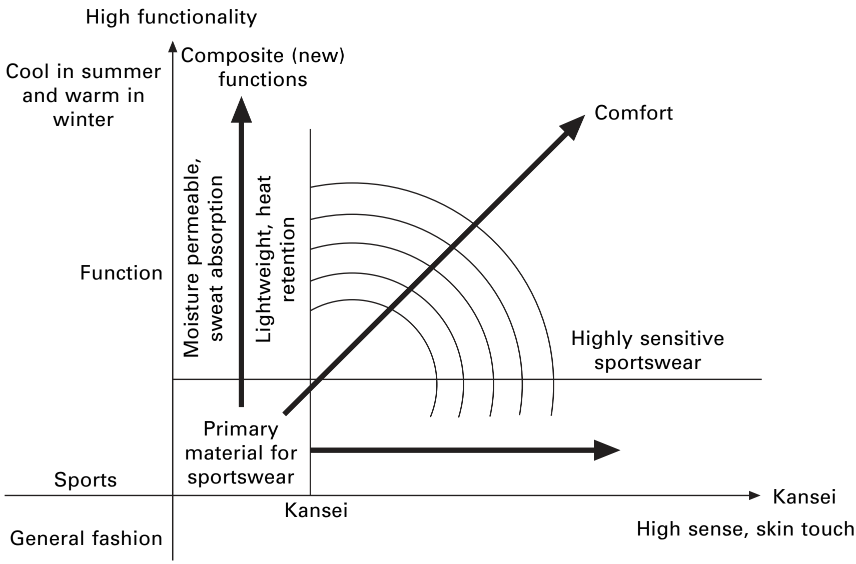


5.12 Functions and performances required for sportswear.

Table 5.1 Purpose of sports and required elements for sportswear

Class of people who enjoy sports	Purposes	Targets	Characteristics	Factors required for sportswear
General people enjoying sports	Hobby Leisure Health	Keeping and improvement of mental and physical health Exchange between areas, family and friends	Not stick to record Achieve targets enjoying sports High school, university and business company clubs	Basic function Kansei is regarded as important Variety of prices in sportswear
Sportsman Semi-professional	Winning Challenge to record Physical and mental training	Realization of purposes Entry to competition Compete at higher level	Preliminary state of professional activity Training of body and spirit during the youth Professional to sports Sports clubs of high school, university and business company	Functions and functional beauty are regarded as important Balance of function and price of wear Special wear for each sport
Professional Athlete	Winning Challenge to record Occupation	Achievement of purpose Entry to international competition Pride of a professional	Sports occupy big part of life Top of sports Very limited number of people	Function and beauty arising from function are regarded as the most important Professional needs attractive and eye-catching costumes

Source: (S. Kagechi, Soen Eye (1993), modified).



5.13 Evaluation of highly sensitive sportswear.

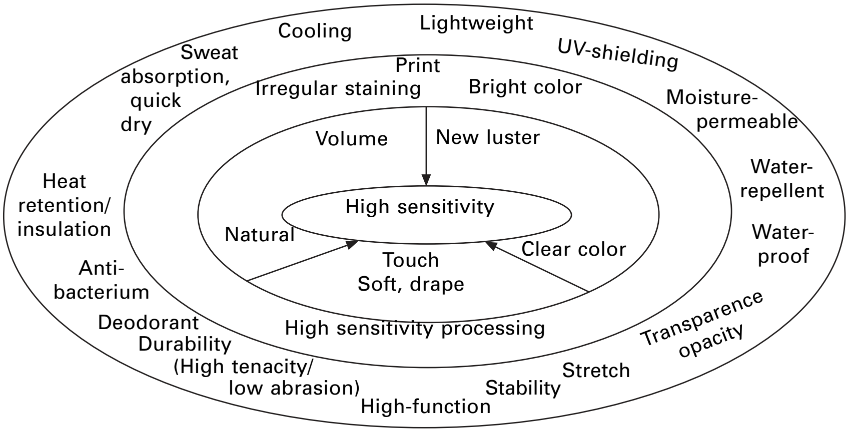
carbon fiber is applied. Carbon fiber has a high Young's modulus and is used in airplanes and space shuttles in the aerospace industry. Although expensive, golf clubs, fishing rods and tennis rackets made of the carbon fiber composite attract sports lovers, since the performance satisfies their requirements.

Necessary performance for sportswear

The various factors of clothing function seem to appear in more emphasized form in sportswear. Sportswear should be light and fit the body for easy movement. Durability and abrasion resistance are also required. The protective function is, of course, a prerequisite. Since heavy sweating during exercise is unpleasant, sportswear should absorb/evaporate sweat quickly and keep the body dry. The body should be kept warm in the case of winter sports. All these functions are also required for conventional clothing, hence the general value of experience in sportswear.

Functions from the type of sports

An elastic response is required for swimming, aerobics and figure-skating. Transparency or non-transparency may be important in some cases. Skiing costumes require both heat insulation and physical mobility. Sportswear functions vary, as each sport requires different functions (see Fig. 5.14). The technology of fiber materials in clothing design is available to cope with the varied required functions.



5.14 Sportswear requires different functions.

The water-repellent/vapor-permeable textile is a typical material for sportswear. The coating/laminate type and the high-density woven fabric are commercially available for water-repellent/vapor-permeable textiles. Goretex® (Goretex Japan) and Microft Lectus® (Teijin) are two commercial examples corresponding to respective types. Commercially available quick-dry textiles are made either from water-absorbing fiber material or with a specially designed fabric structure utilizing a capillary effect to absorb sweat. Fieldsensor® (Toray) has a three-layer woven structure, which prevents absorbed sweat from flowing reversibly. Lightweight fabric is composed of hollow fiber.

Making the fabric surface as smooth as possible can reduce the surface friction of the fabric. Plain-woven high-density fabric of ultra-fine denier fiber has a smooth surface. Teflon-laminate surface is water-repellent, and produces even less friction. Since water- or airflow at the surface will be disturbed less with small surface dimples (a golf ball is a good example), such dimples are provided on the surface of swimming costumes and ski-jump coats. Garments made of heat-storage fiber were used in the Winter Olympic Games in Japan in 1999. Heat-storage fiber is a hollow fiber filled with zirconium carbide. Zirconium carbide absorbs visible light and converts it into far-infrared radiation. Transparent or non-transparent fiber materials are developed to respond to the demands from ladies wishing to wear a white swimming costume. Bodyshell® (Toray) is such a non-transparent white fabric. A conventional white fabric becomes transparent when wet. Bodyshell, however, has a star-shaped core of a different refractive index, which scatters light randomly.

Ultra high strength has been one of the major goals in the fiber/textile field and useful in sportswear. Today gel spinning and liquid crystal spinning are two industrial processes to produce ultra high tenacity fiber, represented by polyethylene and Kevlar, respectively. High tenacity polyethylene is light and strong. Scissors cannot cut aramid fiber such as Technola and Kevlar. However, the tenacity of those ultra high tenacity fibers is about 20% of the tensile strength calculated theoretically from the ideally extended chain model. Conventional polyester or nylon fiber achieves only about 5% of the theoretical tensile strength.

Scaled swimming costume

At the World Swimming Championships in Perth, Australia, 85% (338) of swimmers out of 400 participants used swimming costumes made of a new material Speed® developed by Toray and Mizuno. A water-repellent coating is applied to the surface of Speed. A scale-like pattern of water-repellent sheet is printed as shown in Fig. 5.15. The water-repellent scales produce

5.15 Swimming costume, made of Speed®, with water-repellent coating (Mizuno).

the water flow speed different from that at other parts, and result in vortex in a longitudinal direction to suppress turbulence.

5.2.2 Sportswear for speed competition

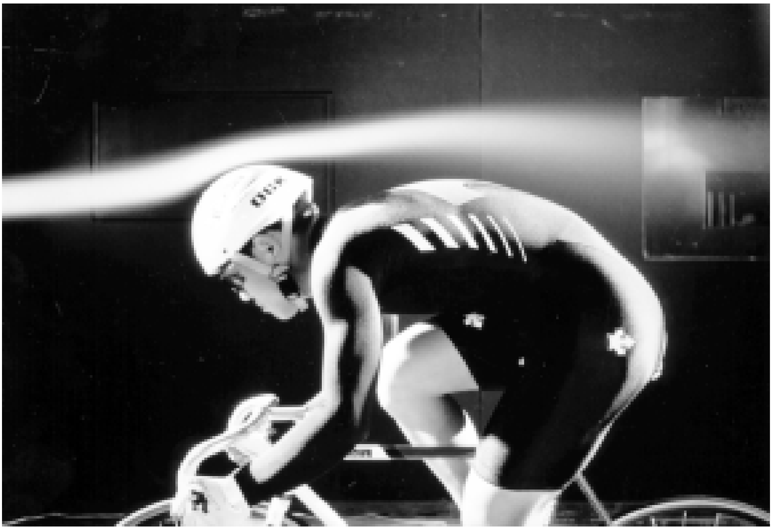
Utilizing the characteristics of an uneven surface

Stars and Stripes from the United States won the 1987 Americas Cup. The yacht had an uneven bottom to reduce water resistance. This uneven surface is also applied to NASA rockets and the pantographs of the bullet trains. Descente applied this uneven surface principle to swimming costumes used at the Barcelona Olympic Games in 1992. This swimming costume has an uneven surface at the bottom and breast (see Fig. 5.16) by pasting on silicone sheets. Cycling wear was also developed with the same principle for the American team (see Fig. 5.17). With this uneven surface, water resistance was reduced by about 12% in the swimming costume, and air resistance by about 3% in cycling wear.

Another use of an uneven surface

The principle of the uneven surface was adapted to reduce the air resistance at the Nagano Winter Olympic Games in 1999. The wear for speed skating had an uneven surface, with a silicon sheet at the back, arms and legs. The athletes from the Netherlands had fringed fins at both sides of their heads, shoulders and legs to reduce air resistance.

5.16 Swimming costume having uneven surface (Descente).



5.17 Cycling wear (Descente).

Descente applied the same principle to the downhill costumes. The International Ski Federation (FIS; *Fédération internationale de Ski*), however, prohibits covering costume surfaces with plastics. The FIS rules specify that the air ventilation must be over 30 liters per second through an area of 1 m^2. Silicon sheets cannot be used since silicon is considered a plastic material. Thus Descente invented the production of dimples by utilizing a special knitting structure, and developed a new fabric with built in dimples – Dimplex®. Karl Mayer (Switzerland) cooperated with Descente, who modified their knitting machines to produce such dimples.

The dimples are applied to the ski jump suit. A major consideration in ski jumping is how to handle air resistance. Speed is the most important factor in an approach run, where the air resistance is small. The second step is the takeoff. After a takeoff, a jumper needs to be lifted up in the air. To obtain enough lift, the air resistance at the front and at the back should be significantly different. Descente developed a jump suit with Dimplex®. Here the outer side (Dimplex®) and the inner (two-way tricot) sandwiches polyurethane foam. Since FIS specifies that the thickness of the suit must be less than 5 mm, the outer and inner fabric must be as thin as possible in order to maintain some rigidity by the insulation material as fluttering causes vortex and loses lift.

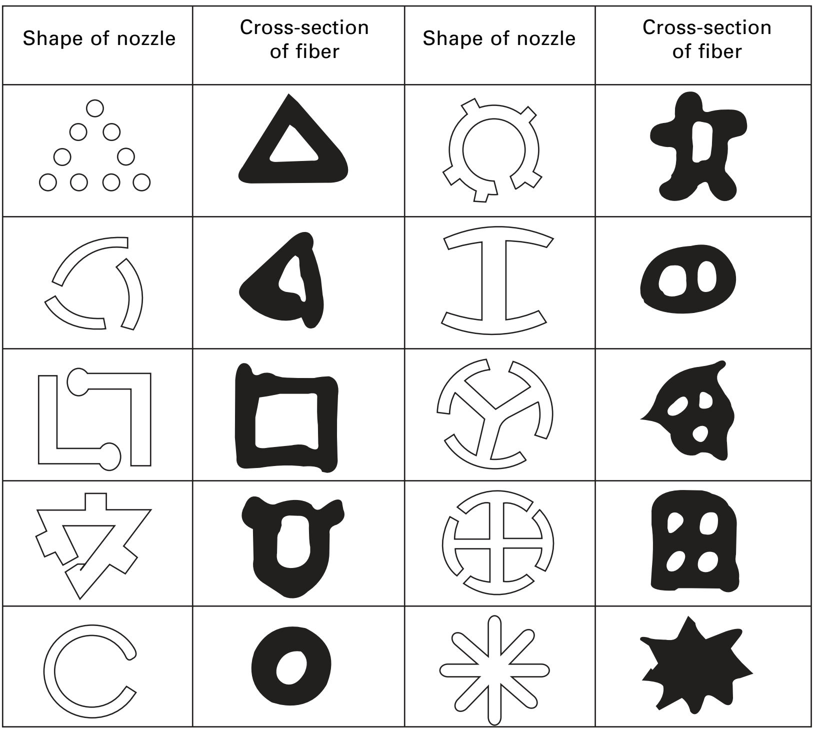
Hollow fiber for light swimming costume

Lightweight and heat-insulating materials have been developed by using hollow fibers for the past ten years. Hollow fibers have now been applied to swimming costumes to provide lift for the body in water and prevent it from being cooled. A hollow fiber is produced by a specially designed spinneret as shown in Fig. 5.18, where respective fiber cross-sections correspond to the shape of a spinneret. Teijin Ltd. produces the polyester hollow fiber Aerocapsule®, and the companies Unitika, Kanebo Gohsen and Toyobo have developed the nylon hollow fibers Microart®, Lightron® and Aircube®, respectively. Because of the hollow, the apparent density of a hollow fiber is less than one, and its heat conductance is small. Consequently, fabric made of a hollow fiber floats on water and insulates heat. A hollow fiber for a swimming costume is shown in Fig. 5.19, and that for clothes is summarized in Table 5.2. Table 5.3 lists the characteristics of a hollow fiber and its applications.

5.3 Comfort function fiber

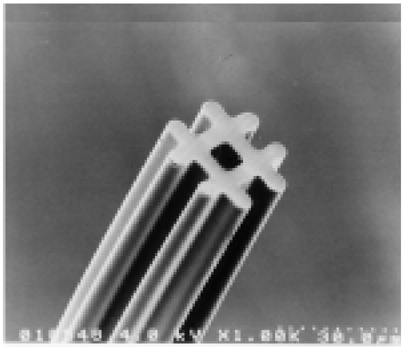
5.3.1 Cooler feeling Eval fiber Sophista®

Kuraray developed an ethylene-vinyl alcohol copolymer (Eval) fiber, 'Sophista®'. Sophista is produced through the mixing of raw materials (Eval

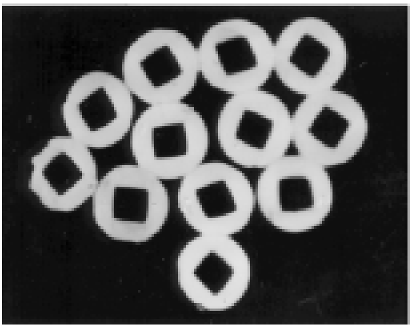


5.18 Shape of spinneret and cross-section of fiber.

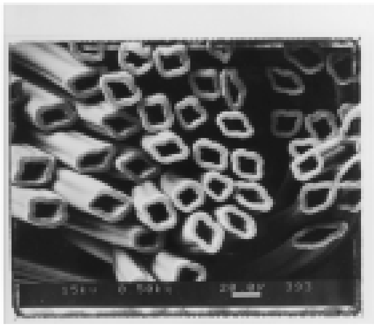
Lightron made of nylon (Kanebo)



Microart made of nylon (Unitika)



Aircube made of nylon (Toyobo)



Airocapsule made of polyester (Teijin)

5.19 Hollow fiber for swimming costume.

Table 5.2 Hollow fiber for clothes

Material	Manufacturer	Hollow ratio (%)
Killatt-P	Kanebo Gohsen	>30
Aerocapsule®	Teijin	35–40
Viareggio®	Toray	20–30
NEATY®	Asahi Kasei	20–30
Airfro®	Unitika	Around 40
GARLAND®	Kuraray	About 20

Source: T. Suzuki, Series of Basic Lectures on Fiber and Textiles I, The Society of Fiber Science and Technology, Japan, May, 1999.

and polyester pellets), melt-spinning and conjugate spinning. Hydroxyl groups in Eval are hydrophilic and enable Sophista to absorb and diffuse water. Sophista can be called aqua-fiber, and feels gentle and comfortable to the touch. Besides, hydroxyl groups can react with a wide range of compounds to give extra performance.

Sophista is available in three different structures (see Fig. 5.20):

Table 5.3 Properties and usage of hollow fibers

Properties of hollow fiber	Usage
Bulkiness, lightweight	Cotton for padding; General clothes
Superior in heat retention	Cotton for padding
Firm and strong	General clothes; Carpet
Soil proof	Carpet
Water absorption and water permeation	Underwear, sportswear
Can be applied to filtration and dialysis	Materials for industry and medical care

(1) Sheath-core type: core: polyester 45%, sheath: ethylene-vinyl alcohol 55%
(2) Multi-layers type: polyester 67%, ethylene-vinyl alcohol 33%
(3) Multi hollows: ethylene-vinyl alcohol 100%.

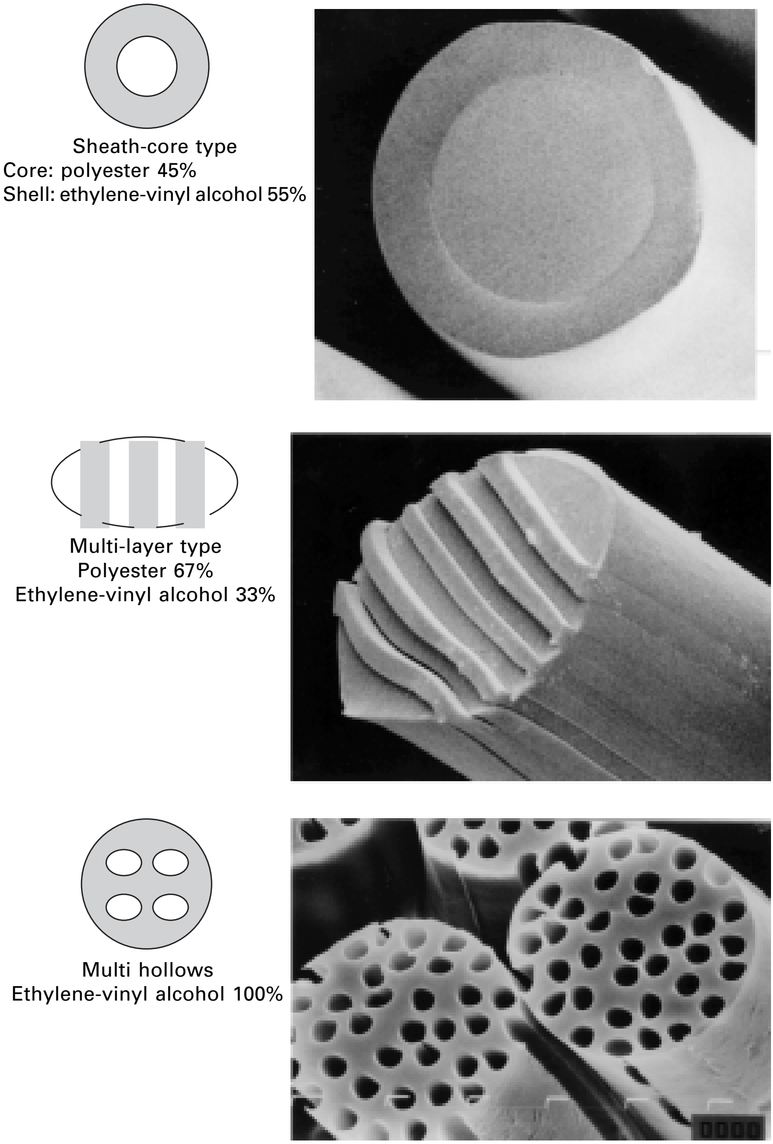
As the melting point of Eval is 160–170°C and it is not resistant to water below 100°C, Eval is not used for clothing. Kuraray introduced a cross-linker into Eval, processed and achieved characteristics such as stainability at 120°C, dry heat set at 160°C and iron-proof.

The basic physical properties of Sophista and comparisons with other fibers are shown in Table 5.4. It shows that Sophista has basic characteristics to be a fiber for clothes.

During the rainy season in Japan, ‘cool’ and ‘fresh’ characteristics are important for comfort. Cool feeling is the most important character for sports clothes. We can feel ‘cool’ and ‘fresh’ when there is no soggy and uncomfortable liquid layer between the fiber and skin. Moreover, less contact resistance, and active ventilation and heat transfer between the inside and the outside of the clothes are important. The material which gives cool feeling should have functions to absorb water/moisture quickly and let them evaporate quickly. A cool feeling cannot be obtained when the modulus decreases with water absorption.

As shown in Table 5.4, Sophista has moisture absorption of 1.5%. Sophista can absorb sweat and water on the fiber surface and evaporate the moisture move quickly than cotton and polyester. As the core of Sophista is polyester, there is no reduction of modulus when wet. It feels smooth and comfortable to touch, not soggy and sticky. During working, Sophista can maintain the body temperature at a comfortable level by latent heat caused by quick absorption and diffusion of water. It also prevents a quick drop of body temperature which occurs mostly after stopping working or exercise. Such properties give comfort to sportswear.

Compounds bonded to hydroxyl groups of Sophista may develop new application fields such as deodorization, waterproofing, and flame resistance.



5.20 Cool-feeling fiber, Sophista (Kuraray).

5.3.2 Comfort feeling materials, CORTICO®

Teijin developed comfort cool-feeling materials composed only of polyester. Using polymer and spinning technology, Teijin developed the polyester material, CORTICO, which is dry and absorbs sweat materials giving aesthetic sense and comfort functions.

Table 5.4 Basic physical properties of various fibers

Material	Tenacity (g/d)	Density	Refractive index	Moisture absorption (%)
Sophista	3–4	1.23	1.52	1.5
Polyester	4–5	1.39	1.72	0.4
Nylon	4–6	1.14	1.53	4.5
Rayon	1.7–2.5	1.50	1.50	11

Source: Kuraray

Materials of CORTICO

CORTICO is polyester filament (long fiber), fabricated using the following technology (see Table 5.5).

- *Polymer technology*: Special particles introduced into polyesters enlarge differences between thicknesses during elongation on spinning. Such particles are easily dissolved in alkaline, so alkaline processing after closing can form minute voids.
- *Spinning technology*: Special elongation technology disperses the elongation point unhomogeneously, so that the fiber axis direction and cross-section of fiber are unhomogeneous in thickness, and therefore have an anisotropic cross-section Fig. 5.21.

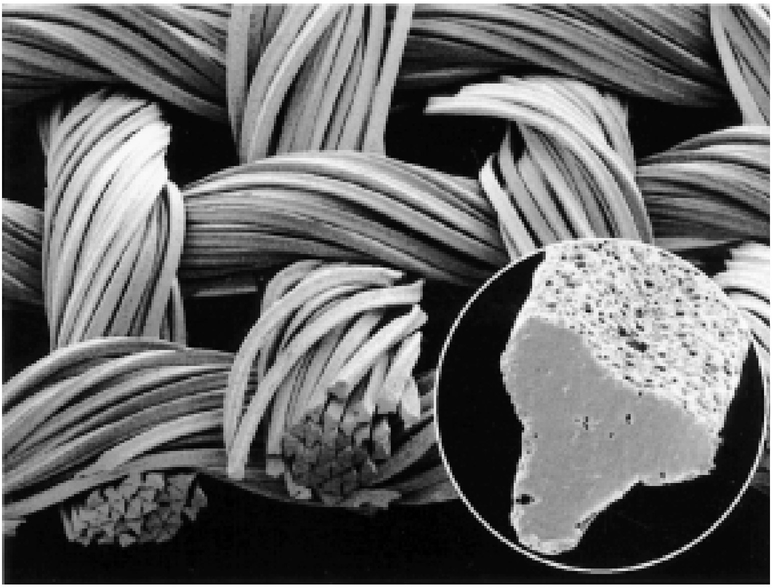
Character of cloths composed of CORTICO

Cloths composed of CORTICO have feel and comfort functions as clothing textiles shown in Table 5.6. These characteristics are displayed in the material by stain dressing processing technology.

Table 5.5 Character of raw fiber of CORTICO and included technologies

Technology	Contents	Action	Character of fibers
Polymer	Special particle method	Depress crystallization orientation Alkaline solubility	Single fiber Maximize differences between structures in thick and thin parts Minute void on fiber surface
Spinning	Special elongation	Unhomogeneous dispersal of elongation point	Unhomogeneous thick-thin marks in fiber axis and cross-section
	Anisotropic spinning hole	Anisotropic shape in fiber cross-section	Anisotropic cross-section

Source: Teijin



5.21 CORTICO having anisotropic cross-section (Teijin).

Table 5.6 Character of CORTICO textiles

Division	Characters
1. Aesthetic sense	Natural appearance, spun yarn feeling Dry touch, mild luster
2. Comfort function	Sweat absorbance, quick dry Remove soggy and sticky touch

Source: Teijin.

Feeling

Natural outside: Natural outside is defined as the outer surface of the cloth where a difference in thickness can be recognized by eye, but no difference in color depth is recognized. CORTICO is a thick-thin fiber where the thick and thin parts are dispersed unhomogeneously so that its thick-thin morphology can be recognized but with no difference in color depth. Conventional polyester thick-thin fiber has a deep outside at the thick part and shallow at the thin part. But CORTICO has a maximum difference in inside structure of both in thick and thin parts, so appropriate stain conditions can be selected to make stains leave more easily from the thick parts. Therefore depth of colour is even throughout.

Dry touch: Alkaline processing in the stain perfection process dissolves special particles and makes minute voids. These random voids between fibers result in inequality at the surface which minimizes the contact area between skin and cloth, producing a dry feel.

Mild gloss: Random voids between fibers and inequality in the surface reflects light randomly. It displays high-class mild gloss.

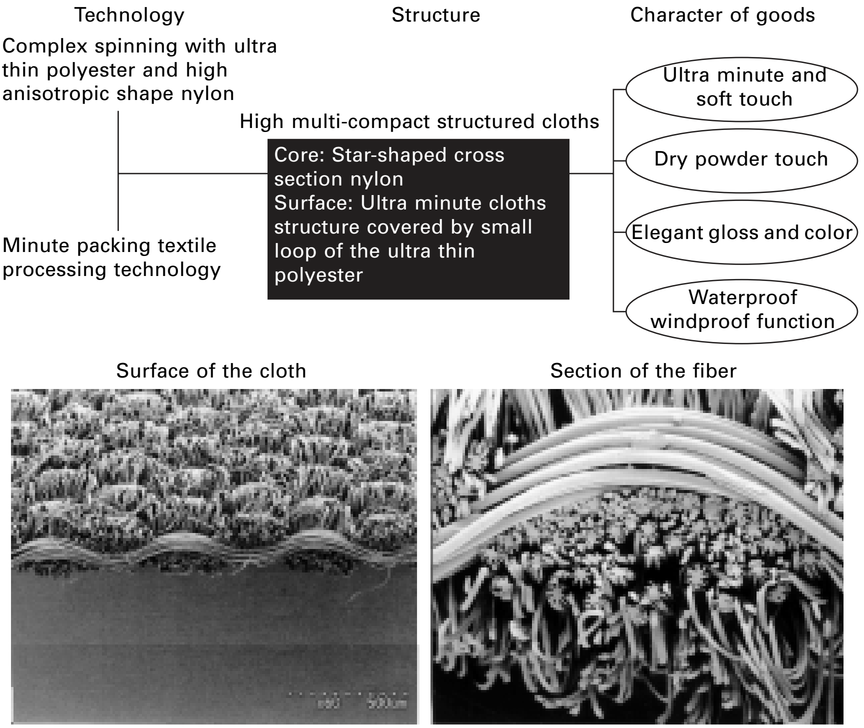
Comfort function

Sweat absorbency and rapid dry: Minute voids maximize the surface area of the fiber. Thus the surface can get wet more easily than cotton.

Without heavy-touch feeling: Material which get wet easily, having capillary effects due to space between fibers can diffuse water rapidly. Thus sweating on clothes, sweat between the skin and clothes is diffused rapidly, so there is no heavy-touch feeling.

5.3.3 ARTIROSA™ having comfort function

Toray developed ARTIROSA, a fiber having comfort function. Its technology, structure and characteristics are shown in Fig. 5.22.



5.22 High multi-compact materials having minute structure and flexible touch ARTIROSA (Toray).

ARTIROSA is composed of raw fibers highly composed of ultra-thin polyester fibers and star-shaped cross-section nylon fibers. Small loops of the ultra-thin polyester cover the surface of the cloths with nylon in flexible inner layers. They form an ultra-high density structure.

The soft touch of nylon and the strength and elasticity of polyester combine on a micron scale to produce a flexible feel. The structure of ultra-high density cloths make after-processing unnecessary to make the cloth waterproof and windproof. The small polyester loops give a dry and comfortable micro powder touch. The interaction between the surface loops and the inner nylon produces a special effect such as a cool and delicate gloss with deep shade.

Trends in autumn and winter coats have moved from using animal hair mixed with wool materials such as cashmere to cotton and now to artificial fiber material type. Outerwear from artificial fiber material must have light wear feeling and excellent functions, and is thus suitable for autumn, winter, and spring.

Surface materials for such clothing needs to be waterproof and windproof, so high density cloths with a flat surface using nylon and polyester, or coating and plastic processing on the surface of the cloth are used at the moment. The wear, feeling, and touch, etc., require the development of new goods using new materials.

The diversification in consumers' lifestyles, calls for a wide variety of uses, with elegant taste. There is a great increase in casual wear. ARTIROSA has high-feel with more comfortable wear-feeling, functionality and touch, so it is a new material accommodating to consumers' needs.

5.4 Biomimetic and intelligent fibers

5.4.1 The history of synthetic fiber development is the history of biomimetics

Professor Breslow of Columbia University (USA) proposed the term 'biomimetics' for a new area of research on enzymatic functions in 1972. However, in the field of fiber/textile technology, synthetic fiber has mimicked natural fibers since the 1960s. The synthetic fiber/textile copies not only the bio-structure, but also the bio-functions. Classic examples are a crimpled fiber mimicking the conjugate structure of wool, and a hollow fiber applied for blood dialysis which mimics the lumen structure of cotton. A traditional Noh costume made of polyester with a triangular cross-section scroops like real silk (see Fig. 5.23). Other examples are the water-repellent fabric mimicking the surface structure of a lotus leaf, the chromophoric fiber mimicking the microstructure of a morpho ala, and the deep colored fiber mimicking the micro-crater structure of the cornea of a moth. The odor-killing fiber mimics the supramolecular structure of an enzyme, and artificial suede micro-denier

5.23 A traditional Noh costume made of polyester with a triangular cross-section (Toray).

fiber copies a high-order structure of natural leather. High function fibers developed using the biomimetic approach are shown in Table 5.7. These high function fibers mimic the conjugate structure, the irregular shape, the uneven surface structure, the fine structural hierarchy, and the catalytic function of natural fibres (Table 5.8). However, the mechanism of the structure formation of natural fibers is still not well understood and could be a profitable area of research.

5.4.2 The challenge to harness nature

Spider silk has excellent mechanical properties with tenacity similar to Kevlar and its elongation at breaking point is over 10%. However, why and how spider silk has such an excellent mechanical property remains a mystery. New function fibers learning from bio-systems are shown in Fig. 5.24. Table 5.9 summarizes the biomimetic functions of fiber and textiles under development.

The characteristics of biomaterials can be summarized as follows:

- Biomaterials are multi-functional composites (high function and multi-function).
- Synthetic materials can surpass biomaterials, but only with respect to a single property.
- Biomaterials exhibit high functions, even when biomaterials are mechanically weak.

Table 5.7 High function fibers developed using biomimetic approach

Discovery/ invention	Structures mimicked	Advanced-function fibers	Discoverer/inventor
	Lumen structure of cotton	Hollow fiber	Du Pont
	Conjugate structure of wool	Elucidation of crimp structure → Crimpled fiber	M. Horio (Kyoto University)
1964	Silver trappings of leather	Artificial leather	O. Fukushima (Kuraray)
1965	Super-fine structure of leather	Micro-denier fiber Artificial suede	M. Okamoto (Toray)
1978	Micro-crater structure of cornea of moth	Fiber with deep colors and luster	S. Yamaguchi (Kuraray)
1979	Supramolecular structure of enzyme	Odor-killing fiber	H. Shirai (Shinshu Univ.)
1980	Triangular cross-section of silk	Shingosen with silk scrooping	Y. Sato (Toray)
1980	Capillary water absorption by tree	Water absorption porous hollow fiber	T. Suzuki (Teijin)
1983	Surface structure of lotus leaf	Water-repellent fabric	F. Shibata (Teijin)
1989	Multi-layered structure	Fiber with light interference function	K. Matsumoto (Kyoto Institute of Technology)
1992	Structure of bioorganisms	Non-transparent fiber	T. Kato (Toray)
1997	Natural color of Morpho alae	Structurally colored fiber	H. Tabata (Nissan Motor) M Yoshimura and K. Iohara (Teijin) S. Shimizu (Tanaka Kikinzoku)

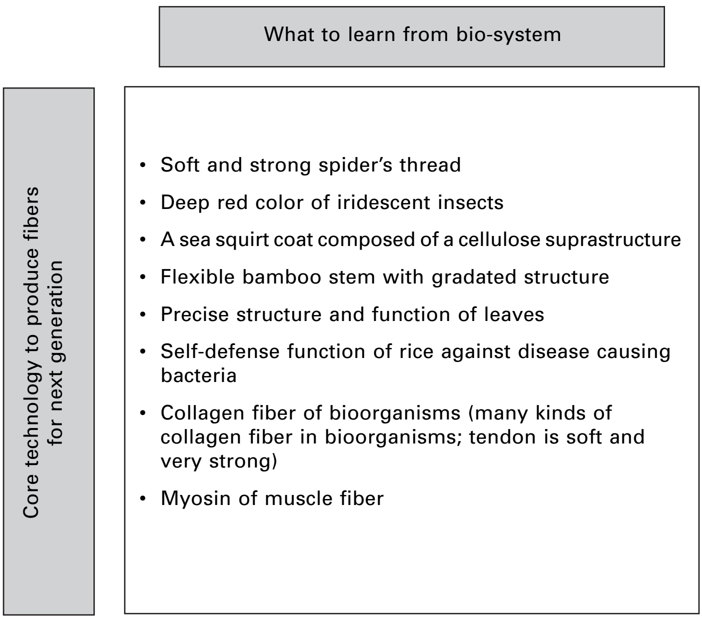
For example, a bamboo exhibits optimum bending rigidity with a minimum amount of the material of density-gradated structure, and a shell a composite structure of multi-layer calcium carbonate bound with protein paste.

Iridescent insects

The color of the ala of a jewel beetle will not fade even after a thousand years, because its color is not due to a dyestuff but to a light interference. The ala electron micrograph of an ala of a jewel beetle reveals a vertical multi-layer. This multi-layer is composed of helices, which related to a specific

Table 5.8 Biomimetics learned from functions and form of bioorganisms

Function	Structure	Bioorganism	Biomimetics
	Conjugate	Natural Leather	Ecsaine (Toray)
Form	Different shape Form beauty	Silk, Wool Butterfly Moth	Glacem (Kanebo) Diphol (Kuraray) Microcrater (Kuraray)
	Surface	Lotus leaf	Microft rectus (Teijin)
	Uneven	Seed of Xanthium strumarium	Hook and loop fastener
Micro-structure	Fluctal surface	Feather of waterfowl Water strider	Fluctal, water repellent
	Spiral (cholosteric liquid crystal)	Insects	Colored fiber without staining Conjugate material



5.24 New function fiber based on biomimetics.

liquid crystal. Such helical structures are one of the most basic structures in nature, and are found, for example, in the cellulose organization in plants, the shell of crabs and insects composed of chitin fibrous assembly, and fish scales. A part of animal bones, the Achilles tendons and eyeballs are made of

Table 5.9 Biomimetic functions of fiber and textiles under development

Unit to express	Structural	Basic function	Systemized function
Molecules/ assembly	Artificial silk/ wool/cotton	Dry-processed liquid crystal, Gel spinning, Highly oriented fiber Artificial spider silk	Matter recognition, Separation transmittance, Artificial enzyme immunity fiber, Suppression, Blood purification, DNA-type fibrous information storage media
Cell/organs	Artificial leather/ feather/bone/ teeth, Fiber reinforced ceramics	Artificial kidney/ lung/skin/muscle/ heart/nervous system	Artificial antimicrobial/ sterilization system, Artificial repairing system, Information recognition/transfer/ processing/memory
Bioorganisms	Marine textiles for fish gathering, Structural material, Geotextiles, Waterstorage fiber, Anchor	Fiber to reduce environmental stimuli, Air/water purification fiber	Function to assist growth and breeding, Material recycling system

helical collagen fiber. The helical structure is energetically stable, and the helical natural polymers are concentrated in the process of growth to form a cholesteric mesophase.

The ala of an insect living in a desert reflects infrared light to survive under the strong sun. This suggests that, if we can duplicate this, we might develop a textile that cuts out the sun's rays in summer. Some synthetic polyglutamic acid esters were found to form the same cholesteric mesophase as the ala of a jewel beetle according to Professor J. Watanabe (Tokyo Institute of Technology). Cellulose derivatives also form cholesteric mesophases. The color appears in the cholesteric mesophase by light interference without dyeing. In future, it might be possible to produce a revolutionary coloring process without using a dyestuff. A similar process could be applied to cut out heat rays or UV radiation.

Intelligent materials

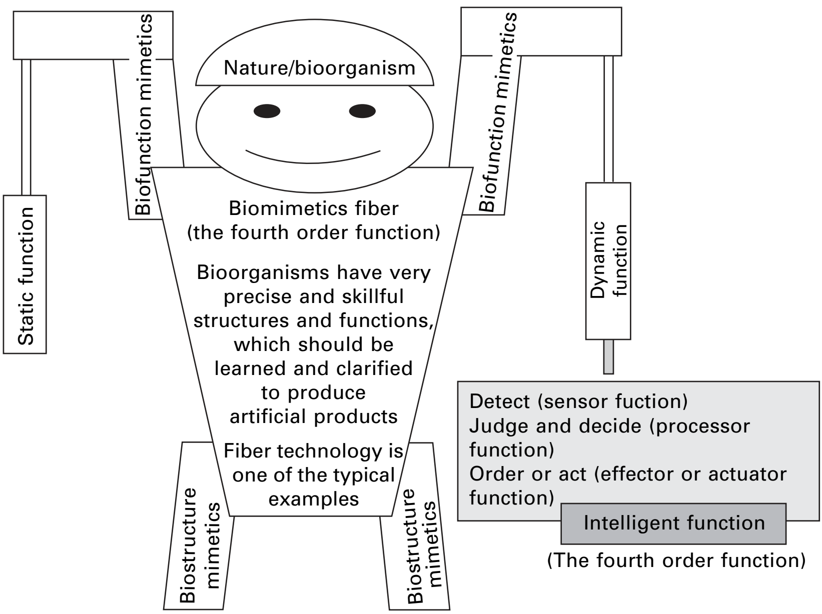
The term 'intelligent materials' first appeared in the 1989 report of the technical council of aero- and electronic-industry in response to the inquiry of the

President of the Agency of Science and Technology of Japan. Intelligent materials are defined as structural materials with high functions. Although there are many disagreements about what exactly constitutes a high function, intelligent fiber, a possible definition is:

> 'fibrous material provided with a sensory function to sense an external stimulus and change its state, a processor function to process its state according to the change, and an actuator function to actuate itself in response to the processing.'

Biomimetic fiber can be classified as structure-mimetic (mimicking the structure of organisms) and function-mimetic (mimicking the function of organisms) fiber. The function-mimetic fiber is further classified into static-function-mimetic fiber and dynamic-function-mimetic fiber. Here the dynamic function is called 'intelligence'. The relation of the biomimetic fiber to intelligent fiber is shown in Fig. 5.25. H. Okamoto has produced a classification chart of organisms based on composite structure (Table 5.10).

Intelligent textiles are now appearing on the market. Table 5.11 shows recent intelligent textiles. To develop intelligent textiles several steps must be considered. For example, for clothing, the type and function of built-in sensor and actuator will be determined by what sort of response is expected from the environmental change by the wearers. Then the materials possessing



5.25 Relation between biomimetic fiber and intelligent fiber.

Table 5.10 Classification chart of organisms based on composite structures

Type	Primary structure	Material	Examples of biological system			
			Constituent material (Matrix)	Structural element		Structural system (composite structure)
Fiber-reinforced	[1-dimensional reinf.] unidirectional	Inorganic	$CaCO_3$/$CaCO_3$ Cellulose	Fiber/crystal (calcite) Vascular tube		Tooth of sea urchin Culm part of bamboo
	[2-dimensional reinf.] laminates cross-ply angle-ply filament winding	Organic	Chitin/protein Collagen/poly-saccharide Actin-myosin Collagen Collagen/proteo-glycan	Cuticle Parenchymal membrane Muscle spindle cuticle		Crust of insect, lobster and crab cornea Heart, blood vessel nematode Intervertebral disk
	[3-dimensional reinf.] Mixed laminate		Cellulose/lignin Actin-myosin (*) * + collagen	 Muscle spindle (**) ** + tunic	Adhesive bonding reinforcement →	Wood Mantle of octopus Mantle of squid
		Organic-Inorganic	Collagen apatite Collagen calcium phosphate	Herversian lamella (crystal structure) hydroxyapatite		Bone, tooth, ivory
Particle-reinforced	Prism structure Nacre structure Foliated structure Crossed lamellar structure		$CaCO_3$/ conchiolin Silicate	(Crystal structure) calcite Aragonite		Shell (outer layer), coral Shell (inner layer), pearl Diatoms

Source: H. Okamoto., *Biomimetics*, 2 (2) 1–13 (1994)

Table 5.11 Intelligent textiles appearing on the market

Uses	Function	Sensor (stimuli)	Processor (mechanism)	Actuator (response)
Window shade/Curtains Clothes for health	Shading UV-shielding	Light UV	Photochromic	Color change Shading
General clothes	Cool feeling Heat retention	Temperature	Exo/endothermic	Endothermic and exothermic by increase and decrease, respectively
Curtains/wall paper	Soundproof	Sound wave	Piezoelectric	Absorption of sound pressure
Bedding	Bedsore-proof	Pressure by weight	Compression by fatigue	Decrease of contact pressure
General clothes	Soil-proof → No washing	Soil by organic matter	Removal by enzyme	Cleaning

Source: M. Fukahara, *New Fiber Science Challenge for New Frontier.*

a required function should be selected or created. The function is revealed by mechanical, thermal, electric, magnetic, optical or chemical forces. Its mechanism is the result of structural and/or phase change of the materials, and depends on the molecular structure, cross-linking, etc. The surface property (the affinity of the boundary), the structural gradation and the distribution of physical units in terms of the size and position are also factors influencing the intelligence of the materials.

Fashion design and wear comfort are the prerequisite factors for clothing. The most difficult problem is to decide where the intelligent function should be incorporated in the process leading from polymer and spinning to a final product. The function can be incorporated in the process of dyeing and finishing by chemical reaction, coating, and/or absorption of functional groups. In the process of weaving or knitting, the fabric organization should be carefully designed. The function will be required at a particular place, but not for the whole fiber.

5.5 The new areas

5.5.1 Wearable computer

Computers in the twenty-first century could change from the portable to the wearable type. Because of the weight reduction and miniaturization of computers, it is now easy to carry a computer and various application fields have been developed on this basis. Since the first international symposium on the subject, held at the Massachusetts Institute of Technology in October 1997, wearable computers have attracted attention.

Research is active into medical-devices-wearing computers which need to have regard to fashion requirements. In the near future, fashionable wearable computers may be seen around town.

5.5.2 Organic electro-luminescence wearable display

Organic electro-luminescence wearable display with a thin screen has been developed and marketed by Pioneer. When a voltage is applied to specific compounds, a luminescence can be produced. Thus plastic films with a thickness of 0.2 mm can be so processed to produce a display which can be attached to clothes, bags, and the arm. The materials will be applied, not only to wearable displays, but also to mobile phones and TV and computer screens.

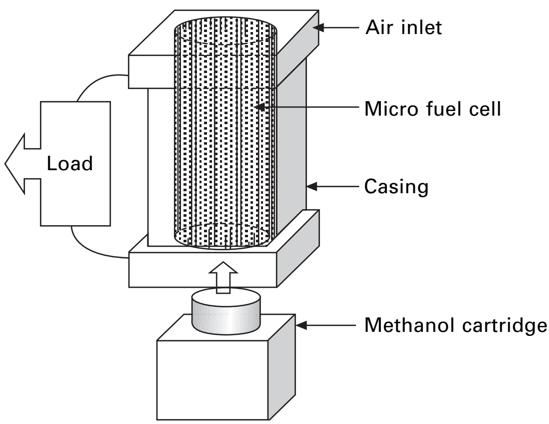
5.5.3 Mobile fuel cell using hollow fiber

The research to use a polyelectrolyte fuel cell as a power source for mobile devices is growing. The methods to supply hydrogen to fuel cells include direct supply of hydrogen to storage vessel/occlusion alloy and modification of methanol to be able to generate hydrogen. As the latter needs a specific device, there are problems in weight and size of the device.

The National Institute of Advanced Industrial Science and Technology (AIST) has now established an elemental technology to generate hydrogen from methanol, using a catalyst and hollow fiber. The technology does not need any specific devices to modify the methanol. Dr T. Okada of AIST has demonstrated the utilization of tubular polymer electrolyte membrane for direct methanol fuel cells (DMFCs). The merit of DMFCs is not only that they allow a reduction in size, but also make possible the usage of the cells by feeding methanol continuously by cartridge or syringe as shown in Fig. 5.26.

5.5.4 Fibrous titanium oxide optical catalyst

Ube Kosan developed a fibrous titanium oxide optical catalyst. Fibrous materials can readily be processed so that they are applied in air purifiers and smoke separators. Ube Kosan established a pilot plant in Ube Factory (Ube, Yamaguchi Prefecture) in 2002, which now markets in the form of fiber and non-woven textile. The market in optical catalysts will be worth trillion yen in 2005. Organic silica polymer and low molecular weight components such as titanium oxide crystal are combined, spun, treated in high temperature air to remove impurities, and processed to give titanium oxide with high purity. The material can hold optical catalytic ability even treated at 100°C. The diameter of the fiber is 5 μm, the core of the fiber is made of silica, and layers of titanium oxide with different crystal densities surround the core, ten to several hundred nm in thickness.



5.26 Assembled micro-tubular DMFC. (Dr T. Okada, AIST).

Optical catalyst decomposes soil when lit and shows deodorant activity. As the development of optical catalyst that can work under visible light has now been achieved, the application fields have turned from exterior to interior use. There seems no limit to the further development of such intelligent fibers.

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