Applications of electrospun nanofibers

ARTICLE *in* CHINESE SCIENCE BULLETIN · AUGUST 2008

Impact Factor: 1.58 · DOI: 10.1007/s11434-008-0319-0

4 AUTHORS, INCLUDING:

Jian Fang
Deakin University
34 PUBLICATIONS **689** CITATIONS
SEE PROFILE

Haitao Niu
Deakin University
37 PUBLICATIONS **717** CITATIONS
SEE PROFILE

Chinese Science Bulletin

Applications of electrospun nanofibers

FANG Jian, NIU HaiTao, LIN Tong† & WANG XunGai

Centre for Material and Fibre Innovation, Deakin University, Geelong, VIC 3217, Australia

Polymeric nanofiber non-woven materials produced by electrospinning have extremely high surface-to-mass (or volume) ratio and a porous structure with excellent pore-interconnectivity. These characteristics plus the functionalities and surface chemistry of the polymer itself impart the nanofibers with desirable properties for a range of advanced applications. This review summarizes the recent progress in electrospun nanofibers, with an emphasis on their applications.

electrospun nanofibers, electrospinning, one-dimension materials, applications, review

Nanofibers can be produced from a wide range of polymers. These fibers have extremely high specific surface area due to their small diameters, and nanofiber mats can be highly porous with excellent pore interconnection. These unique characteristics plus the functionalities from the polymers themselves impart nanofibers with many desirable properties for advanced applications.

Several methods have been developed to fabricate nanofibers, such as template[1,2], self-assembly[3−5], phase separation[6], melt-blown[7] and electrospinning[8 − 11]. Electrospinning is currently the most promising technique to produce continuous nanofibers on a large scale and the fiber diameter can be adjusted from nanometers to microns. Also, electrospinning is a relatively easy and fast process to produce nanofibers.

Although the first patent on electrospinning technique was published as early as in 1934[12], this technique has not been well established until recent times[13−16]. Technically, electrospinning is a process that uses a strong electric field to draw a polymer fluid into fine filaments[17−20]. The basic electrospinning apparatus, shown in Figure 1, consists of a nozzle, a high voltage power supply, a container for polymer fluid and an electrode collector. When a viscous fluid is charged with a high voltage, the electrostatic force draws the fluid into liquid jet. Because of the interaction between the jet and external electric field and charge repulsion inside the jet, the charged jet undergoes a bending or whipping instability to stretch it thinner. Solvent evaporation from the filaments results in solid fibers. In most cases, the as-spun fibers deposit randomly on the electrode collector forming a non-woven nanofiber mat (Figure 1). Aligned nanofibers can also be produced using controlled fiber deposition techniques[21,22]. Until now, more than 100 polymers and many inorganic materials have been electrospun into nanofibers. The nanofibers can

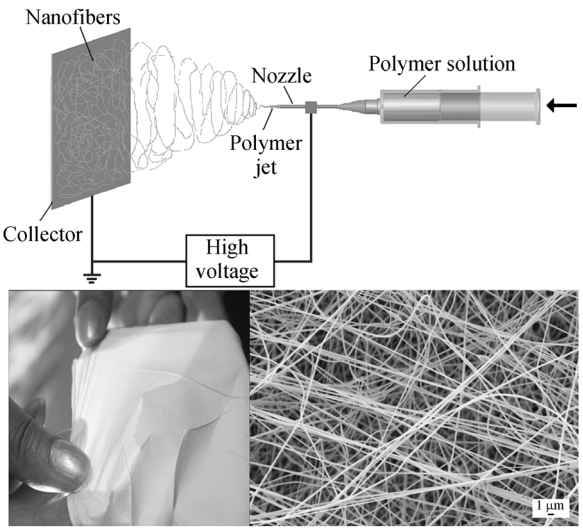

Figure 1 Basic apparatus for electrospinning, typical photographic and SEM images of a nanofiber.

Received December 30, 2007; accepted February 20, 2008
doi: 10.1007/s11434-008-0319-0
†Corresponding author (email: tongl@deakin.edu.au)

have many different morphologies, such as porous-surface nanofibers[23 − 27], core-sheath[28,29] and side-by-side[30] structures. The extremely fine electrospun nanofibers make them very useful in a wide range of advanced applications, and several reviews on nanofibers have been published[17−20,31−46]. But new applications have been explored for these fibers continuously. Here recent progress in electrospun nanofibers is reviewed, covering the following main application areas:

- Filtrations
- Affinity membranes and recovery of metal ions
- Tissue engineering scaffolds
- Wound healing
- Release control
- Catalyst and enzyme carriers
- Sensors
- Energy storage

A number of other applications are briefly discussed also.

1 Filtration

Filters have been widely used in both households and industry for removing substances from air or liquid. Filters for environment protection are used to remove pollutants from air or water. In military, they are used in uniform garments and isolating bags to decontaminate aerosol dusts, bacteria and even virus, while maintaining permeability to moisture vapour for comfort. Respirator is another example that requires an efficient filtration function. Similar function is also needed for some fabrics used in the medical area.

For a fiber-based filter, removal of particles is determined by different mechanisms. Large particles are blocked on the filter surface due to the sieve effect. Particles that are smaller than the surface-pores will penetrate into the filter, which could still be collected by the fibers, via either interception or impaction, or static electrical attraction. Also, very fine particles could be captured due to the Brownian motion effect. The filtration efficiency is normally influenced by the filter physical structure (fiber fineness, matrix structure, thickness, pore size, etc), fiber surface electronic properties, and its surface chemical characteristic (e.g. surface free energy). The particle collecting capability is also related to the size range of particles being collected. Besides the filtration efficiency, other properties such as pressure drop and flux resistance are also important factors to be evaluated for a filter media.

Electrospun nanofibers for filtration application have a long history. A company in US (Donaldson) has produced electrospun nanofiber-based filter products for industry, consumer and defense applications for more than 20 years (Figure 2), and its Ultra-web® nanofiber filter has been developed for nonwoven and filtration industry for a wide range of applications. Recently another company (AMSOIL) has also developed a nanofiber-based fuel filter for automobile applications. DuPont has electrospun fabric products for HVAC, automotive and liquid filtration, bedding protection and apparel applications.

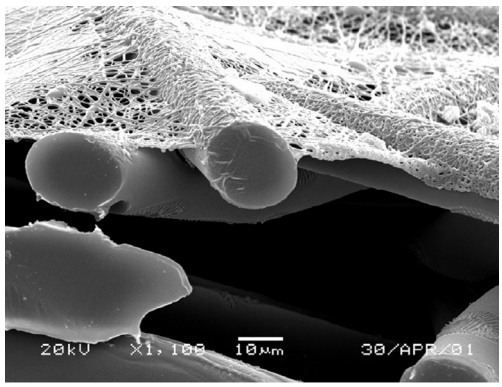

Figure 2 Air filter consisting of layered nanofibers nonwoven material developed by Donaldson.

Electrospun nanofiber membrane provides dramatic increases in filtration efficiency at relatively small decreases in permeability. In comparison with conventional filter fibers at the same pressure drop, nanofibers with a diameter finer than half a micron have a much higher capability to collect the fine particles, because the slip flow around the nanofibers increases the diffusion, interception and inertial impaction efficiencies[47].

Both experimental measurements and theoretical calculations revealed that electrospun nanofiber mats were extremely efficient at trapping airborne particles (0.5—200 μm)[48]. A very thin layer of electrospun nanofibers sprayed onto a porous substrate was sufficient to eliminate the particle penetration. The air flow resistance and aerosol filtration properties correlate with the add-on weight of the electrospun fiber coating. Also, electrospun layers present minimal impedance to moisture vapour diffusion, which is very important for protection clothing in decontamination applications. A comparison study between a nylon-6 electrospun membrane (thickness 100 μm, pore size 0.24 μm) and a commercial high

efficiency particulate air (HEPA) filter (thickness 500 μm, pore size 1.7 μm) using 300 nm test particles indicated that the thin nanofiber membrane had a slightly higher filtration efficiency (99.993%) than the HEPA filter (99.97%)[31].

Besides solid particles, tiny liquid droplets within a liquid-liquid immiscible system could also be removed by a nanofiber membrane (liquid-liquid coalescence filtration). Polystyrene (PS) nanofibers (diameter about 600 nm) were electrospun from a recycled expanded-polystyrene (EPS), and mixed with micro glass fibers to form a filter media for removal of water droplets from a water-in-oil emulsion[49]. The addition of small amount of PS nanofibers was reported to significantly improve the capture efficiency (from 68% to 88%), but the pressure drop of the filters was increased considerably. In another work, electrospun nylon nanofibers were also blended with glass fibers (diameter 5 μm) for the coalescence filtration, and addition of an optimal amount of nanofibers (1.6 wt%) to the coalescence filter improved the capture efficiency, but did not cause excessive pressure drop[50].

Nanofibers were used as a supporting scaffold in ultrafiltration (UF) for oil/water emulsion separation. The reported UF membrane has a three-tier composite structure consisting of a nonporous hydrophilic top layer, a crosslinked poly(vinyl alcohol) (PVA) electrospun nanofibrous mid-layer and a conventional nonwoven microfibrous substrate[51,52]. The electrospun nanofibrous substrate provided a well interconnected porous network with a large specific surface area, so the UF filter has a high flux rate and excellent organic solute rejection capability.

Other works related to the filtration applications include effects of operating parameters in electrospinning on fiber morphology and pore structure for filter media[53], nanofiber membrane for separation of micro particles from liquid[54], and pre-filter nanofiber membrane for particulate removal[55].

2 Affinity membranes and recovery of metal ions

Electrospun nanofibers also have a great potential to be functionalized via incorporation of functional materials into the fibers, or via surface chemistry and coating techniques. The functionalized nanofibers may be able to collect small molecules or metal ions from a solution. For examples, electrospun cellulose nanofibers were surface functionalized with a dye Cibacron Blue F3GA (CB), and the functionalized nanofiber membrane showed strong affinity to bovine serum albumin (BSA) and bilirubin, with a capture ability of 13 mg and 4 mg per gram nanofibers, respectively[37]. A membrane with similar BSA affinity was also prepared from electrospun polysulphone (PSU) fibers which were surface functionalized with another dye, Toluidine Blue O[56]. Both nanofiber-based affinity membranes had a much lower pressure drop and higher flux compared with similar affinity membranes prepared with conventional microfibers. In addition, electrospun wool keratin/silk fibroin blend nanofibers have been proven to have ability to chelate absorb Cu(II) ions from water[57].

In some cases, the functionalized nanofiber membrane was even able to directly covert metal ions collected into elemental metal (electroless recovery). When a nanofiber membrane was surface coated with a thin layer of conducting polymer, polypyrrole, the nanofiber membrane was able to collect gold ions from aqueous solution and simultaneously convert the gold ions into elemental gold particles[58].

3 Tissue engineering scaffolds

Tissue engineering is one of the most exciting interdisciplinary and multidisciplinary research areas today, and there has been exponential growth in the number of research publications in this area in recent years. It involves the use of living cells, manipulated through their extracellular environment or genetically to develop biological substitutes for implantation into the body and/or to foster remodeling of tissues in some active manners. A basic principle of the tissue engineering is illustrated in Figure 3. The purpose is to repair, replace, maintain, or enhance the function of a particular tissue or organ[59].

The core technologies intrinsic to this effort can be organized into three areas: cell technology, scaffold construct technology, and technologies for *in vivo* integration. The scaffold construct technology focuses on designing, manufacturing and characterizing three-dimensional scaffolds for cell seeding and *in vitro* or *in vivo* culturing.

For a scaffold to function effectively by assisting in the formation of neo-tissue, it must possess the correct design parameters. There are a few basic requirements that have been widely accepted for designing polymer

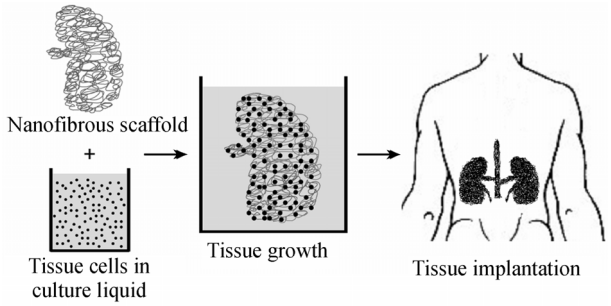

Figure 3 Principle of tissue engineering.

scaffolds[60]. First, a scaffold should possess a high porosity, with an appropriate pore size distribution. Second, a high surface area is needed. Third, biodegradability is often required, with the degradation rate matching the rate of neo-tissue formation. Fourth, the scaffold must possess the required structural integrity to prevent the pores of the scaffold from collapsing during neo-tissue formation, with the appropriate mechanical properties. Finally the scaffold should be non-toxic to cells and biocompatible, positively interacting with the cells to promote cell adhesion, proliferation, migration, and differentiated cell function.

It is now well known that many biologically functional molecules, extracellular matrix (ECM) components, and cells interact on the nanoscale. For example, collagen is a major natural extracellular matrix component, and possesses a fibrous structure with fiber bundles varying in diameter from 50—500 nm[61,62]. Many efforts have been made to search a suitable scaffold material, and an ideal scaffold should have similar physicochemical and biological characteristics to the ECM[63]. In morphology, electrospun nanofiber mat is very similar to human native ECM[38—46,64,65], thus could be a promising scaffolding material for cell culture and tissue engineering application. The electrospinning process makes it possible to produce complex, seamless and three-dimensional (3D) nanofiber scaffolds that support diverse types of cells to grow into the artificial tissues.

So far, hundreds of papers have been published on using electrospun nanofiber mats as tissue scaffolds and related cell growth performance. Nanofibers used come from different polymers including synthetic and natural polymers, biodegradable and non-biodegradable polymers. The cell culture has been conducted for potentially engineering different tissues including muscles, bones and cartilages, skins, neural tissues, blood vessels, and others. Recently, an electrospun synthetic ECM (Ultra-Web™) has been developed by Corning Life Sciences for more consistent and reproducible *in vivo*-like cell phenotypes experiments.

3.1 Muscles

Collagen nanofibers were first used to assess the feasibility of culturing smooth muscle cell[66]. The cell growth on collagen nanofibers was promoted and the cells were well integrated into the nanofiber network after 7 days of seeding. Smooth muscle cells also adhered and proliferated well on nanofiber membranes electrospun from other polymers, such as poly (ethylene-co-vinly alcohol)[67], poly(ester urethane) urea (PEUU)/collagen blend[68], poly(L-lactide-co-ε-caprolactone) (PLLA-CL)[69], poly(ε-caprolactone) (PCL)/collagen[70] and PS[71]. The incorporation of collagen into nanofibers was observed to improve fiber elasticity and tensile strength, and increase the cell adhesion[68,70].

The fiber surface hydrophobicity was observed to influence cell attachment. It was reported that when the PS nanofibers were surface treated with Argon plasma, the fiber wettability was increased significantly. As a result, cell attachment was increased by two folds[71].

The alignment of nanofibers also influenced the cell orientation. The cells cultured on the aligned nanofibers exhibited an alignment factor of 0.74, compared with 0.19 on the randomly orientated scaffold[71].

Nanofiber membrane electrospun from a commercial polyester urethane (DegraPol®) was used for skeletal muscle tissue engineering[72]. In three different cell lines, murine myoblast cell line (C_2C_{12}), rat myoblast cell line (L6) and primary human satellite cells (HSCs), were observed to adhere to, and proliferate well on, the nanofiber membranes.

3.2 Bones

Research on engineering bone tissues using electrospun nanofibers began as early as work on the muscles[73]. Cell growth on poly(lactic-co-glycolic acid) (PLGA) nanofibers indicated that nanofiber structure positively promoted cell-matrix and cell-cell interaction.

For bone tissue engineering, nanofibers from PCL have been extensively studied[74—76]. It was observed that mesenchymal stem cells (MSCs) penetrated into the PCL matrix accompanied with abundant extracellular matrix after 1 week of seeding, and mineralization and type I collagen occurred at 4 weeks. An *in vivo* experiment was also conducted by implanting a MSCs cul-

tured PCL construct (4 weeks) in the omenta of rats[76]. After 4 weeks, the constructs maintained the size and shape of the original scaffolds and had a bone-like appearance.

In addition to the pure PCL nanofibers, nanofibers from gelatin/PCL blend[77] and PCL composite with calcium carbonate nanoparticles and hydroxyapatite (HAp) nanoparticles[78−81] for bone scaffolds have been investigated. The addition of 50% gelatin to PCL improved both the fiber mechanical strength and surface wettability, therefore enhancing the cell attachment and growth on the scaffold surface. Also, the cells were observed to migrate up to 114 μm inside the scaffold within one week of culture. In contrast, PCL nanofibers containing these inorganic nanoparticles were expected to have high osteoblast proliferation and differentiation. In addition, a bond-like calcium phosphate (CaP) was coated on PCL nanofiber surface[82]. The CaP-coated nanofiber membrane showed high wettability. Because of its similar structure to the natural bone, such a mineralized electrospun scaffold is expected to be a potential cell carrier in bone tissue engineering.

A combination of PCL nanofibers and microfibers was used to develop multilayer scaffolds[83,84]. This multilayer fiber mat contained a thin nanofiber upper layer and an inner microfiber fibrous structure. As the top nanofiber layer assisted cell attachment and spread and the inner microfiber layer provided large pores for cell migration, and both the cell attachment and migration were improved.

Silk fibroin (SF) nanofibers for engineering bone tissue were also investigated[85,86]. The SF nanofiber scaffolds had excellent biocompatibility with enhanced bone regeneration, without evidence of any inflammatory reaction. When SF nanofibers contained bone morphogenetic protein-2 (BMP-2) or HAp nanoparticles, the presence of BMP-2 supported higher calcium deposition and enhanced transcript levels of bond-specific markers, while the incorporation of HAp nanoparticles into SF nanofibers improved the bone formation[87]. The coexistence of the two materials gave the largest improvement in the calcium deposition.

Other polymer nanofibers which have been examined for bone scaffolds include polyester urethanes (PEU)[88,89], polyphosphazenes[90], poly(latic acid) (PLA)[91], PLLA containing montmorillonite (MMT) nanoplatelets[92], silicate fibers[93], porous electrospun poly(ethylene oxide terephthalate)-poly(butylene terephthalate) (PEOT/PBT) fibers[94], poly(propylene carbonate)[95], poly(3-hydroxybutyrate) and poly(3-hydroxybutyrate-co-3-hydroxyvalerate)[96], PLGA[97] and PLA/HAp[98]. It is worth noting that a nano porous surface on electrospun fibers (e.g. PEOT/PBT fibers) can significantly enhance the cell proliferation and cells spreading on the fibers[94].

3.3 Cartilages

Articular cartilage, composed of primarily type-II collagen, is the connective tissue covering the ends of long bones, and serves the functions of load-bearing (shock absorber) and joint lubrication. The feasibility of using electrospun collagen (type-II) nanofibers to culture chondrocyte was studied[99,100]. The collagen nanofibers were observed to be compatible with chondrocytes and readily infiltrated the scaffold surface and interior. PCL nanofiber mat was also used to culture chondrocyte cells in a serum-free medium. It was found that PCL matrix promoted phenotypic differentiation and cellar proliferation[101], suggesting that the unique structural features and the biomimetic nature of PCL nanofibers could be an optimal supporter to the differentiation of cells without the aid of serum.

The importance of surface topography was proven via a comparison of cultured chondrocytes on poly (3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) nanofiber mat and cast PHBV film[102,103]. Although the PHBV nanofiber mat showed higher water contact angle than a flat PHBV film, more cells were observed to attach on the PHBV nanofiber mat with greater spread morphology. Also, chitosan/poly(ethylene oxide) (PEO) nanofiber mat showed better support for cell adhesion than its flat film counterpart[104,105].

As the degradation rate of PLGA could be adjusted via the ratio of lactic acid (LA)/glycolic acid (GA) units, the effects of the LA/GA ratio on mechanical properties, degradation rate and cellar responses to the PLGA nanofiber scaffold for cartilage reconstruction were studied[106].

3.4 Skins

As the largest body tissue, skin functions to prevent outside intrusion and regulate water retention and heat loss. Nanofiber mats from many different types of polymers have been evaluated for their cytocompatibility to fibroblast and/or keratinocytes. The polymers studied include natural polymers, such as SF[57,107,108],

collagen[109−112], gelatin[113], chitosan[82,114], hyaluronic acid (HA)[115,116], and synthetic polymers such as PLGA[73,117], PLLA[118−122], PCL[123−127] and many others[128−131]. In most cases, the electrospun nanofiber mats exhibited good capability of supporting cell attachment and proliferation. Cells seeded on the nanofiber structure tended to maintain phenotypic shape and were guided to grow according to the nanofiber orientation.

Collagen-PCL core-sheath nanofiber was prepared by coaxial electrospinning and solution coating[123,132]. The presence of collagen surface shell on PCL nanofiber was found to support cell proliferation and encourage cell migration inside the scaffold. The collagen coating formed directly from the coaxial-electrospinning had higher cell proliferation efficiency than that from the solution coating method.

Nanofibers of polymer blends (e.g. collagen/PCL[124], dextran/PLGA[117], poly(ethylene glycol) PEG/PLLA[118,122], collagen/glycosaminoglycan[111], PHBV/collagen[112], PCL/PEO) were also studied, and showed good cell attachment and proliferation. It was indicated that a small fraction of low molecular weight PEG in PLLA nanofibers increased the hydrophilicity. As a result, biological reactivity of fibroblast cells was improved[118]. The fiber wettability could also be improved by co-electrospinning of two different nanofibers (PLGA and chitosan/PVA) into the same fibrous matrix[82,133]. The presence of hydrophilic nanofibers (chitosan/PVA) increased the absorption to the nutrient fluid during cell culture and thus promoted fibroblast attachment, proliferation, and cell migration and infiltration in the fiber matrix. In addition, grafting nanofiber surface with a hydrophilic polymer also improved the wettability of nanofibers, an example being the treatment of PLLA, PLGA and PGA nanofibers with oxygen plasma followed by a chemical reaction with acrylic acid[120,121].

In addition to improving the wettability, the bioactivity of nanofiber matrices was also enhanced by functionalizing nanofiber surface with a cell adhesive peptide[134]. The cell attachment, spreading and proliferation were greatly enhanced in the modified nanofiber mat compared with the un-modified control.

The effect of nanofiber alignment on the cell adhesion and proliferation was studied[109]. When a rabbit conjunctive fibroblast was seeded on an aligned collagen nanofiber mat, lower cell adhesion but higher cell proliferation was observed on the aligned nanofibers, compared with that on the randomly orientated nanofiber mat.

Cell culture on a three-dimensional (3D) nanofiber mat containing larger pores, was also studied. A 3D SF nanofiber matrix was prepared by directly depositing the newly-electrospun SF nanofibers in a methanol solution[108]. This 3D nanofiber matrix supported the cell proliferation inside the fiber matrix quite well. A 3D nanofiber mat was also prepared by adding a chemical blowing agent (BA) into nanofibers via electrospinning, and a post-electrospinning heat-treatment leading to blowing large pores within the nanofiber mat. These large pores could provide good access to cells to penetrate inside the nanofiber mat[126]. In addition, in a 3D cell culture system using aligned fiber array, the maximum fiber diameter for cell adhesion and the maximum inter-fiber distance bridging cell aggregation were demonstrated to be 10 μm and 200 μm, respectively[119].

3.5 Blood vessels

Blood vessels vary in sizes, mechanical and biochemical properties, cellar content and ultra-structural organization, depending on their location and specific function. It is required that the vascular grafts engineered should have desired characteristics. Blood vessel replacement, particularly a fine blood vessel (diameter<6 mm), has remained a great challenge.

Culturing vascular endothelial cells (ECs) on electrospun nanofiber mats has been investigated. A comparison of cell growth on an electrospun PLLA nanofibers and a cast smooth PLLA film revealed that the function of vascular ECs on the smooth PLLA film, rather than on the electrospun nanofiber mat, was enhanced[135]. Since the electrospun nanofiber mats can give good support to the growth of vascular smooth mussel cells[69], smooth film combining with electrospun nanofiber mat could form a good 3D scaffold for blood vessel tissue engineering.

The effect of fiber diameter on culturing endothelial cells was examined using electrospun cellulose acetate (CA) fibers having three different diameter ranges, 0.01−0.2, 0.2−1, 2−5 μm[136]. It was interesting to note that the endothelial cells showed a growth preference towards larger fibers.

To mimic morphological and mechanical characteristics of a native blood vessel scaffold matrix, a multilayer electrospun nanofiber architecture consisting of a stiff

and oriented PLA outer nanofiber layer and a pliable and randomly oriented PCL inner nanofiber layer was electrospun[137]. Such a hierarchical scaffold was reported to be able to support the attachment, spread and growth of mouse fibroblasts and human myofibroblasts.

Surface modification of electrospun nanofibers with natural proteins, such as collagen or gelatin, was found to be an effective way to promote ECs spreading and proliferation. Examples can be found for collagen-grafted PCL[138] and gelatin-grafted polyethylene terephthalate (PET) nanofibers[139]. The modified-nanofiber mats showed apparent enhancement in the spreading and proliferation of endothelial cells (ECs) compared with the non-grafted ones. ECs readily oriented along the aligned collagen-grafted PCL nanofibers but not on the nonwoven counterparts[138].

Since a fibroblast growth factor (FGF-2) modulates cell growth, differentiation, migration and survival, the ability to bind FGF-2 to electrospun matrix was improved effectively by coating a bioactive recombinant fragment of perlecan on the surface of electrospun nanofibers[140]. Also, an adhesive protein, fibronectin (Fn), was grafted onto electrospun poly(L-lactide-co-caprolactone) (PLLC) nanofibrous scaffold, and the Fn-grafted nanofiber scaffold was observed to promote epithelium regeneration[141].

To match the mechanical characteristic of blood vessel, which has a low-strain mechanical response to blood flow and prevents pulsatile energy from being dissipated as heat, elastin/polymer blend nanofibers were used[142]. The preliminary cell culture studies showed that cells migrated through the full thickness of the elastin-containing grafts, but failed to migrate into pure polymer nanofiber control scaffold. To mimic the ratio of collagen and elastin in native blood vessel, electrospun nanofibers of collagen/elastin/synthetic polymer (e.g. PLGA, PLLA, PCL) (45∶15∶40 *w*/*w*/*w*) blend were assessed[143]. The as-spun nanofiber mat showed no cytotoxicity and was dimensionally stable, and its mechanical properties were similar to the native blood vessels.

Electrospun nanofiber vessel matrices possessing similar mechanical properties to native vessel were prepared using biodegradable elastic PEUU[144], and vessel matrices having a similar composition to the native vessel were prepared with collagen/elastin/PLGA blend[145].

In vivo assessment of cylindrical electrospun nanofiber constructs from collagen, gelatin, and synthetic biodegradable polymers such as poly(glycolic acid) (PGA), PLA and PGA/PLA copolymer were conducted[146]. When implanted into the interstitial space of rat vastus lateralis muscle, collagen construct was rapidly and densely infiltrated by interstitial and endothelial cells, and functional blood vessels were evident within 7 days, while gelatin and synthetic nanofiber constructs were not infiltrated to any great extent and induced fibrosis.

Other polymer nanofiber mats which have been used for culturing endothelia include polyphosphazenes[90,147] and poly(l-lactide-co-ε-caprolactone)(PLCL)[148].

3.6 Neural tissues

In vitro cell culture study of neural stem cells (NSC) on a PLLA nanofiber scaffold revealed that the nanofiber scaffold not only supported the NSC differentiation and neurite outgrowth, but also promoted NSC adhesion[149]. Further work using aligned PLLA nanofiber or microfiber scaffolds showed that the directions of NSC elongation and its neurite outgrowth were parallel to the direction of fiber alignment, however no significant changes were observed on the orientation with respect to the fiber diameters[150]. Also, *in vitro* response of Schwann cells on different types of polymer nanofibers, such as poly(3-hydroxybutyrate) (PHB), PHBV, PCL, PLLA and chitosan, and their solution-cast films was examined[151].

Aligned PCL and collagen/PCL nanofibers were also used as structural guidance for glial cell migration and axonal growth[152]. Both of them supported oriented neurite outgrowth and glial migration from dorsal root ganglia (DRG) explants. In comparison with pure PCL nanofibers, the collagen/PCL nanofibers improved Schwann cell migration, neurite orientation, and process formation of Schwann cells, fibroblasts and olfactory ensheathing cells.

The feasibility of *in vivo* nerve regeneration using PLGA nanofibers was also investigated[153]. After implantation of PLGA nanofiber guidance to the right sciatic nerve of rats, no inflammatory response was observed, and one month after implantation 5 out of 11 rats showed successful nerve regeneration. The *in vitro* test also confirmed that nerve stem cells adhered to, and differentiated on, the PLGA nanofiber mats[154].

3.7 Others

In addition to the above-mentioned tissues, the feasibilities of using nanofiber scaffolds to culture other stem

cells[155−160], and tissues such as heart[161,162] and ligament[163,164] have been reported.

4 Wound healing

Wound healing is a native process of regenerating dermal and epidermal tissues. When an individual is wounded, a set of complex biochemical actions take place in a closely orchestrated cascade to repair the damage. These events can be classified into inflammatory, proliferative, and remodeling phases and epithelialization. Normally, body cannot heal a deep dermal injury. In full thickness burns or deep ulcers, there is no source of cells remaining for regeneration, except from the wound edges. As a result, complete re-epithelialization takes a long time and is complicated with scarring of the base[165].

Dressings for wound healing function to protect the wound, exude extra body fluids from the wound area, decontaminate the exogenous microorganism, improve the appearance and sometimes accelerate the healing process. For these functions, a wound dressing material should provide a physical barrier to a wound, but be permeable to moisture and oxygen. For a full thickness dermal injury, the adhesion and integration of an "artificial dermal layer" consisting of a 3D tissue scaffold with well cultured dermal fibroblasts will considerably assist the re-epithelialization.

Electrospun nanofiber membrane is a good wound dressing candidate because of its unique properties: the highly porous membrane structure and well interconnected pores are particularly important for exuding fluid from the wound; the small pores and very high specific surface area not only inhibit the exogenous microorganism invasions, but also assist the control of fluid drainage; in addition, the electrospinning process provides a simple way to add drugs into the nanofibers for any possible medical treatment and antibacterial purposes.

A study on using electrospun polyurethane membrane as wound dressing material revealed that the membrane effectively exuded fluid from the wound, without fluid accumulation under the membrane cover, and no wound desiccation occurred either[166]. Also the membrane showed a controlled water loss from evaporation, excellent oxygen permeability, and high fluid drainage ability, besides inhibiting the invasion of exogenous micro organism. Histological test also indicated that the rate of epithelialization was increased and the dermis became well organized when the wounds were covered with the electrospun nanofiber membrane[166].

An open wound healing test for an electrospun collagen nanofiber membrane showed that the early-stage healing using collagen nanofiber mat was faster than that of using normal cotton gauze[110]. In the 1st week, the wound surface for the cotton group was covered by fibrinous tissue debris, below which dense infiltration of polymorphonuclear leukocytes and the proliferation of fibroblasts were formed. By comparison, the surface tissue debris in the collagen nanofiber group disappeared, and prominent proliferation of young capillaries and fibroblasts was found. Later stage healing processes were similar for both groups[110].

For dermal wound healing, electrospun nanofiber mats have been used as a scaffold to mimic native extracellular matrix. To achieve this objective, extensive studies have been conducted to develop biocompatible electrospun nanofibrous scaffolds for culturing dermal fibroblasts[167−169]. Details about skin tissue engineering have been summarized already.

In vivo wound healing of diabetic ulcers was investigated using electrospun block copolymer (PCL-PEG) and PCL. When the nanofibers were chemically modified with a recombinant human epidermal growth factor (rhEGF), the expression of keratinocyte-specific genes and EGF-receptor were enhanced[170].

Post-surgery tissue adhesion is a widely recognized problem for abdominal surgeries. It not only renders future operations more difficult but also causes other problems such as small bowel obstruction, female infertility, and chronic debilitating pain[171,172]. An electrospun nanofiber membrane containing antibiotic agents has been used as a barrier to prevent the post-surgery abdominal adhesions. It was found that the nanofiber mat eliminated post-surgery abdominal adhesion significantly, thus improving the healing process[173].

To decontaminate the bacteria invasion, biocides, such as silver[174−176] and iodine complex[168] have been added to the electrospun nanofibers. It was reported that polyvinylpyrrolidone (PVP)-iodine complex (PVP-iodine) gradually released active iodine. Because of the broad-spectrum microbicidal activity of the iodine, electrospun PVP-iodine nanofibers can have external antibacterial, antimycotic and antiviral applications. Silver ion was reported to have a biocidal effect on as many as sixteen types of bacteria including Escherichia coli (Ec)

and Staphylococcus aureus (Sa)[177]. The Ag ions were incorporated into electrospun nanofibers via adding $AgNO_3$ into the polymer solution for electrospinning. To maintain a long term antibacterial activity and control the release of Ag ions, the Ag was embedded in the form of elementary state by a post-electrospinning treatment of Ag ions incorporated. Ag nanoparticles can also be directly incorporated into electrospun nanofibers via the electrospinning process. An Ag/PVA nanofiber membrane exhibited excellent antimicrobial ability and good stability in moisture environment, as well as quick and continuous release with good effectiveness[174].

Besides adding antibacterial additives, antimicrobial nanofibers can also be prepared by directly using antimicrobial polymers. For instance, polyurethanes containing different amounts of quaternary ammonium groups were electrospun into nanofiber nonwovens, and the nanofibers showed very strong antimicrobial activities against Staphylococcus aureus and Escherichia coli[178].

5 Release control

Controlled release is an efficient process of delivering drugs in medical therapy. It can balance the delivery kinetics, minimize the toxicity and side effects, and improve patient convenience[179]. In a controlled release system, the active substance is loaded into a carrier or device first, and then releases at a predictable rate *in vivo* when administered by an injected or non-injected route.

As a potential drug delivery carrier, electrospun nanofibers have exhibited many advantages. The drug loading is very easy to implement via electrospinning process, and the high applied voltage used in the electrospinning process had little influence on the drug activity. The high specific surface area and short diffusion passage length give the nanofiber drug system higher overall release rate than the bulk material (e.g. film). The release profile can be finely controlled by modulation of nanofiber morphology, porosity and composition.

Nanofibers for drug release systems mainly come from biodegradable polymers, such as PLA[180], PCL[26,181,182], poly(D-lactide)(PDLA)[183], PLLA[184−186], PLGA[187,188], and hydrophilic polymers, such as PVA[189−191], PEG[188,192] and PEO[193]. Non-biodegradable polymers, such as PEU[194], were also investigated. Model drugs that have been studied include water soluble[180,183,185], poor-water soluble[192,194−198] and water-insoluble drugs[181,184,199,200]. The release of macro-molecules, such as DNA[187] and bioactive proteins[193,201−204], from nanofibers was also investigated.

Many factors may influence the release performance, such as the type of polymers used, hydrophility and hydrophobicity of drugs and polymers, solubility, drug-polymer comparability, additives, and the existence of enzyme in the buffer solution.

In most cases, water soluble drugs, including DNA and proteins, exhibited an early-stage burst[183,187,188,205]. For some applications, preventing post-surgery induced adhesion for instance, and such an early burst release will be an ideal profile because most infections occur within the first few hours after surgery. However, for a long-lasting release process, it would be essential to maintain the release in an even and stable pace, and any early burst release should be avoided. For a water insoluble drug, the drug release from hydrophobic nanofibers into buffer solution is difficult. However, when an enzyme capable of degrading nanofibers exists in the buffer solution, the drug can be released in a constant rate because of the degradation of nanofibers[184,205]. For example, when rifampin was encapsulated in PLA nanofibers, no drug release was detected from the nanofibers. However, when the buffer solution contained proteinase K, the drug release took place nearly in zero-order kinetics, and no early burst release happened[184]. Similarly, initial burst release did not occur for poor-water soluble drugs, but the release from a non-biodegradable nanofiber could follow different kinetics[194]. In another example, blending a hydrophilic but water-insoluble polymer (PEG-g-CHN) with PLGA could assist the release of a poor-water soluble drug Iburprofen[192]. However, when a water soluble polymer was used, the poor-soluble drug was released accompanied with dissolving of the nanofibers, leading to a low burst release[190,191,195]. In another case, the burst release of ketoprofen from PVA nanofibers was eliminated when the PVA nanofibers were treated with methanol[191].

The early burst release can be reduced when the drug is encapsulated within the nanofiber matrix. When an amphiphilic block copolymer, PEG-b-PLA was added into Mefoxin/PLGA nanofibers, the cumulative amount of the released drug at earlier time points was reduced and the drug release rate at longer time was prolonged[188]. The reason for the reduced burst release was attributed to that some drug molecules were encapsulated within the hydrophilic block of the PEG-b-PLA.

Amphiphilic block copolymer also assisted the dispersion and encapsulation of water-soluble drug into nanofibers when the polymer solution used an oleophilic solvent, such as chloroform, during electrospinning[185]. In this case, a water-in-oil emulation can be electrospun into uniform nanofibers, and drug molecules are trapped by hydrophilic chains. The swelling of the hydrophilic chains during releasing assists the diffusion of drug from nanofibers to the buffer.

Coating nanofibers with a polymer shell could be an effective way to control the release profile. When a thin layer of hydrophobic polymer, such as poly (p-xylylene) (PPX), was coated on PVA nanofibers loaded with BSA/luciferase, the early burst release of the enzyme was prevented[201]. The polymer shell can also be directly applied, via a coaxial co-electrospinning process, and the nanofibers produced are normally named "core-sheath" bicomponent nanofibers. In this case, even a pure drug can be entrapped into nanofiber as the core, and the release profile was less dependent on the solubility of drug released[182,203,206,207].

The early burst release can also be lowered via encapsulating water soluble drugs into nanoparticles, followed by incorporating the drug-loaded nanoparticles into nanofibers[186]. In addition, the rate of releasing a water soluble drug could be slowed down when nanofiber matrix was crosslinked[208].

6 Catalyst and enzyme carriers

In chemistry and biology, a carrier for catalyst is used to preserve high catalysis activity, increase the stability and life of the catalyst, and simplify the reaction process. An inert porous material with a large surface area and high permeability to reactants could be a promising candidate for efficient catalyst carriers. Using an electrospun nanofiber mat as catalyst carrier, the extremely large surface could provide a huge number of active sites, thus enhancing the catalytic capability. The well-interconnected small pores in the nanofiber mat warrant effective interactions between the reactant and catalyst, which is valuable for continuous-flow chemical reactions or biological processes. Also, the catalyst can be grafted onto the electrospun nanofiber surface via surface coating or surface modification.

6.1 Catalyst carriers for chemical reactions

Pd-loaded poly(acrylonitrile-acrylic acid) (PAN-AA) nanofibers were prepared by electrospinning a $PdCl_2$-containing PAN-AA solution into nanofibers and subsequently reducing the $PdCl_2$ embedded into Pd nanoparticles. The static catalytic activity of this Pd-loaded nanofibers for selective hydrogenation of dehydrolinalol was measured, to be about 4.5 times higher than that of the current used Pd/Al_2O_3 catalyst[209]. In a similar work, Pd-loaded PAN-AA nanofibers were confirmed to have high activity and good recycling property for hydrogenation of a-olefin at room temperature. The yield of the hexene to hexane catalyzed by the Pd/PAN-AA nanofibers was 4.7 times higher than that of $Pd/\gamma\text{-}Al_2O_3$[210].

In addition to Pd nanoparticles, Ag nanoparticles were incorporated into silica nanofibers, and the hybrid Ag-silica nanofibers showed catalytic activity to assist $NaBH_4$ to reduce decomposition of methylene blue[211].

When a molecular catalyst was incorporated into nanofibers, the catalyst could leak out of the nanofibers during the catalysis reaction[212]. Surface coating such as catalyst-loaded nanofiber with a thin layer of polymer considerably retained the catalyst in the nanofibers and the catalyst efficiency was improved at the same time. The catalysis performance was influenced by the type of shell polymer and coating thickness[212].

A study on using polyacrylamidoxime (PANOx)-containing PAN nanofibers for hydrolysis of p-nitrophenyl acetate (PNPA) indicated that diffusion resistances among the nanofibers might limit the accessibility of oxime catalytic sites in the fiber and thus influence the catalytic activity[213].

Photocatalysts, such as titania (TiO_2) and TiO_2-SiO_2, were also electrospun into nanofibers, and the photocatalytic activity was evaluated[214,215]. In comparison with other nano-structured TiO_2 materials, such as commercial TiO_2 nanoparticles (P25, Degussa) and mesoporous TiO_2, the nanofibers exhibited higher photocatalytic activities toward the degradation of methylene blue and gaseous formaldehyde[214].

6.2 Enzyme carriers for biological processes

Chemical reactions using enzyme as catalysts have high selectivity and mild reaction conditions. For easy separation from the reaction solution, enzymes are normally immobilized with a carrier. The immobilization efficiency mainly depends on the porous structure and enzyme-matrix interaction. Nano-structured materials are recently used as enzyme carriers because of their large

specific surface area and the high loading capability[216]. To immobilize enzyme on electrospun nanofibers, many approaches have been used[217−229], including grafting enzyme on fiber surface, physical adsorption, and incorporating enzyme into nanofiber via electrospinning followed by crosslinking reaction.

To graft enzymes on nanofiber surface, the polymer used should possess reactive groups for chemical bonding[217−220,229]. In some studies, polymer blends containing at least one reactive polymer were used[221−223] (Figure 4). The immobilized enzymes normally showed a slightly reduced activity in aqueous environment compared with the un-immobilized native counterpart, but the activity in non-aqueous solution was much higher. For example, α-chymotrypsin was used as a model enzyme to bond chemically on the surface of electrospun PS nanofibers. The enzyme was measured to cover over 27.4% monolayer of the nanofiber surface, and the apparent hydrolytic activity of the enzyme-loaded was 65% of the native enzyme, while the activity in non-aqueous solution was over 3 orders of magnitude higher than that of its native enzyme under the same condition[221]. In another study using PAN nanofibers to immobilize lipase, the tensile strength of the nanofiber membrane was improved after lipase immobilization, and the immobilized lipase retained >90% of its initial reactivity after being stored in buffer at 30℃ for 20 days, whereas the free lipase lost 80% of its initial reactivity. Also the immobilized lipase still retained 70% of its specific activity after 10 repeated reaction cycles[217]. In addition, the immobilized enzyme also showed improved pH and thermal stabilities[218].

When redoxases were immobilized, the incorporation of carbon nanotubes into nanofibers apparently increased the enzyme uptake and the activity of the immobilized enzyme was enhanced[224,225]. The presence of carbon nanotubes also improved the stability of the redoxases immobilized. The improvement in the catalysis performance was attributed to that the carbon nanotubes could behave as electron transferors to donate/accept electrons during enzyme catalysis or render the composite nanofibers higher biocompatibility.

In another method, enzymes were incorporated into nanofibers via electrospinning, and subsequent crosslinking the enzymes incorporated effectively prevented their leaching. In the presence of PEO or PVA, casein and lipase were electrospun into ultra-thin fibers. After crosslinking with 4,4'-methylenebis(phenyl diisocyanate) (MDI), the fibers became insoluble, and the lipase encapsulated exhibited 6 times higher hydrolysis activity

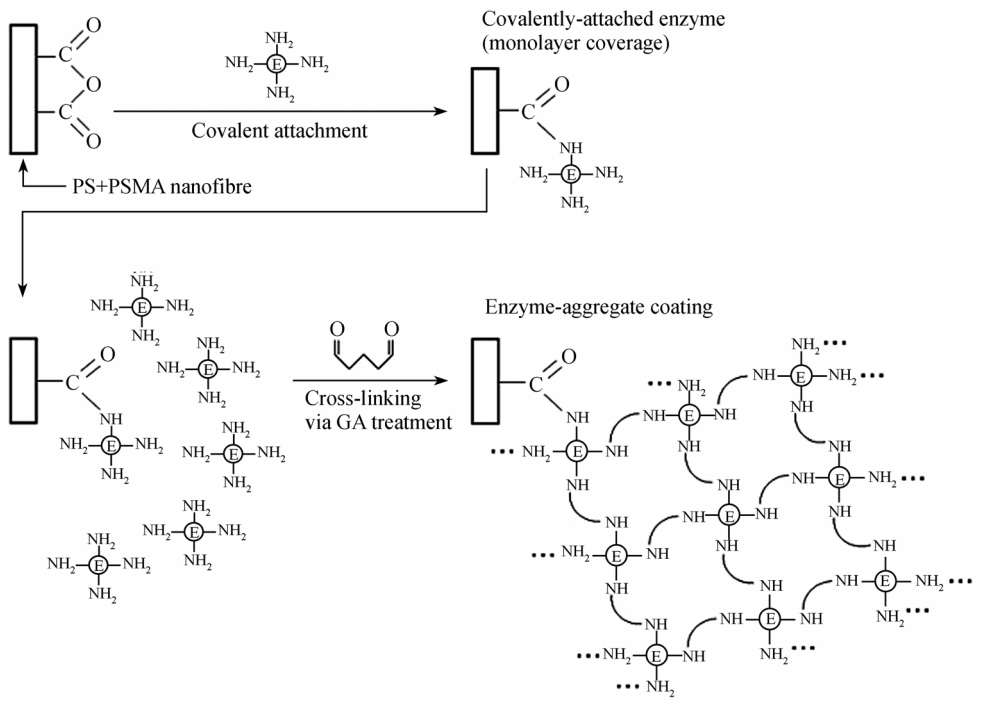

Figure 4 Schematic diagram for the preparation of covalently attached enzymes and enzyme-aggregate coatings on nanofibers[223].

towards olive oil than that of the films cast from the same solution[226]. The crosslinked enzymes in nanofibers showed very high activity and stability. For example, the immobilized α-chymotrypsin in a shaken buffer solution maintained the same activity for more than two weeks[227].

In addition to chemical bonding, the enzymes were also applied onto nanofiber simply via physical adsorption[230,231]. Polyacrylonitriles-2-methacryloyloxyethyl phosphoryl choline (PANCMPC) nanofiber was reported to have high biocompatibility with enzymes because of the formation of phospholipid micro-environment on the nanofiber surface. Lipase on the nanofibers showed a high immobilization rate, strong specific activity and good activity retention (Figure 5)[230].

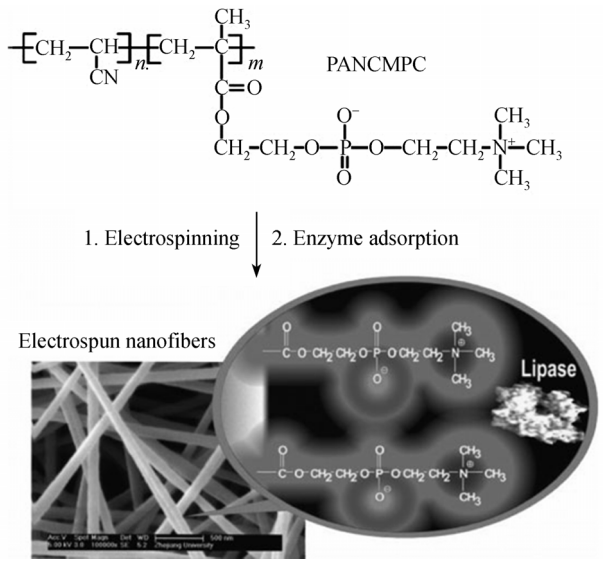

Figure 5 Schematic fabrication of phospholipid-modified nanofibers for lipase immobilization[230].

7 Sensors

Sensors have been widely used to detect chemicals for environment protection, industrial process control, medical diagnosis, safety, security and defense applications. A good sensor should have a small dimension, low fabrication cost and multiple functions, besides the high sensitivity, selectivity and reliability[232]. High sensitivity and fast response require the sensor device to have a large specific surface area and highly porous structure. The characteristics possessed by electrospun nanofibers match well with these requirements. Therefore a nanofibrous structure should be a promising physical structure to form a highly sensitive and fast response sensor.

Several approaches have been used to impart nanofibers with a sensing capability, such as using a polymeric sensing material to electrospin nanofibers, incorporating sensing molecules into nanofibers, or applying sensing material on nanofiber surface via coating/grafting technique.

Early work on electrospun nanofiber-based sensor used a PAA grafted with pyrene methanol (PM) as the sensing material to detect metal ions Fe^{3+} and Hg^{2+}, and a explosive 2,4-dinitrotuloene (DNT) in water[233,234]. Due to the quenching effect of these chemicals to the pyrene moieties, the fluorescent intensity of nanofibers had a linear response to the concentration of quenchers, and the nanofibers showed high sensitivities. Similarly, a PM-grafted poly(methyl methacrylate) PMMA nanofibers showed an order of magnitude higher sensitivity to target analyte DNT than its cast film counterpart[235].

Fluorescence optical sensors were also prepared by a layer-by-layer electrostatic assembly technique to apply a conjugated polymer onto nanofiber surface for detection of methyl viologen and cytochrome c in aqueous solution[236] and porphyrin-doped silica nanofibers were used to trace TNT vapour[237]. All those nanofiber sensors showed high sensitivity and rapid response. Besides fluorescent properties, conjugated polymer embedded electrospun nanofibers were also reported to be able to sense volatile organic compounds (VOCs) based on optical absorption properties[238].

A gas sensor using a specific absorption interaction between ammonia and poly(acrylic acid) (PAA) nanofibers was reported, and weight difference induced by the gas absorption was measured by a quartz crystal microbalance (QCM). This sensor was capable of detecting ppb level NH_3 in air, and the sensitivity was four times higher than that of the PAA cast film (Figure 6)[239]. The absorption of gas also leads to changes in FTIR absorption. PAN nanofibers containing metal oxide nanoparticles, such as iron oxide and zinc oxide, have been used

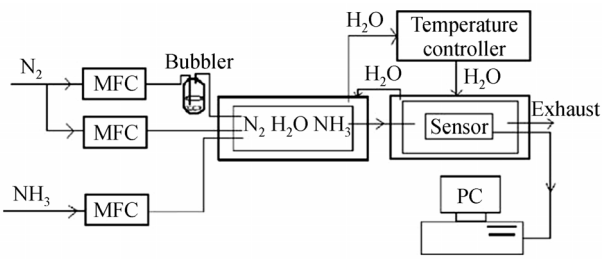

Figure 6 Schematic diagram of a gas testing system for ammonia detection[239].

to detect carbon dioxide[240]. The addition of metal oxide nanoparticles enhanced the gas adsorption and thus improved the sensitivity.

Electrical conductivity is an important property for a sensor device. Conducting nanofibers can be produced from semi-conducting oxides, conducting polymers and non-conductive polymers. Pure oxides nanofibers are normally produced by electrospinning oxide-sol-gel and polymer solution mixture, followed by calcining treatment to remove the polymer. The detection of gas molecules using oxide nanofibers is based on the conductivity changes due to the doping effect of analyst gases to the oxide. A few oxide nanofibers have been assessed for detecting different gases, such as MoO_3[241] nanofibers for ammonia, WO_3 nanofibers for ammonia[242] and NO_2[243], TiO_2 nanofibers for NO_2 and H_2[244]. These sensors exhibited improved sensitivity, faster response and lower detection limit than that of sol-gel based films. In addition, Co-doped ZnO nanofibers were used as photoelectric oxygen sensor with fast response[245].

Conducting polymer is another interesting material for sensor applications. The electrospun polyaniline (PANi)/PS nanofibers containing glucose oxidase have been demonstrated to have a high sensitivity to glucose[246]. PANi/PVP nanofibers also exhibited sensing ability to NO_2[247,248]. Organic/inorganic semiconductor Schottky nanodiode was fabricated by PANi nanofibers and inorganic n-doped semiconductor. The device has rapid response and supersensitive to ammonia[249].

Besides the conducting or semi-conducting materials, insulating polymers were also used to fabricate electrical sensors. In this case, ions or conductive nano-fillers are added to the polymer for improving the conductivity. When nanofibers of PEO were doped with $LiClO_4$, the membrane showed low conductivity and was sensitive to moisture, and the nanofiber mat was reported to have much higher sensitivity than their film-type counterpart[246]. Electrospun nanofibers incorporating carbon black showed sensitivity to VOCs[250]. When the carbon black concentration was near the percolation threshold, the composite fibers changed their resistance in volatile organic compounds. Using different polymer matrices, the sensor can be used to detect toluene, trichloroethylene, methanol, and dichloropentane vapors. In addition, carbon nanotubes/poly(vinylidene fluoride) (PVdF) composite nanofibers showed an increased straining sensing ability (as measured by voltage across the sensor), 35 times higher than that of the film counterpart[251].

In conjunction with enzyme catalysis, a conventional sensor device can be used to detect a chemical beyond its sensing capability. The enzyme specifically converts the target analyte into detectable chemicals, and loading enzyme on nanofibers enables the fast response. For example, the urease-loaded PVP nanofibers converted urea into ammonia and carbon dioxide, and the ammonia can be easily measured by a conventional ammonia sensor[252]. Enzyme immobilized nanofibers were also directly used to detect some chemicals via optical absorption[253] and amperometric current changes[254].

In addition, a nanofiber-based electrochemical senor can be based on a chemical reaction between the polymer and the target chemical. For example, PVdF/poly(aminophenylboronic acid) (PAPBA) nanofibers reacted with glucose, and the change in amperometric properties was detected easily[255].

8 Energy conversion and storage

8.1 Batteries

In most batteries, porous structure is an essential requirement. A sponge-like electrode will have high discharge current and capacity, and a porous separator between the electrodes can effectively stop the short circuit, but allow the exchange of ions freely. Solid electrolytes used in portable batteries, such as lithium ion battery, are typically composed of a gel or porous host to retain the liquid electrolyte inside[256]. To have high ion conductivity, the host material, also called separator, should have high permeability to ions. A porous membrane with well interconnected pores, suitable mechanical strength and high electrochemical stability could be a potential candidate. A lithium ion battery and its charging and discharging processes are depicted in Figure 7.

PVdF electrospun nanofiber membrane has been investigated as separator for lithium battery application[257−260]. The PVdF nanofiber membrane showed high uptake to electrolyte solution (320%−350%) and high ion conductivity (1.7×10^{-3} S/cm at 0℃). The fibrous electrolyte also had high electrochemical stability of more than 5 V. The prototype cell (MCMB/PVdF based electrolyte/$LiCoO_2$) exhibited a very stable charge-discharge behavior[258]. When a thin layer of polyethylene (PE) was plasma polymerized onto the PVdF nanofiber surface, a role of shutter by melting of

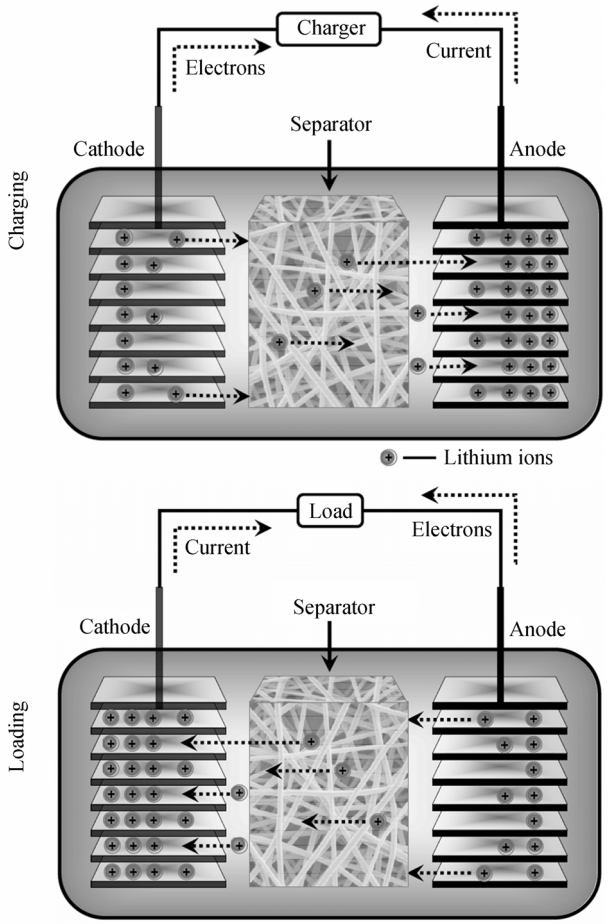

Figure 7 Charging and loading processes of lithium-ion battery.

the PE layer grafted was rendered to the nanofiber membrane, which improved the safety of battery[259]. It was also found that the formation of interconnected web structure via heat treatment improved both the mechanical properties and dimensional stability of nanofiber membranes[259,260]. Similar results were also obtained using poly(vinylidene fluoride-co-hexafluoropropylene) P(VdF-co-HFP) nanofiber membrane as separator[261−263].

Nanofiber membranes from other types of polymers, such as PAN[264], were also studied as lithium battery separator. The electrospun PAN membrane showed high ion conductivity and electrochemical stability. The prototype cell based on the electrospun PAN electrolyte separator with 1 M $LiPF_6$-EC/DMC exhibited an initial discharge capacity of 145 mAh/g, and 94.1% of the initial discharge capacity after 150 cycles at a charge/discharge rate of 0.5 C/0.5 C[264].

Besides being used as a separator, some electrospun nanofiber membranes could also be used as battery electrodes. For example, a carbonated electrospun nanofiber mat was used as anode in lithium ion battery, and the battery showed a large reversible capacity (ca. 450 mAh/g)[265]. Also, MgO nanofibers, $LiCoO_2$-MgO core-sheath nanofibers and $Li_4Ti_5O_{12}$ nanofibers were investigated as electrodes in lithium ion batteries[266−268].

8.2 Photovoltaic cells

In addition to lithium ion battery, electrospun TiO_2 nanofibers could be used in dye-sensitized solar sells (DSSCs) as active electrode[269−272]. It was reported that the electrospun TiO_2 electrode could be effectively penetrated by a viscous polymer gel electrolyte because of the porous structure. As a result, the photocurrent generation with polymer gel electrolytes was found to be over 90% of liquid electrolyte[271,272]. In order to increase the short-circuit current, the electrospun TiO_2 electrode was treated with $TiCl_4$ aqueous solution to form an additional rutile TiO_2 layer on the fiber surface. Such a rutile TiO_2 layer increased the fraction volume of active TiO_2, resulting in an increased photocurrent[269,270].

8.3 Hydrogen-storage

It has been reported that nano-structured carbon materials, such as carbon nanotubes, are able to store hydrogen[273]. The hydrogen-storage capabilities of carbonated electrospun nanofibers have also been assessed[274,275]. To increase graphitization during carbonation, a catalyst Fe (III) acetylacetonate was added into nanofibers. An electrospun PAN-based carbon nanofiber (surface areas of 60−253 m^2/g) was reported to have the H-storage capacity of 0.14%−1.01%[274].

9 Other applications

9.1 Reinforcement

Early studies on electrospun nanofibers also included reinforcement of polymers. As electrospun nanofiber mats have a large specific surface area and an irregular pore structure, mechanical interlocking among the nanofibers should occur. When a thin electrospun nylon-4,6 nanofiber mat was added to epoxy, the composite showed transparency to visible light, and both the stiffness and strength were increased considerably compared with the pure epoxy film[276].

Electrospun polybenzimidazole (PBI) nanofibers have been used as fillers to reinforce epoxy and rubber[277]. An epoxy containing 15 wt% electrospun PBI nanofi-

bers was found to have higher fracture toughness and modulus than the one containing 17 wt% PBI whiskers. Also the Young's modulus and tear strength of styrene-butadiene rubber (SBR) containing the PBI nanofibers were higher than those of pure SBR. In addition, electrospun nylon PA 6 nanofibers were used to improve the mechanical properties of a BISGMA/TEGDMA dental restorative composite resins[278].

9.2 Sound absorption

Nanofibers showed excellent capability to absorb sound. A leading nanofiber technology company, Elmarco, recently patented an electrospun nanofiber material that had unique sound absorption characteristics, with only about one-third of the weight of traditional sound absorption materials. It was able to absorb sounds across a wide range of frequencies, especially low frequency sounds below 1000 Hz.

10 Summary

This review has covered the diverse applications of electrospun nanofibers. The review is by no means exhaustive, and new nanofibers and applications are emerging continuingly. While the potential for nanofibers is enormous, there are also considerable challenges ahead. Most of the studies in this area have been conducted on fibers produced on a very small scale, using a needle based system to electrospin nanofibers from a polymer solution. While large scale production of nanofibers using pilot scale equipment, such as the Nanospider system from Elmarco, is now possible, more work is needed to evaluate the characteristics and performance of the fibers produced on the large scale equipment to ensure consistent fiber quality and address the environmental issues associated with solvent/solution based electrospinning technology. Producing uniform fibers with an average diameter below 100 nm remains a challenge. This is particularly the case for melt electrospinning. Further developments in melt electrospinning technology are needed to expand the range of polymers available for producing nanofibers. It is also worth noting that other non-electrospinning technologies, such as the melt-blown and micro-fiber technologies used in the fiber/textile industry, have the potential of producing submicron fibers. Hybrid technologies are being developed also for mass production of nanofibers.

1 Li H, Ke Y, Hu Y. Polymer nanofibers prepared by template melt extrusion. J Appl Polym Sci, 2006, 99(3): 1018－1023[DOI]
2 Ikegame M, Tajima K, Aida T. Template synthesis of polypyrrole nanofibers insulated within one-dimensional silicate channels: Hexagonal versus lamellar for recombination of polarons into bipolarons. Angew Chem Int Edit, 2003, 42(19): 2154－2157[DOI]
3 Yang Z, Xu B. Supramolecular hydrogels based on biofunctional nanofibers of self-assembled small molecules. J Mater Chem, 2007, 17(23): 2385－2393[DOI]
4 Feng X, Yang G, Xu Q, et al. Self-assembly of polyaniline/Au composites: From nanotubes to nanofibers. Macromol Rapid Comm, 2006, 27(1): 31－36[DOI]
5 Hong Y, Legge R L, Zhang S, et al. Effect of amino acid sequence and pH on nanofiber formation of self-assembling peptides EAK16-II and EAK16-IV. Biomacromolecules, 2003, 4(5): 1433－1442[DOI]
6 Ma P X, Zhang R. Synthetic nano-scale fibrous extracellular matrix. J Biomed Mater Res Part A, 1999, 46(1): 60－72[DOI]
7 Ellison C J, Phatak A, Giles D W, et al. Melt blown nanofibers: Fiber diameter distributions and onset of fiber breakup. Polymer, 2007, 48(20): 3306－3316[DOI]
8 Teo W E, Ramakrishna S. A review on electrospinning design and nanofibre assemblies. Nanotechnology, 2006, 17(14): R89－R106[DOI]
9 Gu B K, Shin M K, Sohn K W, et al. Direct fabrication of twisted nanofibers by electrospinning. Appl Phys Lett, 2007, 90(26): 263902[DOI]
10 Panda P K, Ramakrishna S. Electrospinning of alumina nanofibers using different precursors. J Mater Sci, 2007, 42(6): 2189－2193[DOI]
11 Kim G, Kim W. Formation of oriented nanofibers using electrospinning. Appl Phys Lett, 2006, 88(23): 233101[DOI]
12 Formhals A. Process and apparatus for preparing artificial threads. US Patent 1975504, 1934
13 Doshi J, Reneker D H. Electrospinning process and applications of electrospun fibers. J Electrostat, 1995, 35(2-3): 151－160[DOI]
14 Srinivasan G, Reneker D H. Structure and morphology of small diameter electrospun aramide fibers. Polym Int, 1995, 36(2): 195－201[DOI]
15 Reneker D H, Chun I. Nanometer diameter fibres of polymers, produced by electrospinning. Nanotechnology, 1996, 7(3): 216－223[DOI]
16 Jaeger R, Schonherr H, Vancso G J. Chain packing in electro-spun poly(ethylene oxide) visualized by atome force microscopy. Macromolecules, 1996, 29(23): 7634－7636[DOI]
17 Yarin A L, Koombhongse S, Reneker D H. Bending instability in electrospinning of nanofibers. J Appl Phys, 2001, 89(5): 3018－3026[DOI]
18 Li D, Xia Y. Electrospinning of nanofibers: Reinventing the wheel? Adv Mater, 2004, 16(14): 1151－1170[DOI]
19 Subbiah T, Bhat G S, Tock R W, et al. Electrospinning of nanofibers. J Appl Polym Sci, 2005, 96(2): 557－569[DOI]
20 Greiner A, wendorff J H. Electrospinning: A fascinating method for the preparation of ultrathin fibers. Angew Chem Int Edit, 2007, 46(30): 5670－5703[DOI]
21 Theron A, Zussman E, Yarin A L. Electrostatic field-assisted alignment of electrospun nanofibres. Nanotechnology, 2001, 12(3): 384－390[DOI]
22 Li D, Wang Y, Xia Y. Electrospinning nanofibers as uniaxially aligned arrays and layer-by-layer stacked films. Adv Mater, 2004, 16(4): 361－366[DOI]

23 McCann J T, Li D, Xia Y. Electrospinning of nanofibers with core-sheath, hollow, or porous structures. J Mater Chem, 2005, 15(7): 735－738[DOI]
24 Shim W G, Kim C, Lee J W, et al. Adsorption characteristics of benzene on electrospun-derived porous carbon nanofibers. J Appl Polym Sci, 2006, 102(3): 2454－2462[DOI]
25 Madhugiri S, Sun B, Smirniotis P G, et al. Electrospun mesoporous titanium dioxide fibers. Micropor Mesopor Mater, 2004, 69(1-2): 77－83[DOI]
26 Zhang Y Z, Feng Y, Huang Z M, et al. Fabrication of porous electrospun nanofibres. Nanotechnology, 2006, 17(3): 901－908[DOI]
27 McCann J T, Marquez M, Xia Y. Highly porous fibers by electrospinning into a cryogenic liquid. J Am Chem Soc, 2006, 128(5): 1436－1437[DOI]
28 Sun Z, Zussman E, Yarin A L, et al. Compound core-shell polymer nanofibers by co-electrospinning. Adv Mater, 2003, 15(22): 1929－1932[DOI]
29 Li D, Xia Y. Direct fabrication of composite and ceramic hollow nanofibers by electrospinning. Nano Lett, 2004, 4(5): 933－938[DOI]
30 Lin T, Wang H, Wang X. Self-crimping bicomponent nanofibers electrospun from polyacrylonitrile and elastomeric polyurethane. Adv Mater, 2005, 17(22): 2699－2703[DOI]
31 Barhate R S, Ramakrishna S. Nanofibrous filtering media: Filtration problems and solutions from tiny materials. J Membrane Sci, 2007, 296(1-2): 1－8[DOI]
32 Gibson P, Schreuder-Gibson H, Pentheny C. Electrospinning technology: Direct application of tailorable ultrathin membranes. J Coated Fabrics, 1998, 28(7): 63－72
33 Bognitzki M, Czado W, Frese T, et al. Nanostructured fibers via electrospinning. Adv Mater, 2001, 13(1): 70－72[DOI]
34 Huang Z-M, Zhang Y-Z, Kotaki M, et al. A review on polymer nanofibers by electrospinning and their applications in nanocomposites. Comp Sci Tech, 2003, 63(15): 2223－2253[DOI]
35 Jayaraman K, Kotaki M, Zhang Y, et al. Recent advances in polymer nanofibers. J Nanosci Nanotech, 2004, 4(1-2): 52－65
36 Kameoka J, Czaplewski D, Liu H, et al. Polymeric nanowire architecture. J Mater Chem, 2004, 14(10): 1503[DOI]
37 Ma Z, Kotaki M, Inai R, et al. Potential of nanofiber matrix as tissue-engineering scaffolds. Tissue Eng, 2005, 11(1-2): 101－109[DOI]
38 Wang Y K, Yong T, Ramakrishna S. Nanofibres and their Influence on cells for tissue regeneration. Austr J Chem, 2005, 58(10): 704－712[DOI]
39 Boudriot U, Dersch R, Greiner A, et al. Electrospinning approaches toward scaffold engineering-a brief overview. Artif Organs, 2006, 30(10): 785－792[DOI]
40 Liao S, Li B, Ma Z, et al. Biomimetic electrospun nanofibers for tissue regeneration. Biomed Mater, 2006, 1(3): R45－R53[DOI]
41 Teo W-E, He W, Ramakrishna S. Electrospun scaffold tailored for tissue-specific extracellular matrix. Biotech J, 2006, 1(9): 918－929[DOI]
42 Ashammakhi N, Ndreu A, Yang Y, et al. Tissue engineering: A new take-off using nanofiber-based scaffolds. J Craniofac Surg, 2007, 18(1): 3－17[DOI]
43 Lannutti J, Reneker D, Ma T, et al. Electrospinning for tissue engineering scaffolds. Mater Sci Eng C, 2007, 27(3): 504－509[DOI]
44 Sell S, Barnes C, Smith M, et al. Extracellular matrix regenerated: Tissue engineering via electrospun biomimetic nanofibers. Polym Int, 2007, 56(11): 1349－1360[DOI]
45 Barnes C P, Sell S A, Boland E D, et al. Nanofiber technology: Designing the next generation of tissue engineering scaffolds. Adv Drug Deliver Rev, 2007, 59(14): 1413－1433[DOI]
46 Liang D, Hsiao B S, Chu B. Functional electrospun nanofibrous scaffolds for biomedical applications. Adv Drug Deliver Rev, 2007, 59(14): 1392－1412[DOI]
47 Kosmider K, Scott J. Polymeric nanofibres exhibit an enhanced air filtration performance. Filtr Separat, 2002, 39(6): 20－22[DOI]
48 Gibson P, Schreuder-Gibson H, Rivin D. Transport properties of porous membranes based on electrospun nanofibers. Coll Surf A: Physicochem Eng Asp, 2001, 187-188(8): 469－481[DOI]
49 Shin C, Chase G G, Reneker D H. Recycled expanded polystyrene nanofibers applied in filter media. Coll Surf A: Physicochem Eng Asp, 2005, 262(1-3): 211－215[DOI]
50 Shin C, Chase G G, Reneker D H. The effect of nanofibers on liquid-liquid coalescence filter performance. AIChE J, 2005, 51(12): 3109－3113[DOI]
51 Wang X, Chen X, Yoon K, et al. High flux filtration medium based on nanofibrous substrate with hydrophilic nanocomposite coating. Environ Sci Tech, 2005, 39(19): 7684－7691[DOI]
52 Yoon K, Kim K, Wang X, et al. High flux ultrafiltration membranes based on electrospun nanofibrous PAN scaffolds and chitosan coating. Polymer, 2006, 47(7): 2434－2441[DOI]
53 Barhate R S, Loong C K, Ramakrishna S. Preparation and characterization of nanofibrous filtering media. J Membrane Sci, 2006, 283(1-2): 209－218[DOI]
54 Gopal R, Kaur S, Ma Z, et al. Electrospun nanofibrous filtration membrane. J Membrane Sci, 2006, 281(1-2): 581－586[DOI]
55 Gopal R, Kaur S, Feng C Y, et al. Electrospun nanofibrous polysulfone membranes as pre-filters: Particulate removal. J Membrane Sci, 2007, 289(1-2): 210－219[DOI]
56 Ma Z, Kotaki M, Ramakrishna S. Surface modified nonwoven polysulphone (PSU) fiber mesh by electrospinning: A novel affinity membrane. J Membrane Sci, 2006, 272(1-2): 179－187[DOI]
57 Ki C S, Gang E H, Um I C, et al. Nanofibrous membrane of wool keratose/silk fibroin blend for heavy metal ion adsorption. J Membrane Sci, 2007, 302(1-2): 20－26[DOI]
58 Wang H, Ding J, Lee B, et al. Polypyrrole-coated electrospun nanofibre membranes for recovery of Au(III) from aqueous solution. J Membrane Sci, 2007, 303(1-2): 119－125[DOI]
59 Nerem R M, Saltzman A. Tissue engineering: From biology to biological substitutes. Tissue Eng, 1995, 1(1): 3－13[DOI]
60 Ma P X. Tissue Engineering. In: Encyclopedia of Polymer Science and Technology. NJ: John Wiley & Sons, 2004
61 Hay E D. Cell Biology of Extracellular Matrix. NY: Plenum Press, 1991
62 Elsdale T, Bard J. Collagen substrata for studies on cell behavior. J Cell Biol, 1972, 54(3): 626－637
63 Chiu J B, Liu C, Hsiao B S, et al. Functionalization of poly(L-lactide) nanofibrous scaffolds with bioactive collagen molecules. J Biomed Mater Res Part A, 2007, 83A(4): 1117－1127[DOI]
64 Venugopal J, Low S, Choon A T, et al. Interaction of cells and nanofiber scaffolds in tissue engineering. J Biomed Mater Res Part B: Appl Biomater, 2008, 84B(1): 34－48[DOI]
65 Zhang Y, Lim C T, Ramakrishna S, et al. Recent development of polymer nanofibers for biomedical and biotechnological applications.

J Mater Sci: Mater Med, 2005, 16(10): 933－946[DOI]
66 Matthews J A, Wnek G E, Simpson D G, et al. Electrospinning of Collagen Nanofibers. Biomacromolecules, 2002, 3(2): 232－238[DOI]
67 Kenawy E-R, Layman J M, Watkins J R, et al. Electrospinning of poly(ethylene-co-vinyl alcohol) fibers. Biomaterials, 2003, 24(6): 907－913[DOI]
68 Stankus J J, Guan J, Wagner W R. Fabrication of biodegradable elastomeric scaffolds with sub-micron morphologies. J Biomed Mater Res Part A, 2004, 70A(4): 603－614[DOI]
69 Mo X M, Xu C Y, Kotaki M, et al. Electrospun P(LLA-CL) nanofiber: A biomimetic extracellular matrix for smooth muscle cell and endothelial cell proliferation. Biomaterials, 2004, 25(10): 1883－1890[DOI]
70 Venugopal J, Zhang Y Z, Ramakrishna S. Fabrication of modified and functionalized polycaprolactone nanofibre scaffolds for vascular tissue engineering. Nanotechnology, 2005, 16(10): 2138－2142[DOI]
71 Baker S C, Atkin N, Gunning P A, et al. Characterisation of electrospun polystyrene scaffolds for three-dimensional in vitro biological studies. Biomaterials, 2006, 27(16): 3136－3146[DOI]
72 Riboldi S A, Sampaolesi M, Neuenschwander P, et al. Electrospun degradable polyesterurethane membranes: Potential scaffolds for skeletal muscle tissue engineering. Biomaterials, 2005, 26(22): 4606－4615[DOI]
73 Li W-J, Laurencin C T, Caterson E J, et al. Electrospun nanofibrous structure: A novel scaffold for tissue engineering. J Biomed Mater Res, 2002, 60(4): 613－621[DOI]
74 Yoshimoto H, Shin Y M, Terai H, et al. A biodegradable nanofiber scaffold by electrospinning and its potential for bone tissue engineering. Biomaterials, 2003, 24(12): 2077－2082[DOI]
75 Li W-J, Tuli R, Huang X, et al. Multilineage differentiation of human mesenchymal stem cells in a three-dimensional nanofibrous scaffold. Biomaterials, 2005, 26(25): 5158－5166[DOI]
76 Shin M, Yoshimoto H, Vacanti J P. In vivo bone tissue engineering using mesenchymal stem cells on a novel electrospun nanofibrous scaffold. Tissue Eng, 2004, 10(1-2): 33－41[DOI]
77 Zhang Y, Ouyang H, Lim C T, et al. Electrospinning of gelatin fibers and gelatin/PCL composite fibrous scaffolds. J Biomed Mater Res Part B: Appl Biomater, 2005, 72B(1): 156－165[DOI]
78 Fujihara K, Kotaki M, Ramakrishna S. Guided bone regeneration membrane made of polycaprolactone/calcium carbonate composite nano-fibers. Biomaterials, 2005, 26(19): 4139－4147[DOI]
79 Wutticharoenmongkol P, Sanchavanakit N, Pavasant P, et al. Novel bone scaffolds of electrospun polycaprolactone fibers filled with nanoparticles. J Nanosci Nanotech, 2006, 6(2): 514－522[DOI]
80 Wutticharoenmongkol P, Sanchavanakit N, Pavasant P, et al. Preparation and characterization of novel bone scaffolds based on electrospun polycaprolactone fibers filled with nanoparticles. Macromolecul Biosci, 2006, 6(1): 70－77[DOI]
81 Wutticharoenmongkol P, Pavasant P, Supaphol P. Osteoblastic phenotype expression of MC3T3-E1 cultured on electrospun polycaprolactone fiber mats filled with hydroxyapatite nanoparticles. Biomacromolecules, 2007, 8(8): 2602－2610[DOI]
82 Duan B, Wu L, Li X, et al. Degradation of electrospun PLGA-chitosan/PVA membranes and their cytocompatibility in vitro. J Biomater Sci Polym Edit, 2007, 18(1): 95－115[DOI]
83 Tuzlakoglu K, Bolgen N, Salgado A J, et al. Nano- and micro-fiber combined scaffolds: A new architecture for bone tissue engineering. J Mater Sci: Mater Med, 2005, 16(12): 1099－1104[DOI]
84 Pham Q P, Sharma U, Mikos A G. Electrospun poly(e-caprolactone) microfiber and multilayer nanofiber/microfiber scaffolds: Characterization of scaffolds and measurement of cellular infiltration. Biomacromolecules, 2006, 7(10): 2796－2805[DOI]
85 Jin H J, Chen J, Karageorgiou V, et al. Human bone marrow stromal cell responses on electrospun silk fibroin mats. Biomaterials, 2004, 25(6): 1039－1047[DOI]
86 Kim K-H, Jeong L, Park H-N, et al. Biological efficacy of silk fibroin nanofiber membranes for guided bone regeneration. J Biotech, 2005, 120(3): 327－339[DOI]
87 Xu X, Zhuang X, Chen X, et al. Preparation of core-sheath composite nanofibers by emulsion electrospinning. Macromol Rapid Comm, 2006, 27(19): 1637－1642[DOI]
88 Kim K, Yu M, Zong X, et al. Control of degradation rate and hydrophilicity in electrospun non-woven poly(d,l-lactide) nanofiber scaffolds for biomedical applications. Biomaterials, 2003, 24(27): 4977－4985[DOI]
89 Henry J A, Simonet M, Pandit A, et al. Characterization of a slowly degrading biodegradable polyesterurethane for tissue engineering scaffolds. J Biomed Mater Res Part A, 2007, 82A(3): 669－679[DOI]
90 Nair L S, Bhattacharyya S, Bender J D, et al. Fabrication and optimization of methylphenoxy substituted polyphosphazene nanofibers for biomedical applications. Biomacromolecules, 2004, 5(6): 2212－2220[DOI]
91 Badami A S, Kreke M R, Thompson M S, et al. Effect of fiber diameter on spreading, proliferation, and differentiation of osteoblastic cells on electrospun poly(lactic acid) substrates. Biomaterials, 2006, 27(4): 596－606[DOI]
92 Lee Y H, Lee J H, An I-G, et al. Electrospun dual-porosity structure and biodegradation morphology of Montmorillonite reinforced PLLA nanocomposite scaffolds. Biomaterials, 2005, 26(16): 3165－3172[DOI]
93 Sakai S, Yamada Y, Yamaguchi T, et al. Prospective use of electrospun ultra-fine silicate fibers for bone tissue engineering. Biotech J, 2006, 1(9): 958－962[DOI]
94 Moroni L, Licht R, De Boer J, et al. Fiber diameter and texture of electrospun PEOT/PBT scaffolds influence human mesenchymal stem cell proliferation and morphology, and the release of incorporated compounds. Biomaterials, 2006, 27(28): 4911－4922[DOI]
95 Zhang J, Qi H, Wang H, et al. Engineering of vascular grafts with genetically modified bone marrow mesenchymal stem cells on poly (propylene carbonate) graft. Artif Organs, 2006, 30(12): 898－905[DOI]
96 Sombatmankhong K, Sanchavanakit N, Pavasant P, et al. Bone scaffolds from electrospun fiber mats of poly(3-hydroxybutyrate), poly(3-hydroxybutyrate-co-3-hydroxyvalerate) and their blend. Polymer, 2007, 48(5): 1419－1427[DOI]
97 Xin X, Hussain M, Mao Jeremy J. Continuing differentiation of human mesenchymal stem cells and induced chondrogenic and osteogenic lineages in electrospun PLGA nanofiber scaffold. Biomaterials, 2007, 28(2): 316－325
98 Deng X-L, Sui G, Zhao M-L, et al. Poly(L-lactic acid)/hydroxyapatite hybrid nanofibrous scaffolds prepared by electrospinning. J Biomater Sci Polym Edit, 2007, 18(1): 117－130[DOI]
99 Matthews J A, Boland E D, Wnek G E, et al. Electrospinning of collagen type II: A feasibility study. J Bioact Compat Polym, 2003, 18(2): 125－134[DOI]

100 Shields K J, Beckman M J, Bowlin G L, et al. Mechanical properties and cellular proliferation of electrospun collagen type II. Tissue Eng, 2004, 10(9-10): 1510－1517
101 Li W-J, Danielson K G, Alexander P G, et al. Biological response of chondrocytes cultured in three-dimensional nanofibrous poly(ε-caprolactone) scaffolds. J Biomed Mater Res Part A, 2003, 67A(4): 1105－1114[DOI]
102 Lee I S, Kwon O H, Meng W, et al. Nanofabrication of microbial polyester by electrospinning promotes cell attachment. Macromol Res, 2004, 12(4): 374－378
103 Kwon O H, Lee I S, Ko Y-G, et al. Electrospinning of microbial polyester for cell culture. Biomed Mater, 2007, 2(1): S52－S58[DOI]
104 Subramanian A, Vu D, Larsen G F, et al. Preparation and evaluation of the electrospun chitosan/PEO fibers for potential applications in cartilage tissue engineering. J Biomater Sci, Polym Edit, 2005, 16(7): 861－873[DOI]
105 Bhattarai N, Edmondson D, Veiseh O, et al. Electrospun chitosan-based nanofibers and their cellular compatibility. Biomaterials, 2005, 26(31): 6176－6184[DOI]
106 Shin H J, Lee C H, Cho I H, et al. Electrospun PLGA nanofiber scaffolds for articular cartilage reconstruction: Mechanical stability, degradation and cellular responses under mechanical stimulation in vitro. J Biomater Sci Polym Edit, 2006, 17(1-2): 103－119[DOI]
107 Min B-M, Lee G, Kim S H, et al. Electrospinning of silk fibroin nanofibers and its effect on the adhesion and spreading of normal human keratinocytes and fibroblasts in vitro. Biomaterials, 2003, 25(7-8): 1289－1297[DOI]
108 Chang Seok Ki J W K, Jin Ho Hyun, Ki Hoon Lee, Masahiro Hattori, Dong Kyun Rah, Young Hwan Park,. Electrospun three-dimensional silk fibroin nanofibrous scaffold. J Appl Polym Sci, 2007, 106(6): 3922－3928[DOI]
109 Zhong S, Teo W E, Zhu X, et al. An aligned nanofibrous collagen scaffold by electrospinning and its effects on in vitro fibroblast culture. J Biomed Mater Res Part A, 2006, 79A(3): 456－463[DOI]
110 Rho K S, Jeong L, Lee G, et al. Electrospinning of collagen nanofibers: Effects on the behavior of normal human keratinocytes and early-stage wound healing. Biomaterials, 2006, 27(8): 1452－1461[DOI]
111 Zhong S P, Teo W E, Zhu X, et al. Development of a novel collagen-GAG nanofibrous scaffold via electrospinning. Mater Sci Eng C: Biomim Supramol Syst, 2007, 27(2): 262－266
112 Meng W, Kim S-Y, Yuan J, et al. Electrospun PHBV/collagen composite nanofibrous scaffolds for tissue engineering. J Biomater Sci Polym Edit, 2007, 18(1): 81－94[DOI]
113 Zhang Y Z, Venugopal J, Huang Z M, et al. Crosslinking of the electrospun gelatin nanofibers. Polymer, 2006, 47(8): 2911－2917[DOI]
114 Duan B, Wu L, Yuan X, et al. Hybrid nanofibrous membranes of PLGA/chitosan fabricated via an electrospinning array. J Biomed Mater Res Part A, 2007, 83A(3): 868－878[DOI]
115 Ji Y, Ghosh K, Shu X Z, et al. Electrospun three-dimensional hyaluronic acid nanofibrous scaffolds. Biomaterials, 2006, 27(20): 3782－3792[DOI]
116 Ji Y, Ghosh K, Li B, et al. Dual-syringe reactive electrospinning of cross-linked hyaluronic acid hydrogel nanofibers for tissue engineering applications. Macromol Biosci, 2006, 6(10): 811－817[DOI]
117 Pan H, Jiang H, Chen W. Interaction of dermal fibroblasts with electrospun composite polymer scaffolds prepared from dextran and poly(lactide-co-glycolide). Biomaterials, 2006, 27(17): 3209－3220[DOI]
118 Bhattarai S R, Bhattarai N, Viswanathamurthi P, et al. Hydrophilic nanofibrous structure of polylactide: Fabrication and cell affinity. J Biomed Mater Res Part A, 2006, 78A(2): 247－257[DOI]
119 Sun T, Norton D, McKean R J, et al. Development of a 3D cell culture system for investigating cell interactions with electrospun fibers. Biotech Bioeng, 2007, 97(5): 1318－1328[DOI]
120 Park K, Jung H J, Kim J-J, et al. Acrylic acid-grafted hydrophilic electrospun nanofibrous poly(L-lactic acid) scaffold. Macromol Res, 2006, 14(5): 552－558
121 Park K, Ju Y M, Son J S, et al. Surface modification of biodegradable electrospun nanofiber scaffolds and their interaction with fibroblasts. J Biomater Sci Polym Edit, 2007, 18(4): 369－382[DOI]
122 Spasova M, Stoilova O, Manolova N, et al. Preparation of PLLA/PEG nanofibers by electrospinning and potential applications. J Bioact Comp Polym, 2007, 22(1): 62－76[DOI]
123 Zhang Y Z, Venugopal J, Huang Z M, et al. Characterization of the surface biocompatibility of the electrospun PCL-collagen nanofibers using fibroblasts. Biomacromolecules, 2005, 6(5): 2583－2589[DOI]
124 Venugopal J R, Zhang Y, Ramakrishna S. In vitro culture of human dermal fibroblasts on electrospun polycaprolactone collagen nanofibrous membrane. Artif Organs, 2006, 30(6): 440－446[DOI]
125 Chen M, Patra P K, Warner S B, et al. Optimization of electrospinning process parameters for tissue engineering scaffolds. Biophys Rev Lett, 2006, 1(2): 189－214[DOI]
126 Kim G, Kim W. Highly porous 3D nanofiber scaffold using an electrospinning technique. J Biomed Mater Res Part B: Appl Biomater, 2007, 81B(1): 104－110[DOI]
127 Chen M, Patra P K, Warner S B, et al. Role of fiber diameter in adhesion and proliferation of NIH 3T3 fibroblast on electrospun polycaprolactone scaffolds. Tissue Eng, 2007, 13(3): 579－587[DOI]
128 Bhattarai S R, Bhattarai N, Yi H K, et al. Novel biodegradable electrospun membrane: scaffold for tissue engineering. Biomaterials, 2004, 25(13): 2595－2602[DOI]
129 Jin H-J, Hwang M-O, Yoon J S, et al. Preparation and characterization of electrospun poly(L-lactic acid-co-succinic acid-co-1,4-butane diol) fibrous membranes. Macromol Res, 2005, 13(1): 73－79
130 Suwantong O, Waleetorncheepsawat S, Sanchavanakit N, et al. In vitro biocompatibility of electrospun poly(3-hydroxybutyrate) and poly(3-hydroxybutyrate-co-3-hydroxyvalerate) fiber mats. International J Biol Macromol, 2007, 40(3): 217－223[DOI]
131 Khanam N, Mikoryak C, Draper R K, et al. Electrospun linear polyethyleneimine scaffolds for cell growth. Acta Biomater, 2007, 3(6): 1050－1059[DOI]
132 Zhao P, Jiang H, Pan H, et al. Biodegradable fibrous scaffolds composed of gelatin coated poly(ε-caprolactone) prepared by coaxial electrospinning. J Biomed Mater Res Part A, 2007, 83A(2): 372－382[DOI]
133 Duan B, Yuan X, Zhu Y, et al. A nanofibrous composite membrane of PLGA-chitosan/PVA prepared by electrospinning. Europ Polym J, 2006, 42(9): 2013－2022[DOI]
134 Kim T G, Park T G. Biomimicking extracellular matrix: Cell adhesive RGD peptide modified electrospun poly(D,L-lactic-co-glycolic acid) nanofiber mesh. Tissue Eng, 2006, 12(2): 221－233[DOI]
135 Xu C, Yang F, Wang S, et al. In vitro study of human vascular endothelial cell function on materials with various surface roughness. J Biomed Mater Res Part A, 2004, 71A(1): 154－161[DOI]

136 Rubenstein D, Han D, Goldgraben S, et al. Bioassay chamber for angiogenesis with perfused explanted arteries and electrospun scaffolding. Microcirculation, 2007, 14(7): 723－737[DOI]

137 Vaz C M, van Tuijl S, Bouten C V C, et al. Design of scaffolds for blood vessel tissue engineering using a multi-layering electrospinning technique. Acta Biomater, 2005, 1(5): 575－582[DOI]

138 Ma Z, He W, Yong T, et al. Grafting of gelatin on electrospun poly(ε-caprolactone) nanofibers to improve endothelial cell spreading and proliferation and to control cell orientation. Tissue Eng, 2005, 11(7-8): 1149－1158[DOI]

139 Ma Z, Kotaki M, Yong T, et al. Surface engineering of electrospun polyethylene terephthalate (PET) nanofibers towards development of a new material for blood vessel engineering. Biomaterials, 2005, 26(15): 2527－2536[DOI]

140 Casper C L, Yang W, Farach-Carson M C, et al. Coating electrospun collagen and gelatin fibers with perlecan domain I for increased growth factor binding. Biomacromolecules, 2007, 8(4): 1116－1123[DOI]

141 Zhu Y, Leong Meng F, Ong Wey F, et al. Esophageal epithelium regeneration on fibronectin grafted poly(L-lactide-co-caprolactone) (PLLC) nanofiber scaffold. Biomaterials, 2007, 28(5): 861－868[DOI]

142 Sell S A, McClure M J, Barnes C P, et al. Electrospun polydioxanone-elastin blends: Potential for bioresorbable vascular grafts. Biomed Mater, 2006, 1(2): 72－80[DOI]

143 Lee S J, Yoo J J, Lim G J, et al. In vitro evaluation of electrospun nanofiber scaffolds for vascular graft application. J Biomed Mater Res Part A, 2007, 83A(4): 999－1008[DOI]

144 Stankus J J, Soletti L, Fujimoto K, et al. Fabrication of cell microintegrated blood vessel constructs through electrohydrodynamic atomization. Biomaterials, 2007, 28(17): 2738－2746[DOI]

145 Stitzel J, Liu J, Lee S J, et al. Controlled fabrication of a biological vascular substitute. Biomaterials, 2006, 27(7): 1088－1094[DOI]

146 Telemeco T A, Ayres C, Bowlin G L, et al. Regulation of cellular infiltration into tissue engineering scaffolds composed of submicron diameter fibrils produced by electrospinning. Acta biomater, 2005, 1(4): 377－385[DOI]

147 Carampin P, Conconi M T, Lora S, et al. Electrospun polyphosphazene nanofibers for in vitro rat endothelial cells proliferation. J Biomed Mater Res Part A, 2007, 80A(3): 661－668[DOI]

148 Kwon I K, Kidoaki S, Matsuda T. Electrospun nano- to microfiber fabrics made of biodegradable copolyesters: structural characteristics, mechanical properties and cell adhesion potential. Biomaterials, 2005, 26(18): 3929－3939[DOI]

149 Yang F, Xu C Y, Kotaki M, et al. Characterization of neural stem cells on electrospun poly(L-lactic acid) nanofibrous scaffold. J Biomater Sci Polym Edit, 2004, 15(12): 1483－1497[DOI]

150 Yang F, Murugan R, Wang S, et al. Electrospinning of nano/micro scale poly(L-lactic acid) aligned fibers and their potential in neural tissue engineering. Biomaterials, 2005, 26(15): 2603－2610[DOI]

151 Sangsanoh P, Waleetorncheepsawat S, Suwantong O, et al. In vitro biocompatibility of schwann cells on surfaces of biocompatible polymeric electrospun fibrous and solution-cast film scaffolds. Biomacromolecules, 2007, 8(5): 1587－1594[DOI]

152 Schnell E, Klinkhammer K, Balzer S, et al. Guidance of glial cell migration and axonal growth on electrospun nanofibers of poly(e-caprolactone) and a collagen/poly(e-caprolactone) blend. Biomaterials, 2007, 28(19): 3012－3025[DOI]

153 Bini T B, Gao S, Tan T C, et al. Electrospun poly(L-lactide-co-glycolide) biodegradable polymer nanofiber tubes for peripheral nerve regeneration. Nanotechnology, 2004, 15(11): 1459－1464[DOI]

154 Bini T B, Gao S, Wang S, et al. Poly(l-lactide-co-glycolide) biodegradable microfibers and electrospun nanofibers for nerve tissue engineering: An in vitro study. J Mater Sci, 2006, 41(19): 6453－6459[DOI]

155 Ito Y, Hasuda H, Kamitakahara M, et al. A composite of hydroxyapatite with electrospun biodegradable nanofibers as a tissue engineering material. J Biosci Bioeng, 2005, 100(1): 43－49[DOI]

156 Li M, Mondrinos M J, Gandhi M R, et al. Electrospun protein fibers as matrices for tissue engineering. Biomaterials, 2005, 26(30): 5999－6008[DOI]

157 Boudriot U, Goetz B, Dersch R, et al. Role of electrospun nanofibers in stem cell technologies and tissue engineering. Macromol Symp, 2005, 225(1): 9－16[DOI]

158 Kang X, Xie Y, Powell H M, et al. Adipogenesis of murine embryonic stem cells in a three-dimensional culture system using electrospun polymer scaffolds. Biomaterials, 2007, 28(3): 450－458[DOI]

159 Meechaisue C, Dubin R, Supaphol P, et al. Electrospun mat of tyrosine-derived polycarbonate fibers for potential use as tissue scaffolding material. J Biomater Sci Polym Edit, 2006, 17(9): 1039－1056[DOI]

160 Chua K-N, Chai C, Lee P-C, et al. Surface-aminated electrospun nanofibers enhance adhesion and expansion of human umbilical cord blood hematopoietic stem/progenitor cells. Biomaterials, 2006, 27(36): 6043－6051[DOI]

161 Zong X, Bien H, Chung C-Y, et al. Electrospun fine-textured scaffolds for heart tissue constructs. Biomaterials, 2005, 26(26): 5330－5338[DOI]

162 Li M, Guo Y, Wei Y, et al. Electrospinning polyaniline-contained gelatin nanofibers for tissue engineering applications. Biomaterials, 2006, 27(13): 2705－2715[DOI]

163 Lee C H, Shin H J, Cho I H, et al. Nanofiber alignment and direction of mechanical strain affect the ECM production of human ACL fibroblast. Biomaterials, 2005, 26(11): 1261－1270[DOI]

164 Bashur C A, Dahlgren L A, Goldstein A S. Effect of fiber diameter and orientation on fibroblast morphology and proliferation on electrospun poly(D,L-lactic-co-glycolic acid) meshes. Biomaterials, 2006, 27(33): 5681－5688[DOI]

165 Marler J J, Upton J, Langer R, et al. Transplantation of cells in matrixes for tissue regeneration. Adv Drug Deliver Rev, 1998, 33(1-2): 165－182[DOI]

166 Khil M-s, Cha D-i, Kim H-y, et al. Electrospun nanofibrous polyurethane membrane as wound dressing. J Biomed Mater Res Part B: Appl Biomater, 2003, 67B(2): 675－679[DOI]

167 Noh H K, Lee S W, Kim J-M, et al. Electrospinning of chitin nanofibers: Degradation behavior and cellular response to normal human keratinocytes and fibroblasts. Biomaterials, 2006, 27(21): 3934－3944[DOI]

168 Ignatova M, Manolova N, Rashkov I. Electrospinning of poly(vinyl pyrrolidone)-iodine complex and poly(ethylene oxide)/poly(vinyl pyrrolidone)-iodine complex—a prospective route to antimicrobial wound dressing materials. Europ Polym J, 2007, 43(5): 1609－1623[DOI]

169 Chong E J, Phan T T, Lim I J, et al. Evaluation of electrospun PCL/gelatin nanofibrous scaffold for wound healing and layered dermal reconstitution. Acta Biomater, 2007, 3(3): 321－330[DOI]

170 Choi J S, Leong K W, Yoo H S. In vivo wound healing of diabetic ulcers

using electrospun nanofibers immobilized with human epidermal growth factor (EGF). Biomaterials, 2008, 29(5): 587－596[DOI]
171 DeCherney A H, DiZerega G S. Clinical problem of intraperitoneal postsurgical adhesion formation following general surgery and the use of adhesion prevention barriers. Surg Clinics North Am, 1997, 77(3): 671－688[DOI]
172 Menzies D. Peritoneal adhesions. Incidence, cause, and prevention. Surg Ann, 1992, 24: 27－45
173 Bolgen N, Vargel I, Korkusuz P, et al. In vivo performance of antibiotic embedded electrospun PCL membranes for prevention of abdominal adhesions. J Biomed Mater Res Part B: Appl Biomater, 2007, 81B(2): 530－543[DOI]
174 Hong K H. Preparation and properties of electrospun poly(vinyl alcohol)/silver fiber web as wound dressings. Polymer Eng Sci, 2007, 47(1): 43－49[DOI]
175 Jia J, Duan Y-y, Wang S-h, et al. Preparation and characterization of antibacterial silver-containing nanofibers for wound dressing applications. J US-China Med Sci, 2007, 4(2): 52－54
176 Lala N L, Ramaseshan R, Li B, et al. Fabrication of nanofibers with antimicrobial functionality used as filters: protection against bacterial contaminants. Biotech Bioeng, 2007, 97(6): 1357－1365[DOI]
177 Spadaro J A, Berger T J, Barranco S D, et al. Antibacterial effects of silver electrodes with weak direct current. Antimicrob Agents Chemother, 1974, 6(5): 637－642
178 Jeong E H, Yang J, Youk J H. Preparation of polyurethane cationomer nanofiber mats for use in antimicrobial nanofilter applications. Mater Lett, 2007, 61(18): 3991－3994[DOI]
179 Yih T C, Al-Fandi M. Engineered nanoparticles as precise drug delivery systems. J Cell Biochem, 2006, 97(6): 1184－1190[DOI]
180 Kenawy E-R, Bowlin G L, Mansfield K, et al. Release of tetracycline hydrochloride from electrospun poly(ethylene-co-vinylacetate), poly(lactic acid), and a blend. J Contr Rel, 2002, 81(1-2): 57－64[DOI]
181 Luong-Van E, Grondahl L, Chua K N, et al. Controlled release of heparin from poly(e-caprolactone) electrospun fibers. Biomaterials, 2006, 27(9): 2042－2050[DOI]
182 Jiang H, Hu Y, Zhao P, et al. Modulation of protein release from biodegradable core-shell structured fibers prepared by coaxial electrospinning. J Biomed Mater Res Part B: Appl Biomater, 2006, 79B(1): 50－57[DOI]
183 Zong X, Kim K, Fang D, et al. Structure and process relationship of electrospun bioabsorbable nanofiber membranes. Polymer, 2002, 43(16): 4403－4412[DOI]
184 Zeng J, Xu X, Chen X, et al. Biodegradable electrospun fibers for drug delivery. J Contr Rel, 2003, 92(3): 227－231[DOI]
185 Xu X, Yang L, Xu X, et al. Ultrafine medicated fibers electrospun from W/O emulsions. J Contr Rel, 2005, 108(1): 33－42[DOI]
186 Qi H, Hu P, Xu J, et al. Encapsulation of drug reservoirs in fibers by emulsion electrospinning: morphology characterization and preliminary release assessment. Biomacromolecules, 2006, 7(8): 2327－2330[DOI]
187 Luu Y K, Kim K, Hsiao B S, et al. Development of a nanostructured DNA delivery scaffold via electrospinning of PLGA and PLA-PEG block copolymers. J Contr Rel, 2003, 89(2): 341－353[DOI]
188 Kim K, Luu Y K, Chang C, et al. Incorporation and controlled release of a hydrophilic antibiotic using poly(lactide-co-glycolide)-based electrospun nanofibrous scaffolds. J Contr Rel, 2004, 98(1): 47－56[DOI]
189 Taepaiboon P, Rungsardthong U, Supaphol P. Drug-loaded electrospun mats of poly(vinyl alcohol) fibres and their release characteristics of four model drugs. Nanotechnology, 2006, 17(9): 2317－2329[DOI]
190 Yang D, Li Y, Nie J. Preparation of gelatin/PVA nanofibers and their potential application in controlled release of drugs. Carbohydr Polym, 2007, 69(3): 538－543[DOI]
191 Kenawy E-R, Abdel-Hay F I, El-Newehy M H, et al. Controlled release of ketoprofen from electrospun poly(vinyl alcohol) nanofibers. Mater Sci Eng A: Struct Mater Prop Microstruct Proc, 2007, A459(1-2): 390－396
192 Jiang H, Fang D, Hsiao B, et al. Preparation and characterization of ibuprofen-loaded poly(lactide-co-glycolide)/poly(ethylene glycol)-g-chitosan electrospun membranes. J Biomater Sci Polym Edit, 2004, 15(3): 279－296[DOI]
193 Kim T G, Lee D S, Park T G. Controlled protein release from electrospun biodegradable fiber mesh composed of poly(e-caprolactone) and poly(ethylene oxide). Int J Pharm, 2007, 338(1-2): 276－283[DOI]
194 Verreck G, Chun I, Rosenblatt J, et al. Incorporation of drugs in an amorphous state into electrospun nanofibers composed of a water-insoluble, nonbiodegradable polymer. J Contr Rel, 2003, 92(3): 349－360[DOI]
195 Verreck G, Chun I, Peeters J, et al. Preparation and characterization of nanofibers containing amorphous drug dispersions generated by electrostatic spinning. Pharm Res, 2003, 20(5): 810－817[DOI]
196 Cui W, Li X, Zhu X, et al. Investigation of drug release and matrix degradation of electrospun poly(DL-lactide) fibers with paracetanol inoculation. Biomacromolecules, 2006, 7(5): 1623－1629[DOI]
197 Xie J, Wang C. Electrospun micro- and nanofibers for sustained delivery of paclitaxel to treat C6 glioma in vitro. Pharm Res, 2006, 23(8): 1817－1826[DOI]
198 Wang M, Wang L, Huang Y. Electrospun hydroxypropyl methyl cellulose phthalate (HPMCP)/erythromycin fibers for targeted release in intestine. J Appl Polym Sci, 2007, 106(4): 2177－2184[DOI]
199 Tungprapa S, Jangchud I, Supaphol P. Release characteristics of four model drugs from drug-loaded electrospun cellulose acetate fiber mats. Polymer, 2007, 48(17): 5030－5041[DOI]
200 Pornsopone V, Supaphol P, Rangkupan R, et al. Electrospun methacrylate-based copolymer/indomethacin fibers and their release characteristics of indomethacin. J Polym Res, 2007, 14(1): 53－59[DOI]
201 Zeng J, Aigner A, Czubayko F, et al. Poly(vinyl alcohol) nanofibers by electrospinning as a protein delivery system and the retardation of enzyme release by additional polymer coatings. Biomacromolecules, 2005, 6(3): 1484－1488[DOI]
202 Chunder A, Sarkar S, Yu Y, et al. Fabrication of ultrathin polyelectrolyte fibers and their controlled release properties. Coll Surf B: Biointerf, 2007, 58(2): 172－179[DOI]
203 Jiang H, Hu Y, Li Y, et al. A facile technique to prepare biodegradable coaxial electrospun nanofibers for controlled release of bioactive agents. J Contr Rel, 2005, 108(2-3): 237－243[DOI]
204 Chew S Y, Wen J, Yim E K F, et al. Sustained release of proteins from electrospun biodegradable fibers. Biomacromolecules, 2005, 6(4): 2017－2024[DOI]
205 Zeng J, Yang L, Liang Q, et al. Influence of the drug compatibility with polymer solution on the release kinetics of electrospun fiber formulation. J Contr Rel, 2005, 105(1-2): 43－51[DOI]
206 Huang Z-M, He C-L, Yang A, et al. Encapsulating drugs in biode-

gradable ultrafine fibers through co-axial electrospinning. J Biomed Mater Res Part A, 2006, 77A(1): 169－179[DOI]
207 Zhang Y Z, Wang X, Feng Y, et al. Coaxial electrospinning of (fluorescein isothiocyanate-conjugated bovine serum albumin)-encapsulated poly(e-caprolactone) nanofibers for sustained release. Biomacromolecules, 2006, 7(4): 1049－1057[DOI]
208 Taepaiboon P, Rungsardthong U, Supaphol P. Effect of cross-linking on properties and release characteristics of sodium salicylate-loaded electrospun poly(vinyl alcohol) fibre mats. Nanotechnology, 2007, 18(17): 175102[DOI]
209 Demir M M, Gulgun M A, Menceloglu Y Z, et al. Palladium nanoparticles by electrospinning from poly(acrylonitrile-co-acrylic acid)-PdCl2 solutions. Relations between preparation conditions, particle size, and catalytic activity. Macromolecules, 2004, 37(5): 1787－1792[DOI]
210 Yu J, Liu T. Preparation of nano-fiber supported palladium catalysts and their use for the catalytic hydrogenation of olefins. Acta Polym Sin, 2007, (6): 514－518
211 Patel A C, Li S, Wang C, et al. Electrospinning of porous silica nanofibers containing silver nanoparticles for catalytic applications. Chem Mater, 2007, 19(6): 1231－1238[DOI]
212 Stasiak M, Studer A, Greiner A, et al. Polymer fibers as carriers for homogeneous catalysts. Chem A Europ J, 2007, 13(21): 6150－6156[DOI]
213 Chen L, Bromberg L, Hatton T A, et al. Catalytic hydrolysis of p-nitrophenyl acetate by electrospun polyacrylamidoxime nanofibers. Polymer, 2007, 48(16): 4675－4682[DOI]
214 Zhan S, Chen D, Jiao X, et al. Long TiO_2 hollow fibers with mesoporous walls: Sol-gel combined electrospun fabrication and photocatalytic properties. J Phys Chem B, 2006, 110(23): 11199－11204[DOI]
215 Jin M, Zhang X, Emeline A V, et al. Fibrous TiO_2-SiO_2 nanocomposite photocatalyst. Chem Commun, 2006, (43): 4483－4485
216 Matatov-Meytal Y, Sheintuch M. Catalytic fibers and cloths. Appl Catal A, 2002, 231(1-2): 1－16
217 Li S-F, Chen J-P, Wu W-T. Electrospun polyacrylonitrile nanofibrous membranes for lipase immobilization. J Mol Catal B: Enzym, 2007, 47(3-4): 117－124
218 Huang X-J, Ge D, Xu Z-K. Preparation and characterization of stable chitosan nanofibrous membrane for lipase immobilization. Europ Polym J, 2007, 43(9): 3710－3718[DOI]
219 Ye P, Xu Z-K, Wu J, et al. Nanofibrous membranes containing reactive groups: Electrospinning from poly(acrylonitrile-co-maleic acid) for lipase immobilization. Macromolecules, 2006, 39(3): 1041－1045[DOI]
220 Lee K H, Ki C S, Baek D H, et al. Application of electrospun silk fibroin nanofibers as an immobilization support of enzyme. Fibers Polym, 2005, 6(3): 181－185[DOI]
221 Jia H, Zhu G, Vugrinovich B, et al. Enzyme-carrying polymeric nanofibers prepared via electrospinning for use as unique biocatalysts. Biotech Prog, 2002, 18(5): 1027－1032[DOI]
222 Kim T G, Park T G. Surface Functionalized Electrospun Biodegradable Nanofibersfor Immobilization of Bioactive Molecules. Biotech Prog, 2006, 22(4): 1108－1113[DOI]
223 Kim B C, Nair S, Kim J, et al. Preparation of biocatalytic nanofibers with high activity and stability via enzyme aggregate coating on polymer nanofibers. Nanotechnology, 2005, 16(7): 382－388[DOI]
224 Wang Z-G, Xu Z-K, Wan L-S, et al. Nanofibrous membranes containing carbon nanotubes: electrospun for redox enzyme immobilization. Macromol Rapid Commun, 2006, 27(7): 516－521[DOI]
225 Wang Z-G, Ke B-B, Xu Z-K. Covalent immobilization of redox enzyme on electrospun nonwoven poly(acrylonitrile-co-acrylic acid) nanofiber mesh filled with carbon nanotubes: a comprehensive study. Biotech Bioeng, 2007, 97(4): 708－720[DOI]
226 Xie J, Hsieh Y-L. Ultra-high surface fibrous membranes from electrospinning of natural proteins: casein and lipase enzyme. J Mater Sci, 2003, 38(10): 2125－2133[DOI]
227 Herricks T E, Kim S-H, Kim J, et al. Direct fabrication of enzyme-carrying polymer nanofibers by electrospinning. J Mater Chem, 2005, 15(31): 3241－3245[DOI]
228 Nakane K, Hotta T, Ogihara T, et al. Synthesis of (Z)-3-hexen-1-yl acetate by lipase immobilized in polyvinyl alcohol nanofibers. J Appl Polym Sci, 2007, 106(2): 863－867[DOI]
229 Wang Y, Hsieh Y-L. Enzyme immobilization to ultra-fine cellulose fibers via amphiphilic polyethylene glycol spacers. J Polym Sci Part A: Polym Chem, 2004, 42(17): 4289－4299[DOI]
230 Huang X-J, Xu Z-K, Wan L-S, et al. Electro-spun nano fibers modified with phospholipid moieties for enzyme immobilization. Macromol Rapid Commun, 2006, 27(16): 1341－1345[DOI]
231 Wang Z-G, Wang J-Q, Xu Z-K. Immobilization of lipase from Candida rugosa on electrospun polysulfone nanofibrous membranes by adsorption. J Mol Catal B: Enzym, 2006, 42(1-2): 45－51[DOI]
232 Ursula E. Spichiger-Keller. Chemical Sensors & Biosensors for Medical and Biological Applications. Weinheim: Wily-VCH, 1998. 377－378
233 Wang X, Lee S-H, Drew C, et al. Electrospun nanofibrous membranes for optical sensing. Polym Mater Sci Eng, 2001, 85: 617－618
234 Wang X, Drew C, Lee S-H, et al. Electrospun nanofibrous membrane for highly sensitive optical sensors. Nano Lett, 2002, 2(11): 1273－1275[DOI]
235 Wang X, Lee S-H, Ku B-C, et al. Synthesis and electrospinning of a novel fluorescent polymer PMMA-PM for quenching-based optical sensing. J Macromol Sci Part A Pure Appl Chem, 2002, A39(10): 1241－1249
236 Wang X, Kim Y-G, Drew C, et al. Electrostatic assembly of conjugated polymer thin layers on electrospun nanofibrous membranes for biosensors. Nano Lett, 2004, 4(2): 331－334[DOI]
237 Tao S, Li G, Yin J. Fluorescent nanofibrous membranes for trace detection of TNT vapor. J Mater Chem, 2007, 17(26): 2730－2736[DOI]
238 Yoon J, Chae S K, Kim J-M. Colorimetric sensors for volatile organic compounds (VOCs) based on conjugated polymer-embedded electrospun fibers. J Am Chem Soc, 2007, 129(11): 3038－3039[DOI]
239 Ding B, Yamazaki M, Shiratori S. Electrospun fibrous polyacrylic acid membrane-based gas sensors. Sens Actuat B: Chem, 2005, B106(1): 477－483
240 Luoh R, Hahn H T. Electrospun nanocomposite fiber mats as gas sensors. Comp Sci Tech, 2006, 66(14): 2436－2441[DOI]
241 Gouma P I. Nanostructured polymorphic oxides for advanced chemosensors. Rev Adv Mater Sci, 2003, 5(2): 147－154
242 Wang G, Ji Y, Huang X, et al. Fabrication and characterization of polycrystalline WO_3 nanofibers and their application for ammonia sensing. J Phys Chem B, 2006, 110(47): 23777－23782[DOI]
243 Sawicka K M, Prasad A K, Gouma P I. Metal oxide nanowires for use in chemical sensing applications. Sens Lett, 2005, 3(1): 31－35[DOI]

244 Kim I-D, Rothschild A, Lee B H, et al. Ultrasensitive chemiresistors based on electrospun TiO_2 nanofibers. Nano Lett, 2006, 6(9): 2009－2013[DOI]
245 Yang M, Xie T F, Peng L, et al. Fabrication and photoelectric oxygen sensing characteristics of electrospun Co doped ZnO nanofibres. Appl Phys A Mater Sci Proc, 2007, 89(2): 427－430[DOI]
246 Aussawasathien D, Dong J H, Dai L. Electrospun polymer nanofiber sensors. Synth Metals, 2005, 154(1-3): 37－40[DOI]
247 Bishop A, Gouma P. Leuco-emeraldine based polyaniline－poly-vinyl-pyrrolidone electrospun composites and bio-composites: A preliminary study of sensing behavior. Rev Adv Mater Sci, 2005, 10(3): 209－214
248 Bishop-Haynes A, Gouma P. Electrospun polyaniline composites for NO_2 detection. Mater Manufact Proc, 2007, 22(6): 764－767[DOI]
249 Pinto N J, Gonzalez R, Johnson A T, et al. Electrospun hybrid organic/inorganic semiconductor Schottky nanodiode. Appl Phys Lett, 2006, 89(3): 033505[DOI]
250 Kessick R, Tepper G. Electrospun polymer composite fiber arrays for the detection and identification of volatile organic compounds. Sens Actuat B: Chem, 2006, B117(1): 205－210[DOI]
251 Laxminarayana K, Jalili N. Functional nanotube-based textiles: Pathway to next generation fabrics with enhanced sensing capabilities. Text Res J, 2005, 75(9): 670－680[DOI]
252 Sawicka K, Gouma P, Simon S. Electrospun biocomposite nanofibers for urea biosensing. Sens Actuat B: Chem, 2005, B108(1-2): 585－588
253 Patel A C, Li S, Yuan J-M, et al. In situ encapsulation of horseradish peroxidase in electrospun porous silica fibers for potential biosensor applications. Nano Lett, 2006, 6(5): 1042－1046[DOI]
254 Ren G, Xu X, Liu Q, et al. Electrospun poly(vinyl alcohol)/glucose oxidase biocomposite membranes for biosensor applications. React Funct Polym, 2006, 66(12): 1559－1564[DOI]
255 Manesh K M, Santhosh P, Gopalan A, et al. Electrospun poly(vinylidene fluoride)/poly(aminophenylboronic acid) composite nanofibrous membrane as a novel glucose sensor. Anal Biochem, 2007, 360(2): 189－195[DOI]
256 Arora P, Zhang Z. Battery Separators. Chem Rev, 2004, 104(10): 4419－4462[DOI]
257 Choi S W, Jo S M, Lee W S, et al. An electrospun poly(vinylidene fluoride) nanofibrous membrane and its battery applications. Adv Mater, 2003, 15(23): 2027－2032[DOI]
258 Kim J R, Choi S W, Jo S M, et al. Electrospun PVdF-based fibrous polymer electrolytes for lithium ion polymer batteries. Electrochim Acta, 2004, 50(1): 69－75[DOI]
259 Choi S-S, Lee Y S, Joo C W, et al. Electrospun PVDF nanofiber web as polymer electrolyte or separator. Electrochim Acta, 2004, 50(2-3): 339－343[DOI]
260 Gao K, Hu X, Dai C, et al. Crystal structures of electrospun PVDF membranes and its separator application for rechargeable lithium metal cells. Mater Sci Eng B: Solid-State Mater Adv Tech, 2006, 131(1-3): 100－105
261 Kim J R, Choi S W, Jo S M, et al. Characterization and properties of P(VdF-HFP)-based fibrous polymer electrolyte membrane prepared by electrospinning. J Electrochem Soc, 2005, 152(2): A295－A300[DOI]
262 Li X, Cheruvally G, Kim J-K, et al. Polymer electrolytes based on an electrospun poly(vinylidene fluoride-co-hexafluoropropylene) membrane for lithium batteries. J Power Sources, 2007, 167(2): 491－498[DOI]
263 Kim J-K, Cheruvally G, Choi J-W, et al. Rechargeable organic radical battery with electrospun, fibrous membrane-based polymer electrolyte. J Electrochem Soc, 2007, 154(9): A839－A843[DOI]
264 Choi S W, Kim J R, Jo S M, et al. Electrochemical and spectroscopic properties of electrospun PAN-based fibrous polymer electrolytes. J Electrochem Soc, 2005, 152(5): A989－A995[DOI]
265 Ahn Y C, Park S K, G.T. K, et al. Development of high efficiency nanofilters made of nanofibers. Curr Appl Phys, 2006, 6(6): 1030－1035[DOI]
266 Fan Q, Whittingham M S. Electrospun manganese oxide nanofibers as anodes for lithium-ion batteries. Electrochem Solid-State Lett, 2007, 10(3): A48－A51[DOI]
267 Gu Y, Chen D, Jiao X, et al. $LiCoO_2$-MgO coaxial fibers: Co-electrospun fabrication, characterization and electrochemical properties. J Mater Chem, 2007, 17(18): 1769－1776[DOI]
268 Lu H-W, Zeng W, Li Y-S, et al. Fabrication and electrochemical properties of three-dimensional net architectures of anatase TiO_2 and spinel $Li_4Ti_5O_{12}$ nanofibers. J Power Sources, 2007, 164(2): 874－879[DOI]
269 Song M Y, Kim D K, Ihn K J, et al. Electrospun TiO_2 electrodes for dye-sensitized solar cells. Nanotechnology, 2004, 15(12): 1861－1865[DOI]
270 Song M Y, Kim D K, Jo S M, et al. Enhancement of the photocurrent generation in dye-sensitized solar cell based on electrospun TiO_2 electrode by surface treatment. Synth Metals, 2005, 155(3): 635－638[DOI]
271 Jo S M, Song M Y, Ahn Y R, et al. Nanofibril formation of electrospun TiO_2 fibers and its application to dye-sensitized solar cells. J Macromol Sci Part A Pure Appl Chem, 2005, A42(11): 1529－1540
272 Song M Y, Kim D K, Ihn K J, et al. New application of electrospun TiO2 electrode to solid-state dye-sensitized solar cells. Synth Metals, 2005, 153(1-3): 77－80[DOI]
273 Dillon A C, Jones K M, Bekkedahl T A, et al. Storage of hydrogen in single-walled carbon nanotubes. Nature, 1997, 386(6623): 377－379[DOI]
274 Kim D-K, Park S H, Kim B C, et al. Electrospun polyacrylonitrile-based carbon nanofibers and their hydrogen storage. Macromol Res, 2005, 13(6): 521－528
275 Hong S E, Kim D-K, Jo S M, et al. Graphite nanofibers prepared from catalytic graphitization of electrospun poly(vinylidene fluoride) nanofibers and their hydrogen storage capacity. Catal Today, 2007, 120(3-4): 413－419[DOI]
276 Bergshoef M M, Vancso G J. Transparent nanocomposites with ultrathin, electrospun nylon-4,6 fiber reinforcement. Adv Mater, 1999, 11(16): 1362－1365[DOI]
277 Kim J-S, Eneker D H. Mechanical properties of composites using ultrafine electrospun fibers. Polym Comp, 1999, 20(1): 124－131[DOI]
278 Fong H. Electrospun nylon 6 nanofiber reinforced BIS-GMA/TEGDMA dental restorative composite resins. Polymer, 2004, 45(7): 2427－2432[DOI]