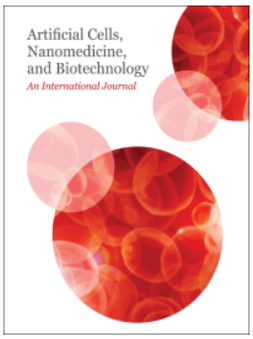

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REVIEW ARTICLE

Nanofiber: Synthesis and biomedical applications

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Abstract

Electrospinning uses an electrical charge to draw very fine (typically on the micro or nano scale) fibers from a liquid. Electrospinning or electrostatic spinning shares characteristics of both electrospraying and conventional solution dry spinning of fibers.

The method does not need the use of coagulation chemistry or high temperatures to produce solid threads from solution. This makes the process particularly suited for the production of fibers using large and complex molecules. Because the full potential of biomaterials being used in various applications, field of nanofibers have involved considerable interest in biotechnology and medicine and there has been fast development in this area in recent years.

Keywords: biomaterials, electrospinning, nanofibers, nanofibrous materials

Introduction

Electrostatic spinning or electrospinning is a well-known established process that is able to fabricate non-woven and ultrafine nanoscale fibers with diameters tens of nanometers to microns which can be evaluated by usual non-woven fiber fabrication techniques. Electrospinning technology was coined in the 1990s by Reneker and co-workers.

The electrospinning technique possesses the unique features of simplicity, affordability, wide range of materials selection, very high surface-to-volume ratio, tunable porosity, and flexibility to adopt over a broad range of sizes and shapes.

Nanofibrous materials are being studied and developed because they embrace considerable promise for variety of applications and achieve some advantages of nanostructured materials. Nanofibrous materials can be synthesized of biocompatible and biodegradable polymers and produced by electrospinning processes. Because of the full potential of using biomaterials in different applications, field of nanofibers have attracted considerable interest in biotechnology and medicine and there has been fast development in this area in recent years.

Methods for fabrication of nanofibers

There are many ways to fabricate nanofibers, such as template synthesis (Li and Xia 2004, Reneker and Chun 1996, Doshi and Reneker 1995, Liang et al. 2007), drawing (Zhong et al. 2011, Lu et al. 2005), self-assembly (Williamson and Coombes 2004, Naik et al. 2003), electrospinning (Badami et al. 2006, Bhattarai et al. 2005, Kweon et al. 2003, Yang et al. 2005, Zhang et al. 2005, Choi et al. 2004) (random, aligned, and core-shell nanofibers), and phase separation (Ma and Zhang 1999, Widmer et al. 1998). Because template synthesis does not able to produce continuous fibers and in drawing process only viscoelastic materials can be used which tolerate applied tensions, the three most important methods to produce nanofibers are self-assembly, electrospinning, and phase separation (Ito et al. 2005).

Phase separation

One of best method for production of nanoporous foams which preferentially can be used in many areas is Phase separation, but because of the long time needed to complete the entire process, this method is not the best (Ashammakhi et al. 2007).

The polymer solution quenched below the freezing point of solvent is freeze-dried to produce a porous structure (Schugens et al. 1996). Various nanoporous foams are easily obtained through this process by modifying thermodynamic and kinetic factors. Using phase separation process, fabrication of foam scaffolds occur in five basic steps: suspension of polymer, phase separation and gelation, extraction of solvent from the gel by means of water, freezing, and then freeze-drying under vacuum (Ma and Zhang 1999). Influences of nanoporous morphology is determined via gelation. The creation of nanoscale fiber complex is caused by low gelation temperature, while as a consequence of crystals nucleation and their development, high gelation temperature produces the creation of platelet-like construction and is managed by increasing of cooling rate, which can produce uniform nanofibers (Venugopal et al. 2008).

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Self-assembly

In this method, molecules and atoms sort out and assemble themselves in the course of fragile and non-covalent forces, for example hydrophobic forces, electrostatic interactions and hydrogen bonding, and create a stable construction (Hartgerink et al. 2001, Zhang 2003). Self-assembly method can be used to make different structures, for example unilamellar and multilamellar vesicles, bilayer, nanoparticles, membranes, fibers, films, micelles, tubes and capsule (Venugopal et al. 2008).

Based on the self-assembly system, an amphiphilic peptide that allows creation of thermally stable protein was designed (Berndt et al. 1995).

Obtained fiber with self-assembly method can be much thinner than those produced by electrospinning, but complication of procedure with low productivityare the major problem associated with self-assembly method (Ma et al. 2005).

Electrospinning

Electrospinning possesses unique properties such as simplicity, affordability, high porosity (good pore size distribution), and yields continuous fibers. In this method variety of biomaterials can be used to produce nanofibers and very low amounts of initial solutions are needed.

Fibers produced using electrospinning method have the diameter in range of 3 nm to several micrometers, whereas fibers obtained using other procedures have the diameter in range of 500 nm up to a few microns (Zhang et al. 2005).

Because of these extremely appreciable properties, electrospinning is a most popular technique for the production of nanofibers. Nanofibers that fell on the stationary collector harvests randomly arranged nanofiber (125–600 nm) matrices, although aligned nanofiber (750–850 nm) mats are synthesized by means of rotatory or disk collector with high-pitched edge (Venugopal et al. 2008).

Electrospinning machine and synthesis of nanofibers using electrospinning process

The standard electrospinning machine consists of spinneret (or needle), high-voltage power supply with a wide range of voltage, a glass syringe with a small needle, and a metal collector (Figure 1). Electrospinning nanofibers can be synthesized using an electrical potential to a polymeric solution. Needle attached to and driven by a syringe pump which is accustomed to manage the flow rate and volume of the polymer is ejected. A polymer solution is loaded into the syringe that ejects the polymer solution at a constant rate (Merritt et al. 2012). After loading of polymer solution, solution is charged and at the tip of the syringe an electrically charged polymer droplet is formed. Because of the repulsive force between the similar charges in electrically conductive liquid and electric field, polymer solution tends to deform the droplet into a conical-shaped structure known as Taylor cone, Taylor who has made essential studies on the jet formation (Taylor 1969). Initially increase of electrical potential causes elongation of semicircular outward of solution at the tip of the needle and forms the Taylor cone. After a threshold charge density, cone becomes unstable and emits a jet of liquid (Huang et al. 2003). In the presence of an electric field, the jet travels a path to the ground and as a consequence of elongation, solvent evaporation forms a continuous slim liquid fiber (Frenot and Chronakis 2003, Reneker et al. 2000), and finally charged electro-spun fibers are collected on the Collector. The electrode plate or Collector electrode are located on a place made of acrylic acid. The electrode is usually flatted and is used for the collection

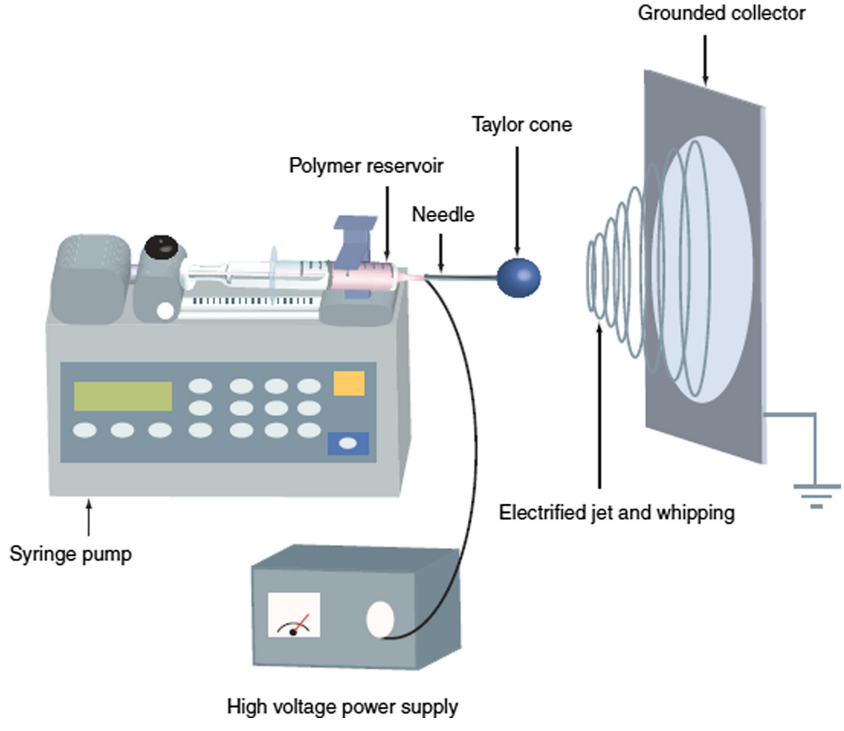

Figure 1. The schematic diagram of electrospinning device for the production of nanofibers.

of both random and aligned fibers (Huang et al. 2003, Baji et al. 2010, Park et al. 2007).

In the field of electrospinning and nanofiber production, there are two main obsession and key point; choosing polymer and collector. The alignment of the fibers (Figure 2) affected by the orientation of the collector and sets the morphology and the properties of synthesized nanofibers. There are different types of collectors such as plate collector (Tan et al. 2005), rotatory collector (Teo and Ramakrishna 2006), grid-type collector (Teo et al. 2011), edge-type collector (Chaurey et al. 2010), collector with parallel electrode (Kawahara et al. 2008), collector with blade auxiliary electrode (Jianrui et al. 2009), water bath collector (Polaskova et al. 2013), continuous collector and other (Figure 3).

There are many biodegradable polymers can be used to produce nanofibers such as natural, synthetic, and composite of the two. Biodegradable polymers were used to develop nanofibers with different functions based on the requirement. Some can be used to deliver temporary function such as agent delivery, cell carrier, and short-time scaffolds (until new tissue become mature and independent). In this group, polymer will replaced by native tissue. Some polymers have been used for long-term purpose such as an implant in surgery. At some point in the procedure of electrospinning using synthetic polymers, the charge on the polymer solution makes it promising to govern its trajectory using an electric field (Hohman et al. 2001).

The most commonly used and studied synthetic polymers are PCL (Luong-Van et al. 2006, Khil et al. 2005, Venugopal et al. 2005, Yoshimoto et al. 2003, Zeng et al. 2003, Bölgen et al. 2005), PLDLA (Cui et al. 2006, Zong et al. 2002), PLLA (Badami et al. 2006, Chew et al. 2005, Yang et al. 2004, Zong et al. 2005), PLGA (Badami et al. 2006, Chew et al. 2005, Yang et al. 2004, Zong et al. 2005, Li et al. 2002, 2003, Liang et al. 2005), and copolymers such as PCL-PEG, PCL-PLLA (Nikkola et al. 2005, Xu et al. 2004), PLGA-PEG, PLLA-PEG, and etc.

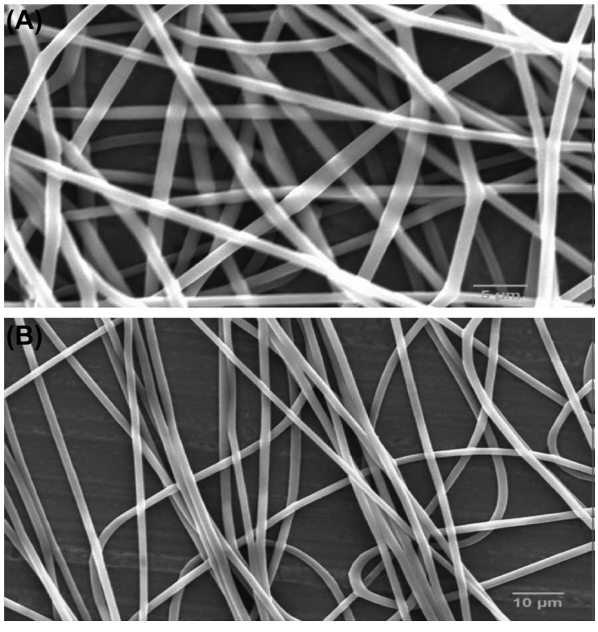

Figure 2. SEM micrographs of 5% PHBV-P (L,DL-LA) (1:1). (A) unoriented (B) oriented.

At some point in the procedure of electrospinning of synthetic polymers, the charge on the polymer solution makes it promising to govern its trajectory using an electric field (Jukola et al. 2008).

Studied Polymer with natural essence have been used to produce nanofibers, have drawn increasing research interests, including elastin(Boland et al. 2004), collagen (Venugopal et al. 2005, Huang et al. 2001, Shields et al. 2004), silk protein (Jin et al. 2004, Kim et al. 2003, Min et al. 2004), tropoelastin(Li et al. 2005), elastin-mimetic peptide (Huang et al. 2000), fibrin(Jukola et al. 2008, Tuzlakoglu et al. 2005), fibrinogen(Sindelar et al. 2006, Wnek et al. 2003), oxidized cellulose (Son et al. 2004), and hyaluronic acid (Um et al. 2004).

Furthermore, bio-corrosion of intense polymers is based on the factors such as fluctuations in pH, that is, pH-responsive polymers have also been planned (Piras et al. 2006).

Blends of synthetic polymer and polymer with natural essence were also used for merging properties of both.

Studied merging polymer involved gelatin-loaded PCL (Ma et al. 2005), collagen-loaded PLLA-PCL (He et al. 2005), composites of PEO and silk (Li et al. 2006), composites of PLLA-PCL and collagen (He et al. 2005), composites of PCL and starch (Um et al. 2004), composites of hyaluronic acid and PCL (Yang et al. 2006),composites of PLGA with PHBV (Zhu et al. 2009), and composites of PLGA, elastin and collagen (Stitzel et al. 2000).

The method of electrospinning is influenced by two groups of factors, system factors and process factors. System factors, for example distribution and polymer molecular weight, control the proportion of degradation of nanofibers, while other system factors such as polymer solution rate, that is viscosity, outward rigidity, and conductivity, govern the nanofiber thickness and decrease the possibility for globule creation. Process factors, for example orifice thickness, flow proportion of polymer, and electric potential, impact fiber diameter, whereas other process factors, for example space between needle and collector, govern the range of solvent evaporation within nanofibers and fall on the collector, while, gesture of collector governs the form of fiber throughout fiber fall (Zong et al. 2002, Shin et al. 2001).

One of the best advantages of polymer with natural essence is similarity and is identical to some molecular substances that exist in the human body.

One disadvantage of polymer with natural essence can be their reduced mechanical properties when isolated, thus this polymer requires additional processing for handling.

Two main classes of matrix proteins in the extracellular matrix (ECM) of human body are composed of proteoglycans and fibrous proteins. In the human body fibrous proteins, depending on tissue type have fiber diameter with ranging between 50 and 150 nm (Elsdale and Bard 1972, Kadler 2004).

Polymers with natural essence that are used as biomaterials or scaffolds for tissue engineering are cellulose, gelatin, fibrin, fibrinogen, chitosan, chitin, elastin, hyaluronic acid,

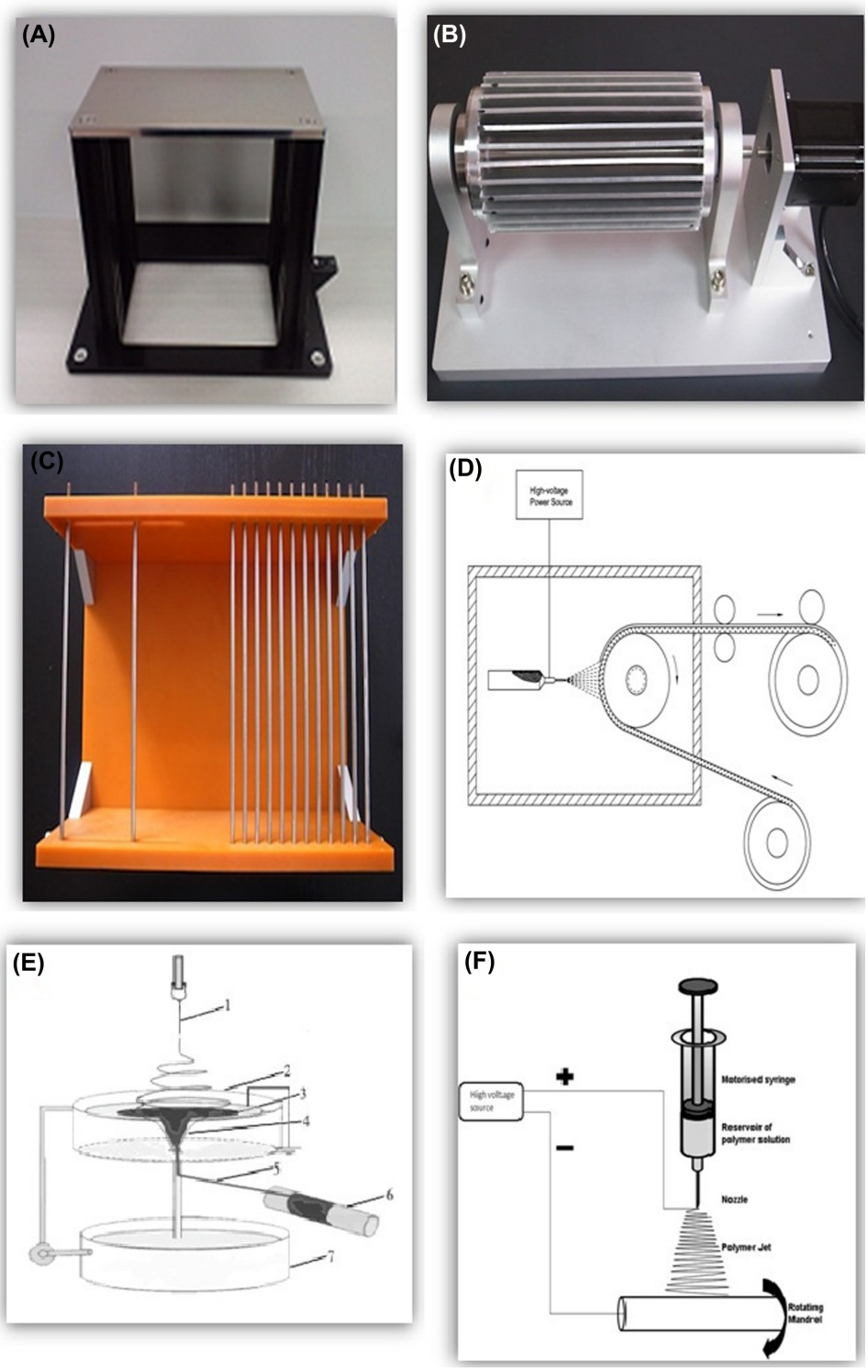

Figure 3. Different types of collectors. (A) Plate collector (B) Working-like parallel-electrodes collector (2014) (C) Collector with parallel electrode (Collector with parallel electrode 2014) (D) Continuous collector (2014) (E) Water bath collector (2014) (F) Rotatory collector.

collagen, and silk. Fabrication of this material into scaffolds for tissue engineering may possibly convey new possessions to biomaterials. Biomaterials produced with this polymer are mechanically stronger, physically lighter and more porous, optically more tunable optical emission, chemically more reactive or less corrosive, electrically more conductive and magnetically more paramagnetic (Huang et al. 2001, West and Halas 2000).

Electrospinning techniques are used for tissue engineering and mimicking of the size and morphology of natural ECM and design of collagen nanofibrous scaffolds. By this way, nanofiber of type I and III collagen were produced which can mimic properties of natural collagen (Matthews et al. 2002).

Electrospinning can be used for production of nanofibrous scaffolds which mimic the natural fibrous structure in

human body and regeneration of blood vessel,(Venugopal et al. 2005) bones, (Fujihara et al. 2005) dermis, (Venugopal et al. 2005, Venugopal and Ramakrishna 2005), and nerve (Yang et al. 2004).

Composition of polycaprolactone with collagen nanofiber were produced as a goal of flexibility, elasticity and consequently promising way for the creation of smooth muscle tissues for engineering of blood vessel (Venugopal et al. 2005).

Wnek et al. using fibrinogen produced a nanofiber scaffolds for wound dressing or hemostatic products (Wnek et al. 2003).

Gelatin promotes cell adhesion, migration and form a polyelectrolyte complex because contains Arg-Gly-Asp (RGD)-like sequence. Blends of gelatin and chitosan improve the biological and cellular activity and this composition was tested in restoring various tissues including skin, cartilage, and bone (Bhattarai et al. 2005, Huang et al. 2005).

Coaxial electrospinning

Fabrication of core-shell nanofibers can be provided using coaxial electrospinning (also known as co-electrospinning) technique and is an adjustment or extension to the traditional electrospinning technique. As compared to traditional electrospinning, coaxial electrospinning (Figure 4A) makes use of complex spinneret (needle) which consists of a multiple solution feed system with one or more inner channels shelled by an outer tube which is required for the injection of one material into another at the tip of the spinneret and collected into a core-sheath–structured composite fiber (Sun et al. 2003) to generate composite nanofibers with core-shell structures (Figure 4B).

Many factors can have effect on the entrapment of components in the inner channels such as viscoelasticity of the two solutions, interfacial tension and feeding rate of the inner and outer fluids (Sun et al. 2003, Chakraborty et al. 2009).

There are variety of novel and functional polymeric nanofibers from coaxial electrospinning, such as basic bi-component nanofiber, surface-coated/-modified nanofiber, nanocomposite nanofiber, and hollow nanofibers (Zhang et al. 2007).

Recently, coaxial electrospinning has achieved greater than before popularity in the protein delivery field because the fabricated core-shell fibers have great potential in maintaining proteins at some point in the electrospinning procedure and it provides uniform protein distribution throughout the fibers, and proteins have potential to be delivered in an organized manner as a result of the shell blockade.

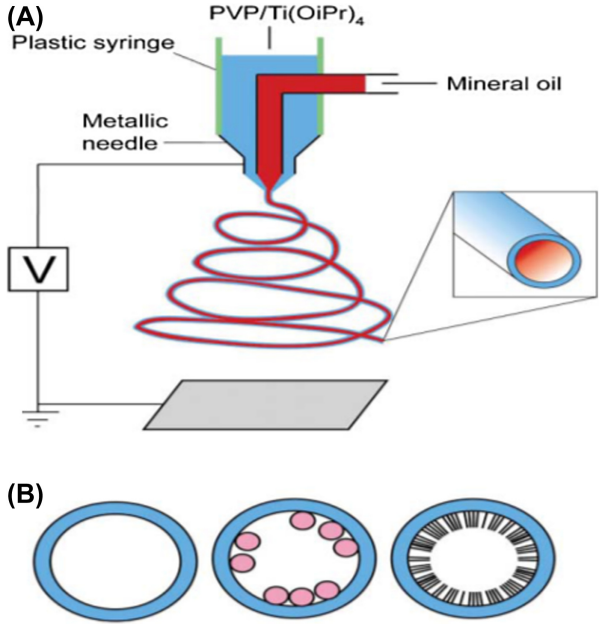

Figure 4. Schematic for fabrication of core-shell nanofibers with a coaxial spinneret. (A) the coaxial spinneret (B) different type of nanofiber which can produced by coaxial electrospinning.

Biomedical application

Tissue engineering

One of the main areas of research in biomedical application is tissue engineering. Electrospinning is a very efficient method for production of nanofiber scaffolds. Many different types of scaffolds were produced for tissue engineering and organ regeneration, such as skin, cartilage, bone, collagen, dentin and liver (Table I). Nanofibers have been used in making these scaffolds using both natural and synthetic polymer electrospuns. These scaffolds are used to regenerate, replace, and repair the tissue and therefore need to be well designed and must have dimensional equality.

As mentioned above, nanofiber scaffolds produced using electrospinning, have many good properties which require for tissue engineering such as biodegradability, large surface area, ability to maintain structural integrity with tissue, high porosity, high-quality mechanical properties, and non-toxicity to cell (Elsdale and Bard 1972).

Using of nanofibers composite materials, which are similar to ECM proteins such as collagen and glycosaminoglycans, can support and improve cell function and cell–cell or cell–ECM attachment. Therefore, nanofiber scaffolds produced by these materials would improve the nanofiber efficiency.

Studies have shown that thinner fibers with sizes ranging between 60 and 200 nm can increase proliferation, osteoblast adhesion, alkaline phosphatase activity, and ECM secretion on carbon nanofibers (Webster et al. 1999).

Because of unique properties of core-shell nanofibers including versatility, potential for encapsulation of biological molecules, and nanocomposites as well as potential for modifying the surfaces of electrospun fibers, it can be used for tissue engineering. Another important factor that can improve nanofibers for tissue engineering is modifying the electrical and mechanical properties of the nanofibers and it is achieved by integration of nanofiber scaffolds with wall carbon nanotubes (SWNT).

The purpose and concept of drug delivery methods is to deliver a predetermined amount of drug correctly, efficiently, tissue or cell specific and for a defined period of time. Drug delivery through electrospun nanofiber has been mainly functional and useful for tissue engineering.

Table I. Example of nanofiber application in tissue engineering.

Tissue	Nanofiber scaffolds	Brief function	Cell or tissue	Reference(s)
Bone	Starch/PCL	Enhance cell attachment, organization and alkaline phosphatase (AP) activity	Human osteoblast cell line and rat bone marrow stromal cells	Tuzlakoglu et al. (2005)
	PCL	Enhance ECM formation	Neonatal rat bone marrow-derived MSCs	Yoshimoto et al. (2003)
	PCL/hyaluronan	Enhance ECM formation, better cell attachment	Neonatal rat bone marrow-derived MSCs	Yang et al. (2006)
	Bioactive silk fibroin/bone morphogenetic protein-2 (BMP-2),	Higher calcium deposition, enhance transcription levels of bone-specific markers	Human bone marrow-derived MSCs	Li et al. (2006)
	Bioactive silk fibroin/hydroxyapatite (nHAp)	Improve bone formation	Human bone marrow-derived MSCs	Li et al. (2006)
	PCL/CaCO3	Good cell attachment and proliferation of human osteoblasts	Human osteoblasts	Fujihara et al. (2005)
Cartilage	PLGA	Provide mechanical properties appropriate for cartilage tissue	Mouse fibroblast cells and bone marrow-derived MSCs	Li et al. (2002)
	Collagen type II	Adherence, propagation, and infiltration of the chondrocytes, the creation of pseudopodia	Human articular chondrocytes cell line	Shields et al. (2004)
	PCL	Support chondrocyte proliferation, increase expression of cartilage specific ECM genes	Fetal bovine chondrocytes (FBCs), rat bone marrow stromal cells (rBMSC)	Li et al. (2003, 2005)
Muscle	Poly(ε-caprolactone-co-glycolide)-diol bonded to a diisocyanate, polyesterurethane linked with poly((R)-3-hydroxybutyric acid)-diol	Satisfactory mechanical properties and the absence of toxic residuals	Rat myoblast cell line (L6), murine myoblast cell line (C2C12) and primary human satellite cells (HSCs)	Riboldi et al. (2005)
Ligament/ Tendon	Polyurethane (PU)	Increase ECM production	Human ligament fibroblast (HLF)	Lee et al. (2005)
	PLGA/knitted scaffold.	Increase of cell proliferation and cell function	Porcine bone marrow stromal cells	Sahoo et al. (2006)
Blood vessels	Collagen-blended P(LLA-CL)	Enhance of cell viability, attachment, spreading and preserve human coronary artery endothelial cells (EC) markers	Human coronary artery endothelial cells (EC)	He et al. (2005)
	Collagen-coated PCL fibers	Enhance cell attachment, migration, and proliferation, high quality morphology of α-actin filaments	Human coronary artery endothelial cells (HCAECs)	He et al. (2005)
	Gelatin-grafted PCL nanofibers	Improve cell proliferation, maintain morphology of endothelial cells (EC)	Endothelial cells (ECs)	Ma et al. (2005)
	Poly(L-lactide-co-ε-caprolactone) [P(LLA-CL)]	Increase in cell density, migration and proliferation	SMCs and ECs	Mo et al. (2004)
	PLLA-CL	Enhance attachment and proliferation	Human coronary artery SMCs and ECs	Xu et al. (2004)
	Poly(ester urethane)urea (PEUU)	Higher cellular density in perfusion cultures, No significant change in static cultures	Rat aortic SMCs	Son et al. (2004)
	Composition of collagen type I, elastin and poly(D,L-lactide-co-glycolide)	Improve physical properties	ECs and SMCs	Stitzel et al. (2006)

Drug, Nucleic acid and growth factor delivery.

Accordingly, dissolution rate of drug can be increased by enlargement surface area of the drug and the corresponding carrier (Table II).

Low solubility and instability make hydrophobic agents difficult to have continued release of active molecules with appropriate concentration within a satisfactory period of time.

Using of electrospun nanofiber scaffolds can be delivered both via viral and nonviral nucleic acids.

Degree of success in viral gene delivery can be determined by the parameters such as gene structure, the type of cells and viruses, and type of delivery technique.

As propose of in situ viral delivery of genes, it is necessary to develop and use of novel and more efficient carriers, for the most part polymeric carriers.

As compare to viral vectors, nonviral gene delivery and vectors have appropriate properties such as low toxicity and potential for using of large DNA with varying sizes (Liao and Leong 2011).

Electrospun nanofibers have been used as scaffolds for delivery of nucleic acids (e.g., DNA and siRNA) because of owning appropriate properties such as high porosity, high surface area, interrelated pores beneficial for oxygen/nutrient

Table II. Example of nanofiber application in delivery.

		Tissue/cell	Properties	Reference(s)
Nucleic acid	siRNA/PCL	Human embryonic kidney 293 cells	Repression efficiency of 61–81%, high cellular uptake and successful transfection but slow release rate	Cao et al. (2010)
	siRNA/TKO(a transfection reagent)/ poly(caprolactone-co-ethyl ethylene phosphate)	Mouse fibroblast NIH 3T3 cells	Fast siRNA release rate, significant gene silencing	Rujitanaroj et al. (2011)
	Matrix metalloproteinase (MMP)-assisted siRNA/ nanofibrous matrix	Diabetic ulcers	Increase the wound recovery rates of diabetic ulcers	Kim and Yoo (2013)
	chitosan/siRNA/PLGA	H1299 cells	High gene silencing activity	Chen et al. (2012)
	DNA-incorporated nanofibrous matrix	Diabetic ulcers	Controlled release of DNA in response to MMPs	Kim and Yoo (2010)
	Plasmid DNA/PLGA or PLA-PEG composite scaffolds	Preosteoblastic cell line, MC3T3-E1	Sustained release over a 20-day study period	Luu et al. (2003)
	Adenovirus encoding the gene for green fluorescent protein/PCL	HEK 293 cells	Low immune response such as reduced the activation of macrophage cells by the viral vector was	Liao et al. (2009)
	plasmid DNA (pDNA)/ poly(ethylenimine)-hyaluronic acid (PEI-HA)/ PCL/PEG	fibroblast-like cells	High transfection rate, induce expression of enhanced green fluorescent protein (EGFP)	Saraf et al. (2010)
	PLGA/Hydroxylapatite (HAp) composite scaffolds incorporated with DNA	human marrow stem cells (hMSCs)	Higher cell viablility, higher cell attachment and desirable transfection efficiency of DNA	Nie and Wang (2007)
Growth factors	Nerve GF (NGF) surface-conjugated CS/PVA scaffolds	SKNMC (human neuroblastoma) and U373 (human glioblastoma-astrocytoma) cell lines	Improve adhesion and proliferation	Mottaghitalab et al. (2011)
	heparin-containing polyelectrolyte complex nanoparticles (PCNs)/ fibroblast GF (FGF-2)	ovine bone marrow-derived mesenchymal stem cells	Exhibited mitogenic activity	Zomer Volpato et al. (2012)
	angiogenic or lymphangiogenic growth factors	Skeletal myoblasts isolated from the quadriceps of mice	Increase vascular or lymphatic network infiltration	Liao and Leong (2011)

transferal and unfastened bonding between fibers favorable for cell migration and infiltration (Yang et al. 2011) and cell adhesion/proliferation (Zou et al. 2012).

Improper encapsulation and transfection efficiency is one of the unsatisfactory results among the diverse techniques of blending DNA with an electrospun nanofiber scaffolds. In order to overcome this low encapsulation and transfection efficiency were tested incorporation of DNA-loaded particles into core-shell nanofibers, (Saraf et al. 2010, Liao et al. 2009) nanofibers, (Nie and Wang 2007) and surface modification (Kim and Yoo 2010). Another group of molecules that can be delivered using of nanofiber scaffold delivery system are growth factors or GFs which can regulate biological processes by regulating migration, proliferation, and differentiation of cells, transferring signals between cells and their ECM and by this means enhance tissue regeneration (Chen et al. 2010). Therefore, the incorporation of GFs with ECM-mimicking scaffolds possibly will be advantageous for tissue regeneration and other proposes (Tabata 2000).

Scientists achieve the controlled release of GFs but the instability of GFs hampers the thriving improvement of GF-loaded tissue-engineered scaffolds.

Various techniques were applied for GF incorporation into nanofibrous scaffolds, such as coaxial electrospinning, (Liao and Leong 2011) specific or nonspecific surface

Table III. Example of nanofiber application in wound dressings.

Nanofiber scaffolds	Brief function	Reference(s)
Blend of PVA, poly(vinyl acetate) with ciprofloxacin hydrochloride	Prolonging drug release	Jannesari et al. (2011)
fusidic acid/PLGA	Prohibition of bacterial biofilm formation	Said et al. (2011)
epidermal GF (EGF)-loaded silk nanofibers	Contribution toward the healing process, decreasing the time of wound closure	Schneider et al. (2009)
Blends of vitamins and anti-inflammatory and antioxidant drugs with PVA and cellulose acetate		Im et al. (2010), Ngawhirunpat et al. (2009), Suwantong et al. (2007), Taepaiboon et al. (2007)
poly(vinyl alcohol)/poly(acrylic acid)/multi-walled carbon nanotube (PVA/PAA/MWCNT)	More than 80% cell viability	Yun et al. (2011)

Table IV. Example of nanofiber application in cancer therapy.

Scaffolds	Tissue or cell	Brief function	Reference(s)
Dichloroacetate/PLA	Cervical carcinoma	Reduction in tumor volume	Liu et al. (2012)
paclitaxel-loaded chitosan (CS) nanofibers with hyaluronic acid	Prostate cancer cells	Inhibit the attachment and proliferation	Ma et al. (2011)
green tea polyphenol (GTP)/PCL/MWCNT	Human hepatocellular carcinoma cells, (Hep G2)	High antiproliferative effect	Shao et al. (2011)
titanocene dichloride/PLLA	Lung tumor cells	Inhibitory activity	Chen et al. (2010)
hydroxycamptothecin (HCPT)/poly(d,l-lactic acid)-PEG	Human mammary gland MCF-7 cancer cells	High inhibitory activity	Xie et al. (2010)

modifications, (Zomer Volpato et al. 2012) blending, (Zhang et al. 2012) emulsion electrospinning (Tian et al. 2012, Yang et al. 2011) and these yielded varied levels of success.

Burst release of EGF was obtained from silk nanofibers blended with EGF, due to the hydrophobic nature of EGF (Schneider et al. 2009). Different substances were used for conjugation with GFs such as polysaccharides (Mottaghitalab et al. 2011) and heparin (Zou et al. 2011).

Wound dressings

Wound dressings give a hand in shielding the wound from external microorganisms, absorbing exudates, accelerate the wound-healing process, and lastly improving surface manifestation (Zhang et al. 2005, Khil et al. 2003).

Up till now, bioactive wound dressing materials, which typically necessitated in the initial period of wound healing incorporated with antibiotic, have been introduced such as foams, sponges, hydrogels, and films (Jannesari et al. 2011).

Electrospun nanofibers have great facility for wound dressing (Table III) because of owning special characteristics, for example high surface area, and as a result electrospun nanofibers can professionally suck up exudates and regulates the wound humidity (Khil et al. 2003). The porosity of nanofibrous can directly impact on wound dressing because high porosity scaffold effectively contributes to air permeability and provide required oxygen for cell respiration, but small porosity contributes to preserving the wound from bacterial infections.

Two main requirements for completely covering problematical wounds are improved hemostasis and more flexibility in dressing, which are achievable through nanofibrous dressings. Furthermore, as an esthetic point of view, nanofibers provide the better-quality advantage of scar-free regeneration (Tian et al. 2012, Boateng et al. 2008).

Cancer therapy

Administration of anticancer drugs (both orally and intravenously) may have some disadvantages such as low efficacy, poor solubility, low instability, side effects on healthy tissues, need for several injection, and high removal rate by the reticuloendothelial system (Shao et al. 2011, Xie et al. 2010).

Scientists have been exploring many methods in order to improve a minimized unwanted side effects to healthy tissues, maximized efficiency, and extended period of function such as restricted and continued postsurgical drug delivery (Pradilla et al. 2006).

Blends of anticancer drugs with electrospun nanofiber scaffolds can cover up such a disadvantages and it can easily insert to the solid tumor site (Table IV). This can provide high local dosage with incorporation of small amounts of the drug but also reduces the need for frequent administrations, and therefore provide patient convenience.

Conclusion

Nanofibrous materials can be synthesized of biocompatible and biodegradable polymers and produced using electrospinning processes. Continuous production of electrospun nanofibers webs with high efficiency and discontinuous production of nanofiber webs from very small amount of liquid (one droplet) for very expensive polymers usage. Production of composite materials consisting of electrospun layers with incorporated powder between nanofibers or inside nanofibers. Production of hybrid yarns—classical base yarn covered by electrospun nanofibers and is protective.

Nanofibers have applications in medicine, including artificial organ components, tissue engineering, implant material, drug delivery, wound dressing, and medical textile materials.

Authors' contributions

AE conceived of the study and participated in its design and coordination. AA assisted in the numerical calculations. HD participated in the sequence alignment and drafted the manuscript. AA supervised the whole study. All authors read and approved the final manuscript.

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Declaration of interest

The authors report no declarations of interest. The authors alone are responsible for the content and writing of the paper.

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