

BIOMEDICAL PATCHES WITH SPATIALLY ARRANGED FIBERS

BACKGROUND

[0001] Numerous pathological conditions and surgical procedures result in substantial defects in a variety of organs, tissues, and anatomical structures. In the majority of such cases, surgeons and physicians are required to repair such defects utilizing specialized types of surgical meshes, materials, and/or scaffolds. Unfortunately, the *in vivo* performance of known surgical materials is negatively impacted by a number of limiting factors. For instance, existing synthetic surgical meshes typically result in excessive fibrosis or scarification leading to poor tissue integration and increased risk of post-operative pain. Simultaneously, known biologic materials may induce strong immune reactions and aberrant tissue ingrowth which negatively impact patient outcomes. Additionally, existing synthetic surgical meshes can create scarification, post-operative pain, limited mobility, limited range of motion, adhesions, infections, erosion, poor biomechanical properties, and/or poor intraoperative handling.

[0002] Nanofabricated or nanofiber meshes or materials composed of reabsorbable polymer fibers tens to thousands of times smaller than individual human cells have recently been proposed as a unique substrate for implantable surgical meshes and materials. Generally, existing nanofiber materials tend to possess suboptimal mechanical performance compared to known surgical meshes. Existing nanofiber materials do not possess the tensile strength, tear resistance, and burst strength needed for numerous surgical applications or for basic intraoperative handling prior to *in vivo* placement. To combat this deficiency, known meshes are formed using higher fiber densities as a means of improving mechanical strength. Yet, utilization of such high-density meshes can decrease effective cellular ingrowth into the mesh, decrease mesh integration with native tissue, and reduce the biocompatibility of the polymeric implant. As a result, nanofiber materials with increased thickness and/or strength and favorable cellular and/or tissue integration and biocompatibility is needed as well as a method for producing nanofiber materials.

SUMMARY

[0003] A system for producing a structure including a plurality of fibers is provided. The system includes a polymer collector having a predefined pattern, wherein the collector is charged at a first polarity, and a spinneret configured to dispense a polymer, wherein the spinneret is charged at a second polarity substantially opposite the first polarity such that polymer dispensed from the spinneret forms a plurality of fibers on the predefined pattern of the fiber collector.

[0004] A method for producing a structure including a plurality of fibers is provided. The method includes providing a collector with a predefined pattern, charging the collector with a first polarity, providing a spinneret, the spinneret configured to dispense a polymer on the provided collector, charging the spinneret to a second polarity substantially opposite the first, and dispensing a polymer on the collector, such that the polymer forms a plurality of fibers defining the structure, wherein the structure has at least two densities formed by the plurality of fibers.

[0004a] In one aspect, the present disclosure provides a method for producing a structure including a plurality of fibers, the method comprising: providing a collector with a predefined pattern, the collector including at least one of a plurality of ribs and a plurality of seams that are interconnected to form the predefined pattern, the collector further including at least one surface which is a filling of a void formed between the at least one of the plurality of ribs and the plurality of seams; charging the collector with a first polarity; providing a spinneret, the spinneret configured to dispense a polymer on the provided collector; charging the spinneret to a second polarity opposite the first; and dispensing the polymer on the collector via a focusing device, such that the polymer forms a plurality of fibers defining the structure, wherein the structure has at least two densities formed by the plurality of fibers.

[0005] A method for repairing a defect of a substrate. The method includes providing a substrate with a defect, providing a structure formed from a plurality of polymeric fibers, the structure having a plurality of densities, and applying the structure to the substrate.

[0006] A method for producing a structure for use in repairing a defect in a substrate is provided. The method includes providing a first layer formed by a plurality of polymeric fibers, providing a second layer formed by a plurality of polymeric fibers, the second layer having a plurality of densities, and coupling the first layer and the second layer together using a first coupling process such that the first and second layers are configured to separate after at least one of a predetermined time and an environmental condition.

[0007] A structure for use in repairing a defect in a substrate is provided. The structure includes a first layer formed by a plurality of polymeric fibers and a second layer coupled to the first layer using a first coupling process, the second layer having a plurality of densities formed by a plurality of polymeric fibers, wherein the first and second layers are configured to separate after at least one of a predetermined time and an environmental condition.

[0008] A method for repairing a defect of a substrate is provided. The method includes providing a substrate with a defect, providing a structure formed from a plurality of polymeric

fibers, the structure comprising a first layer formed by a plurality of polymeric fibers, and a second layer coupled to the first layer, the second layer having a plurality of densities formed by a plurality of polymeric fibers, wherein the first and second layers are configured to separate after at least one of a predetermined time and an environmental condition, and applying the structure to the substrate.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] The embodiments described herein may be better understood by referring to the following description in conjunction with the accompanying drawings.

[0010] FIG. 1 is a diagram illustrating an electrospinning system for producing a structure of spatially arranged fibers.

[0011] FIG. 2 is a diagram of a collector removed from the electrospinning system of FIG. 1 and having a plurality of fibers deposited thereon forming a patch.

[0012] FIG. 3 is an illustration of a biomedical patch including a plurality of spatially arranged electrospun fibers deposited on a collector shown in FIG. 1.

[0013] FIG. 4 is another illustration of a biomedical patch including a plurality of spatially arranged electrospun fibers deposited on a collector shown in FIG. 1.

[0014] FIG. 5 is an illustration of a solid fiber spinneret shown in FIG. 1.

[0015] FIG. 6 is an illustration of a co-axial fiber spinneret shown in FIG. 1.

[0016] FIG. 7 is an illustration of a multi-layer biomedical patch.

[0017] FIG. 8 is an illustration of a delamination of patches, such as the patch shown in FIG. 7, using various fusion strengths over time.

[0018] FIGS. 9 and 10 are histological cross-sections of regenerated dura repaired with multi-laminar nanofiber material such as a patch shown in Fig. 8.

[0019] Figs. 11 and 12 are histological cross-sections of regenerated dura repaired with multi-laminar nanofiber material such as a patch shown in Fig. 8.

[0020] Fig. 13 is an illustration of a delamination of patches, such as the patch shown in FIG. 7, using various fusion methods and strengths over time.

[0021] FIG. 14 is a flowchart of an exemplary method 700 for producing a structure of spatially arranged fibers using system 100 shown in FIG. 1.

[0022] FIG. 15 is a flowchart of an exemplary method 750 for fusing or coupling together structures or patch layers produced by method 700 shown in FIG. 14.

[0023] FIG. 16 is a flowchart of an exemplary method 800 for repairing a defect in a biological tissue using the structures produced by methods 700 and 750 shown in FIGS. 14 and 15.

DETAILED DESCRIPTION

[0024] Embodiments provided herein facilitate repairing biological tissue or reinforcing biomedical material with the use of a biomedical patch including a plurality of fibers. Such

fibers may have a very small cross-sectional diameter (e.g., from 1-3000 nanometers) and, accordingly, may be referred to as nanofibers and/or microfibers. While biomedical patches are described herein with reference to dura mater and use as a surgical mesh, embodiments described may be applied to any biological tissue. Moreover, although described as biomedical patches, structures with aligned fibers may be used for other purposes. Accordingly, embodiments described are not limited to biomedical patches.

[0025] In operation, biomedical patches provided herein facilitate cell growth, provide reinforcement, and may be referred to as “membranes,” “scaffolds,” “matrices,” “meshes”, “implants”, or “substrates.” Biomedical patches with varying densities, as described herein, may promote significantly faster healing and/or regeneration of tissue such as the dura mater than existing patches constructed using conventional designs.

[0026] Dura mater is a membranous connective tissue comprising the outermost layer of the meninges surrounding the brain and spinal cord, which covers and supports the dural sinuses. Surgical meshes are often needed during neurosurgical, orthopedic, or reconstructive surgical procedures to repair, expand, reinforce, or replace the incised, damaged, or resected dura mater.

[0027] Although many efforts have been made, the challenge to develop a suitable surgical mesh for dural repair has been met with limited success. Autografts (e.g., fascia lata, temporalis fascia, and pericranium) are preferable because they do not provoke severe inflammatory or immunologic reactions. Potential drawbacks of autografts include the difficulty in achieving a watertight closure, formation of scar tissue, insufficient availability of graft materials to close large dural defects, increased risk of infection, donor site morbidity, and the need for an additional operative site. Allografts and xenograft materials are often associated with adverse effects such as graft dissolution, encapsulation, foreign body reaction, immunological reaction, contracture, scarring, adhesion formation, and toxicity-induced side effects from immunosuppressive regimens. Lyophilized human dura mater as a dural substitute has also been reported as a source of transmittable diseases, specifically involving prions, such as Creutzfeldt-Jakob disease.

[0028] In terms of synthetic surgical mesh materials, non-absorbable synthetic polymers, such as silicone and expanded polytetrafluoroethylene (ePTFE), often cause serious complications that may include induction of granulation tissue formation due to their chronic stimulation of the foreign body response. Natural absorbable polymers, including collagen, fibrin, and cellulose, may present a risk of infection and disease transmission. As a result, synthetic absorbable polymers such as poly (3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV),

poly (lactic acid) (PLA), polyglycolic acid (PGA), poly (lactic-co-glycolic acid) (PLGA), PLA-PCL-PGA ternary copolymers, and hydroxyethylmethacrylate hydrogels have recently attracted attention as biodegradable implant materials for dural repair. Methods and systems described herein may be practiced with these materials and/or any biomedical polymer whether the polymer is non-absorbable or absorbable, or synthetic in origin.

[0029] In order to facilitate successful regeneration and/or repair of the dura mater following surgery, a synthetic surgical mesh or biomedical patch should promote: i) adhesion of dural fibroblasts (the primary cell type present in the dura) to the surface of the biomedical patch; ii) migration of dural fibroblasts from the periphery of the biomedical patch into the center of the patch; iii) reinforcement or replacement of existing tissues; iv) minimal immune response; v) water tight closure of the dural membrane / dura mater; vi) mechanical support of the native dural post-operatively and during tissue regeneration / neoduralization; vii) rapid closure of the dural defect; and viii) increased ease of use.

[0030] Electrospinning is an enabling technique which can produce nanoscale fibers from a large number of polymers. The electrospun nanofibers are typically collected as a randomly-oriented, nonwoven mat. Uniaxially or radially aligned arrays of nanofibers can also be obtained under certain conditions. However, traditional nanofiber scaffolds may lack the optimal mechanical and biological properties necessary for some biomedical or surgical applications post-operatively.

[0031] In order to increase the strength of nanofiber scaffolds, custom fabrication of scaffolds into particular patterns would be highly advantageous. Additionally, multiple layers of nanofiber materials fused/coupled together in a manner that allows for a purposeful degradation of the layers can also provide strength while allowing for cellular penetration and/or tissue integration.

[0032] Many polymers are available for use in electrospinning. In some embodiments described herein, nanofibers for dura substitutes are produced as the electrospun polymer from poly (ϵ -caprolactone) (PCL), an FDA approved, semicrystalline polyester that can degrade via hydrolysis of its ester linkages under physiological conditions with nontoxic degradation products. This polymer has been extensively utilized and studied in the human body as a material for fabrication of drug delivery carriers, sutures, or adhesion barriers. As described herein, electrospun PCL nanofibers may be used to generate scaffolds that are useful as surgical meshes.

[0033] Embodiments provided herein facilitate producing a novel type of artificial tissue substitute including a polymeric nanofiber material, which is formed through a novel method of electrospinning. This polymeric material includes non-woven nanofibers (e.g., fibers having a diameter of 1-3000 nanometers) which are arranged or organized and aligned into patterns both within and across a material sheet.

[0034] FIG. 1 is a diagram illustrating a perspective view of an exemplary electrospinning system 100 for producing a structure of spatially arranged or organized fibers. System 100 includes a collector 105 with a predetermined pattern 110 including a plurality of reinforcement features 112. System 100 also includes a spinneret 120.

[0035] System 100 is configured to create an electric potential between one or more collectors 105 and one or more spinnerets 120. In one embodiment, collector 105 and features 112 are configured to be electrically charged at a first amplitude and/or polarity. For example, collector 105 and features 112 may be electrically coupled to one or more power supplies 130 via one or more conductors 135. Power supply 130 is configured to charge collector 105 and features 112 at the first amplitude and/or polarity via conductor 135.

[0036] In the embodiment illustrated in Fig. 1, collector 105 includes pattern 110 that is a grid pattern formed by features 112 such that collector 105 is substantially rectangular. In other embodiments, collector 105 may have any shape including, but not limited to, circular, elliptical, ovalar, square, and/or triangular. In one embodiment, features 112 include ribs 114, seams 116, and surfaces 118 configured to receive and/or collect polymer fibers. In one embodiment, rib 114 is substantially cylindrical and has a circumference between 5um - 100cm, seam 116 is substantially rectangular having a thickness between 5um- 100cm, and surface 118 is a filling of a void or feature space 119 formed between ribs 114 and/or seams 116. In one embodiment, surface has a thickness between 5um – 10cm. In the exemplary embodiment, features 112 are made fabricated from at least a portion of metallic substance, including, but not limited to steel, aluminum, tin, copper, silver, gold, platinum, and any alloy or mixture thereof. In one embodiment, features 112 include a coating applied to collector 105. Coatings can include, but are not limited to anodization, chemical coatings, material coatings (conductive or non-conductive), and gradient coatings that facilitate the creation of continuous gradients of fibers. However, it should be noted that features 112 (e.g., ribs 114, seams 116, and surface 118) can have any shape and be fabricated from any material that facilitates producing patches as disclosed herein.

[0037] In the exemplary embodiment, pattern 110 is formed by spatially organizing features 112. In one embodiment, features 112 (e.g., ribs 114 and seams 116) are interconnected at nodes 115 such that a feature space 119 is formed between features 112 in the range of 10 μm and 10 cm. In one embodiment, pattern 110 includes a plurality of spaces 119 such that multiple varying distances are formed between features 112. It should be noted that pattern can be formed to be symmetrical, repeating, and asymmetrical. In the exemplary embodiment, the shape of collector 105 enables the biomedical patch formed on collector to include additional support and/or reinforcement properties. Such additional support and/or reinforcement properties are achieved by creating high density fiber deposition areas on charged features 112 and having low density fiber deposition areas over feature spaces 119.

[0038] For example, a diamond shaped collector 105 including a diamond shaped array pattern 110 enables a diamond-shaped patch to be produced on the diamond shaped collector 105 to have different mechanical properties from a rectangular-shaped or a circular-shaped patch such as, but not limited to, tensile strength, tear resistance, terminal strain, failure mechanisms or rates, and/or controlled anisotropic properties, such as greater strength in one axis relative to another.

[0039] In one embodiment, pattern 110 defines a collector plane 127 and spinneret 120 is orthogonally offset from the collector plane 127 at a variable distance. For example, spinneret 120 may be orthogonally offset from the collector plane 127 at a distance of 50 micrometers to 100 centimeters. Alternatively, spinneret 120 can be offset from collector 105 in any manner that facilitates creating patches as described herein, including but not limited to, horizontal and diagonal or skew.

[0040] Spinneret 120 is configured to dispense a polymer 140 while electrically charged at a second amplitude and/or polarity opposite the first amplitude and/or polarity. As shown in FIG. 1, spinneret 120 is electrically coupled to one or more power supplies 130 by one or more conductors 145. Power supply 130 is configured to charge one or more spinnerets 120 at the second amplitude and/or polarity via conductor 145. In some embodiments, power supplies 130 provides a direct current and/or static or time variant voltage (e.g., between 1 - 50 kilovolts). In one embodiment, conductor 145 is charged positively, and collector 105 is also charged positively. In all embodiments, power supply 130 is configured to allow adjustment of a current, a voltage, and/or a power.

[0041] In one embodiment, spinneret 120 is coupled to a dispensing mechanism 150 containing polymer 140 in a liquid solution form. In such an embodiment, dispensing

mechanism 150 is operated manually by a dispensing pump 155. Alternatively, dispensing mechanism 150 can be operated automatically with any mechanism configured to dispense nanofibers as described herein. In the exemplary embodiment, spinneret 120 includes a metallic needle having an aperture between 10 micrometers and 3 millimeters in diameter for dispensing nanofibers.

[0042] As dispensing mechanism 150 pressurizes polymer 140, spinneret 120 dispenses polymer 140 as a jet or stream 160. In one embodiment, stream 160 is dispensed in a horizontal or sideways stream from spinneret 120. Stream 160 has a diameter approximately equal to the aperture diameter of spinneret 120. Stream 160 descends toward collector 105 forming a Taylor cone. For example, stream 160 may fall downward under the influence of gravity and/or may be attracted downward by charge distributed on the fibers and on features 112. As stream 160 descends, polymer 140 forms one or more solid polymeric fibers 165. In the exemplary embodiment, fibers 165 are solid, however it should be noted that fibers 165 can have any structure including by not limited to, core or shell, porous, co-axial, and co-axial. Alternatively, polymer 140 deposition can be accomplished by any other fiber deposition method including but not limited to, solvent electrospinning, force electrospinning, melt electrospinning, extrusion, and melt blowing.

[0043] In some embodiments, a mask 164 composed of a conducting or non-conducting material is applied to collector 105 to manipulate deposition of fibers 165. For example, mask 164 may be positioned between spinneret 120 and collector 105 such that no fibers 165 are deposited on collector 105 beneath mask 164. Moreover, mask 164 may be used as a time-variant mask by adjusting its position between the spinneret and the collector while spinneret 120 dispenses polymer 140, facilitating spatial variation of fiber density on collector 105. While mask 164 is shown as circular, mask 164 may have any shape (e.g., rectangular or semi-circular) and size suitable for use with system 100. Alternatively, or in addition, deposition of fibers 165 on collector 105 may be manipulated by adjusting the position of collector 105 with respect to spinneret 120 or by spatially varying the electrical potential applied between the spinneret 120 and/or the electrodes making up the collector 105. For example, positioning one side of collector 105 directly beneath spinneret 120 may cause more fibers 165 to be deposited on that side than are deposited on the opposite side of collector 105 in a Gaussian distribution. To modulate the spatial distribution of fibers forming on collector 105, in some embodiments, a focusing device 138 is utilized to focus fiber deposition in a particular special region. In such an embodiment, focusing device 138 is charged with a polarity similar to spinneret 120 and includes an aperture allowing fiber deposition to occur substantially in the space under the aperture. Focusing device

138 may have any geometry that allows for receipt of nanofibers from spinneret 120 and deposition of the received nanofibers onto collector 105 as described herein.

[0044] FIG. 2 is a diagram of collector 105 removed from electrospinning system 100 (shown in FIG. 1) and having a plurality of fibers 165 deposited thereon forming a patch 170. Fibers 165 are oriented such that they correspond to the position of features 112 (shown in FIG. 1).

[0045] Patch 170 is illustrated with a small quantity of fibers 165 in FIG. 2 for clarity. In some embodiments, patch 170 includes thousands, tens of thousands, hundreds of thousands, or more fibers 165, distributed on collector 105. Even with millions of fibers 165, patch 170 retains predictable properties such as being flexible and/or pliable. As such, the predictable properties facilitate the application of patch 170 to uneven biological tissue surfaces, such as the surface of the dura mater.

[0046] The alignment of fibers 165 illustrates a patch 170 with varying densities. Patch 170 enables reinforcement or structural integrity to be provided in predetermined locations. For example, a larger deposition of fibers occurs in various locations, such as portion 167, which provide structural reinforcement. Accordingly, system 100 enables the creation of customized materials 170 for individual biomedical or clinical and non-clinical applications.

[0047] In the exemplary embodiment, fibers 165 have a diameter of 1-3000 nanometers. In one embodiment, fibers have a diameter of approximately 220 nanometers (e.g., 215 nm to 225 nm). It should be noted that the diameter of the fibers 165, thickness of the patch 170, and/or fiber density within the patch 170 may affect the durability (e.g., tensile strength, suture pullout strength, conformability, etc.) of patch 170. As such, the diameter of the fibers 165, thickness of the patch 170, and/or fiber density within the patch 170 can be selected according to the requirements of the end application of the material. Patch 170 may be produced with various mechanical properties by varying the thickness and/or the fiber density, spatial patterning, polymer composition, and/or number of layers of the patch 170 by operating electrospinning system 100 for relatively longer or shorter durations, changing the polymeric solution, changing the chemical composition, changing collector 105, changing collector design, and/or changing the manner of fiber deposition.

[0048] Fig. 3 is an illustration 305 of a patch 170 including a plurality of electrospun fibers deposited on collector 105 and Fig. 4 is an illustration 405 of a patch 170 including a plurality of electrospun fibers deposited on collector 105. In the exemplary embodiment, collectors 105 respectively provide an increased deposition of fibers on and substantial near features 112. Such

additional support and/or reinforcement properties are achieved by creating high density fiber deposition areas on charged features 112 and having low density fiber deposition areas over feature spaces 119. It should be noted that collector 105 can include any pattern or combination of patterns such as the grid pattern shown in Fig. 3 and the hexagonal or honeycomb pattern shown in Fig. 4.

[0049] Referring to FIGS. 1-4, fibers 165 may be solid, core/shell, co-axial, or porous. In some embodiments, the size and/or structure of fibers 165 is determined by the design and/or size of spinneret 120, and/or polymer solution which includes viscosity, solvent or method of preparation of the solution, voltage or electric charge, distance between spinneret 120 and collector 105, and rate of deposition. FIG. 5 is an illustration of a solid fiber spinneret 120A. Solid fiber spinneret 120A includes a truncated conical body 180 defining a center line 182. At a dispensing end 184, body 180 includes an annulus 186. Annulus 186 defines a circular aperture 190A, through which polymer 140 may be dispensed. Fibers 165 produced with solid fiber spinneret 120A have a solid composition.

[0050] FIG. 6 is an illustration of a co-axial fiber spinneret 120B. Like solid fiber spinneret 120A, co-axial fiber spinneret 120B includes a truncated conical body 180 with an annulus 186 at a dispensing end 184. Co-axial fiber spinneret 120B also includes a central body 188B positioned within annulus 186. Annulus 186 and central body 188B define an annular aperture 190B. Accordingly, when polymer 140 is dispensed by co-axial fiber spinneret 120B, fibers 165 have a co-axial composition, with an exterior wall surrounding a cavity. The exterior wall of a fiber 165 dispensed by co-axial fiber spinneret 120B defines an outer diameter corresponding to the inner diameter of annulus 186 and an inner diameter corresponding to the diameter of central body 188B. Accordingly, the outer diameter and inner diameter of co-axial fibers 165 may be adjusted by adjusting the diameters of annulus 186 and central body 188B.

[0051] Fiber spinnerets 120A and 120B facilitate incorporating a substance, such as a biological agent, growth factor, and/or a drug (e.g., a chemotherapeutic substance), into patch 170. For example, the substance may be deposited within a cavity defined by co-axial fibers 165 of patch 170. In one embodiment, polymer 140 is selected to create porous and/or semi-soluble fibers 165, and the substance is dispensed from the cavity through fibers 165. In another embodiment, polymer 140 is degradable, and the substance is dispensed as fibers 165 degrade in vivo. For example, fibers 165 may be configured to degrade within a second to 1 second to 12 months. In one embodiment, a burst release of the substance occurs upon entry into a system and an elution occurs over a predetermined period of time. The degradation rate of polymer 140

may be manipulated by any loading and/or release method such as adjusting a ratio of constituent polymers within polymer 140, loading the agent into the bulk of the material, functionalizing the agent to the surface of the fibers, and/or releasing the agent by degradation of the polymer or by diffusion of the agent from the polymer. In another embodiment, a substance is delivered by solid fibers 165. For example, a solid fiber 165 may be created from a polymer 140 including the substance in solution. As solid fiber 165 degrades, the substance is released into the surrounding tissue.

[0052] As shown in FIGS. 5 and 6, annulus 186 is perpendicular to center line 182. In an alternative embodiment, annulus 186 is oblique (e.g., oriented at an acute or obtuse angle) with respect to center line 182. The outside diameter of fibers 165 may be determined by the inside diameter of annulus 186.

[0053] FIG. 7 is an illustration of a multi-layer biomedical patch 435. Patch 435 includes a biomedical patch layer with a plurality of symmetrical spatially organized fibers 420 and a biomedical patch layer with a plurality of spatially organized fibers having varying densities 425 such as increased density portions 430. As shown in FIG. 7, biomedical patch layers 420 and 425 are combined (e.g., fused, joined, adhered, overlaid) to produce multi-layer biomedical patch 435 with reinforcement fiber layers. It should be noted that any combination, number, or type of fiber layers may be combined to create biomedical patch 435. Combining the patches, especially layers 420 and 425, facilitates providing a biomedical patch that promotes cell migration to a center of the biomedical patch while exhibiting potentially greater durability (e.g., tensile strength) than a biomedical patch having only standard, randomly-organized fibers. It should be noted that patch 435 can be formed of layers having various densities and/or thicknesses (both individually and collectively), fiber organizations, polymer compositions, surface coatings, and types of concentrations of agents and/or drugs.

[0054] In some embodiments, multiple biomedical patch layers 410-425 may be combined to create a multi-layer biomedical patch. For example, referring to FIGS. 1-4, after depositing a first set of fibers on collector 105, one may wait for the first set of fibers 165 to solidify completely or cure and then deposit a second set of fibers 165 on collector 105. The second set of fibers 165 may be deposited directly over the first set of fibers 165 on collector 105. Alternatively, the first set of fibers 165 may be removed from collector 105, and the second set of fibers 165 may be deposited on conductive surface 162 and/or collector 105 and then removed and adhered/overlaid on the first set of fibers 165. Such embodiments facilitate increased structural or mechanical reinforcement of the patch in predetermined locations, and added spatial

control of cell migration/activity imparted by the layers 2-dimensionally and stacked layers 3-dimensionally. In some embodiments, a non nanofiber intermediate layer (e.g., hydrogel or polymeric scaffold) may be disposed between biomedical patch layers 400 and/or biomedical patch layers 410.

[0055] In the exemplary embodiment, individual layers are fused or coupled together such that the layers delaminate or separate under specific environmental or temporal conditions. Such controlled delamination results in maximization of mechanical stability of the nanofiber material and the biological interaction (e.g. cellular ingrowth, tissue integration, cellular exposure, etc.) between adjacent layers of nanofibers. In the exemplary embodiment, the process of fusing or coupling layers includes, but is not limited to, heating, applying mechanical stress/pressure, applying an adhesive, chemical processing, cross-linking, and functionalization.

[0056] In one embodiment, adjacent layers are similarly or variably fused, adhered, or joined such that each layer delaminates or separates at a substantially similar rate within patch 435. Alternatively, layers can be fused together with variable methods such that each layer delaminates at different rates. FIG. 8 illustrates delamination of patches 440, 445, and 450 with various fusion strengths over time. In the exemplary embodiment, a low strength adhesion 455, such as but not limited to mild-chemical treatment or crosslinking, low-pressure physical lamination, or low-temperature thermal processing, is used to fuse layers of patch 440 together. Similarly, a moderate strength adhesion 460 such as but not limited to moderate chemical crosslinking, prolonged thermal processing, moderate mechanical entanglement, application of moderate adhesives, or high-pressure physical lamination is used to fuse the layers of patch 445 and a high strength adhesion 465, such as but not limited to extensive chemical crosslinking, extensive high-temperature thermal processing, extensive mechanical entanglement, fiber interweaving or knitting, or application of aggressive adhesives is used to fuse layers of patch 450 together. In the exemplary embodiment, a separation 470 of patches 440, 445, and 450 is shown after a short increment of time, such as, but not limited to 1 day – 30 days and a separation 475 of patches 440, 445, and 450 is shown after a long increment of time, such as, but not limited to 30 days – 3 years. As is shown, patch 440 is substantially separated 470 after a short period of time acting as an accelerated separation, patch 445 is substantially separated 475 after the long period of time acting as a delayed separation, and patch 450 provided substantially no separation.

[0057] FIGS. 9 and 10 are histological cross-sections 500 and 502 of dura mater repaired with multi-laminar nanofiber material such as patch 440 shown in FIG. 8. Referring to FIG. 9,

patch 440 is shown as being inserted into dura 504 two weeks post-operatively. Regenerative dural tissue ("neodura") 504 is demonstrated extending on and around the implanted nanofiber material 440. Regenerative dural fibroblasts are also shown to have penetrated the bulk of the nanofiber material 440, demonstrating progressive cellularization of the implanted nanofiber construct. Two weeks following implantation of the multi-layer nanofiber material 440 no delamination is noted upon histological examination of the explanted tissue. The nanofiber material 440 is observed as a homogeneous block of material with low to moderate cellular ingrowth, yet no singular nanofiber layer or separation of nanofiber layers is observed. FIG. 10 illustrates controlled delamination of patch 440 six weeks post-operatively and integration of the patch within the native and/or regenerated dural tissue 504. Regenerative dural tissue ("neodura") 504 is demonstrated extending on and around the implanted nanofiber material 440. Additionally, regenerative dural tissue ("neodura") is demonstrated extending inbetween delaminated layers of the nanofiber material. Regenerative dural fibroblasts are shown to have significantly penetrated the bulk of the nanofiber material 440, demonstrating robust cellularization and integration of the implanted nanofiber construct. Delamination of individual layers of nanofibers within the implant construct is noted upon histological examination of the explanted tissue. The nanofiber material 440 is observed as two heterogeneous layers of material separated by a thin layer of regenerated dural tissue extending along the adjoining surface of the nanofiber monolayers. Evidence of controlled delamination of the implanted material post-operatively is specifically demonstrated by observation that multiple layers of the material remain fused in proximity of sutures utilized to secure the material to the native tissue.

[0058] FIGS. 11 and 12 are histological cross-sections 506 and 508 of regenerated dura repaired with multi-laminar nanofiber material such as patch 450 shown in FIG. 8. Referring to FIG. 11, patch 450 is shown as being inserted into dura 504 two weeks post-operatively. Regenerative dural tissue ("neodura") 504 is demonstrated extending on and around the implanted nanofiber material 450. Regenerative dural fibroblasts are also shown to have penetrated the bulk of the nanofiber material 450, demonstrating cellularization of the implanted nanofiber construct. No delamination is noted upon histological examination of the explanted tissue. The nanofiber material 450 is observed as a homogeneous block of material with low to moderate cellular ingrowth, yet no singular nanofiber layer or separation of nanofiber layers is observed. FIG. 12 illustrates that the high strength adhesion has enabled layers of patch 450 to remain substantially fused together six week post-operatively as dural tissue 504 regenerated around patch 450. Regenerative dural tissue ("neodura") 504 is again demonstrated extending on and around the implanted nanofiber material 450. Dural fibroblasts substantially penetrate the

bulk of the nanofiber material 450, demonstrating robust cellularization of the implanted nanofiber construct. Unlike nanofiber patch 440, no delamination of nanofiber patch 450 is noted upon histological examination of the explanted tissue following chronic implantation. The nanofiber material 450 is observed as a secure composite material demonstrating cellular ingrowth yet no separation or observation of singular nanofiber layers.

[0059] FIG. 13 illustrates separation of layers within patches 600, 602, and 604 at varying rates. Each patch 600, 602, and 604 includes a first layer 606, a second layer, 608, a third layer 610, and a fourth layer 612. It should be noted that while patches 600, 602, and 604 are shown with four layers, patches can be fabricated to have any number of layers. Referring to patch 600, low strength adhesion 455 is used to fuse layers 606, 608, and 610 together and high strength adhesion 465 is used to fuse layers 610 and 612 together. After a short time period, a separation 614 of layers 606, 608, and 610 has occurred and layers remain substantially fused together. As shown in patch 602, moderate strength adhesion 460 is used to fuse together layers 606 and 608, while high strength adhesion 465 is used to fuse together layers 608, 610, and 612. A separation 616 of layers 606 and 608 occurs after a long period of time while substantially no separation occurs between layers 608, 610, and 612. Referring to patch 604, a high strength adhesion 465 is used between layers 606, 608, 610, and 612 such that substantially no separation occurs between the layers.

[0060] A multi-layered biomedical patch may be useful for dural grafts as well as other tissue engineering applications. Sequential layers of fibers can be created with varying orders (e.g., radially aligned, reinforced, or randomly oriented), densities (e.g., low, high, or mixture of fiber density), patterns or reinforcement, and compositions (polymer), which may allow specific types of cells to infiltrate and populate select layers of the artificial biomedical patch. For example, biomedical patches containing a high fiber density generally prohibit cellular migration and infiltration, while biomedical patches containing a low fiber density generally enhance cellular migration and infiltration. Such additional support and/or reinforcement properties are achieved by creating high density fiber deposition that discourages cellular penetration and having low density fiber deposition areas that promote cellular penetration and/or ingrowth.

[0061] Overall, the ability to form multi-layered fiber materials, as described herein, may be extremely beneficial in the construction of biomedical patches designed to recapitulate the natural multi-laminar structure of not only dura mater, but also other biological tissues such as skin, heart valve leaflets, pericardium, and/or any other biological tissue. Furthermore, one or more layers of a biomedical patch may be fabricated from bioresorbable polymers such that the

resulting nanofiber materials fully resorb following implantation. Manipulation of the chemical composition of the polymers utilized to fabricate these scaffolds may further allow for specific control of the rate of degradation and/or resorption of a biomedical patch following implantation.

[0062] FIG. 14 is a flowchart of an exemplary method 700 for producing a structure of spatially organized fibers using system 100 shown in FIG. 1. While one embodiment of method 700 is shown in FIG. 14, it is contemplated that any of the operations illustrated may be omitted and that the operations may be performed in a different order than is shown. In the exemplary embodiment, method 700 includes electrically charging 705 collector 105 at a first amplitude and/or polarity (e.g., negatively charging or grounding). Spinneret 120 is electrically charged 710 at a second amplitude and/or polarity opposite the first amplitude and/or polarity (e.g., positively charged). A polymer (e.g., a liquid polymer) is dispensed 715 from spinneret 120. In the exemplary embodiment, dispensed 715 polymers are collected 720 on collector 105 to form a plurality of polymeric fibers on or substantially near features 112 that creates a structure or patch. After the dispensed 615 polymers are collected 720 and a structure is created, the structure may undergo post-processing 725. Such post-processing 725 can include, but is not limited to, lamination, layer stacking, coupling and/or fusing, chemically treating, and applying a biological agent, growth factor, and/or drug.

[0063] FIG. 15 is a flowchart of an exemplary method 750 for fusing or coupling together structures or patch layers produced by method 700 shown in FIG. 14. Method 750 includes providing 755 a first, second, and third patch layer. First patch layer is coupled 760 to second patch layer using a first coupling technique. The coupled 760 first and second layers are then coupled 765 to the third patch layer using a second coupling technique different than the first coupling technique. In the exemplary embodiment, coupling techniques, include but are not limited to, heating, applying mechanical stress/pressure, chemical processing, cross-linking, and functionalization. While method 750 illustrates a first patch layer coupled to a second patch layer, it should be noted that multiple layers (e.g., 3, 5, 6,) can be coupled together simultaneously. Additionally, the process may be repeated to add layers to structures produced by method 750.

[0064] FIG. 16 is a flowchart of an exemplary method 800 for repairing a defect of a substrate using a structure produced by methods 700 and 750 shown in FIGS. 14 and 15. In one embodiment, method 800 includes providing 805 a substrate substance with a defect. The defect may include a void, tissue defect, injury, insult, and/or any other condition resulting in diminished function of biological tissue. In the exemplary embodiment, the substrate is

biological tissue. Alternatively, the substrate can be any substrate including but not limited to, filtration media, textiles, membrane media, and coatings. In one embodiment, the defect provided 805 includes a void created by surgical incision to provide access to an underlying tissue (e.g., a tumor). In another embodiment, a void is created 805 by excising necrotic tissue (e.g., skin cells). In the exemplary embodiment, one or more patches capable of covering the defect are selected 810. For example, a plurality of biomedical patches may be selected 810 for a large and/or complex (e.g., irregularly shaped) defect. In the exemplary embodiment, a biomedical patch having a diameter greater than the diameter of an approximately circular defect is selected 810. Alternatively, a patch is selected 810 and customized, pre-operation or intra-operation, to fit the defect. It should be noted that any size, shape, and/or geometry of structure may be used in the selection 810 of the patch.

[0065] In one embodiment, a substance such as a growth factor and/or a drug (e.g., a chemotherapeutic drug) is applied 815 to the biomedical patch. In the exemplary embodiment growth factor and/or a drug is applied 815 pre-operatively. However, it should be noted that growth factor and/or a drug may be applied 815 at any time including, but not limited to, intra-operatively and post-operatively. In one embodiment, the biomedical patch may be immersed in the substance to allow the substance to occupy a cavity within co-axial fibers of the biomedical patch, dope the polymer comprising the fibers in the biomedical patch, or coat the surface of the fibers within the biomedical patch.

[0066] In the exemplary embodiment, the patch is applied 820 to (e.g., overlaid on) the biological tissue to cover, repair, reinforce, and/or fill at least a portion of the defect. For example, the biomedical patch may be applied 820 to dura mater tissue, cardiac tissue, and/or any biological tissue including a defect. In one embodiment, the perimeter of the biomedical patch extends past the perimeter of the defect, such that the entire defect is covered by the biomedical patch. In some embodiments, the biomedical patch is coupled 825 to the biological tissue with a plurality of sutures, adhesive, and/or any other means of attaching the biomedical patch to the biological tissue (inlay). In an alternative embodiment, the biomedical patch is simply allowed to fuse to the biological tissue, such as by adhesion of biological cells to the biomedical patch (onlay). In another embodiment, biomedical patch may be directly coupled to the edge of the tissue with no overlap. In one embodiment, biomedical patch may be overlaid on top of a wound/defect or injury covering the entirety of the defect or injury without filling the defect.

[0067] In one embodiment, after the biomedical patch is applied 820 and optionally coupled 825 to the biological tissue, the biological tissue is covered 830. Alternatively, the patch may be the terminal covering. In such an embodiment, a backing that is either non-permeable or permeable may be coupled to the patch. In one embodiment, other tissue overlaying the defect (e.g., dermis and/or epidermis) is repaired (e.g., sutured closed). In another embodiment, one or more protective layers are applied over the biological tissue. For example, a bandage may be applied to a skin graft, with or without a protective substance, such as a gel, an ointment, and/or an antibacterial agent. In one embodiment, the protective layer includes, but is not limited to, a covering, film tissue, dressing, mesh, and nanofiber structure, such as an additional biomedical patch, as described herein.

[0068] Embodiments described herein are operable with any surgical procedure involving the repair, replacement, or expansion of the dura mater, including, but not limited to, a transphenoidal procedure (e.g., surgical removal of pituitary adenomas), various types of skull base surgeries, and/or surgical removal of cranial or spinal tumors (e.g., meningiomas and/or astrocytomas). In one embodiment, a biomedical patch may be applied to a bone fracture (e.g., a complex fracture). In another embodiment, a biomedical patch may be applied to a defect in the skin (e.g. a burn).

[0069] Moreover, such embodiments provide a dura mater substitute, a biomedical patch for a skin graft (e.g., dermal or epidermal), a biomedical patch for tracheal repair, a scaffold for an artificial heart valve leaflet, an artificial mesh for surgical repair of a gastrointestinal tract (e.g., an abdominal hernia or an ulcer), an artificial mesh for surgical repair of cardiac defects. Embodiments described herein facilitate providing a cardiac patch of sufficient flexibility to enable movement of the biomedical patch by a biological tissue (e.g., cardiomyocytes or cardiac tissue, muscle, skin, connective tissue, intestinal tissue, stomach tissue, bone, gastrointestinal tract, and mucosa).

[0070] In some embodiments, a biomedical patch has a thickness greater or less than a thickness of the biological tissue being repaired. Biomedical patches with spatially organized polymeric fibers facilitate reducing the expense of tissue repair, improving tissue healing time, and reducing or eliminating the risk of zoonotic infection. Moreover, such biomedical patches are relatively simple to manufacture, enabling customization of shape, size, and chemical composition and improved availability and non-immunogenicity. In addition, biomedical patches with spatially organized polymeric fibers exhibit excellent handling properties due to their cloth-like composition, eliminate the need for a second surgery to harvest autologous graft tissue, and reduce the risk of contracture and adhesion when compared with known products.

Additionally, the patches described herein facilitate reinforcement, buttressing, lamination, and/or sealing in a variety of applications such as but not limited to clinical and non-clinical applications.

[0071] Although the foregoing description contains many specifics, these should not be construed as limiting the scope of the present disclosure, but merely as providing illustrations of some of the presently preferred embodiments. Similarly, other embodiments of the invention may be devised which do not depart from the spirit or scope of the present invention. For example, while the illustrative examples have been used in with clinical applications, the above described nanofiber structures can have non-clinical application such as filtration, textiles, membrane technology, and coatings. Features from different embodiments may be employed in combination. The scope of the invention is, therefore, indicated and limited only by the appended claims and their legal equivalents, rather than by the foregoing description. All additions, deletions, and modifications to the invention as disclosed herein which fall within the meaning and scope of the claims are to be embraced thereby.

[0072] As used herein, an element or step recited in the singular and proceeded with the word "a" or "an" should be understood as not excluding plural elements or steps, unless such exclusion is explicitly recited. Furthermore, references to "one embodiment" of the present invention are not intended to be interpreted as excluding the existence of additional embodiments that also incorporate the recited features.

[0073] This written description uses examples to disclose various embodiments, which include the best mode, to enable any person skilled in the art to practice those embodiments, including making and using any devices or systems and performing any incorporated methods. The patentable scope is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal languages of the claims.

WHAT IS CLAIMED IS:

1. A method for producing a structure including a plurality of fibers, the method comprising:

providing a collector with a predefined pattern, the collector including at least one of a plurality of ribs and a plurality of seams that are interconnected to form the predefined pattern, the collector further including at least one surface which is a filling of a void formed between the at least one of the plurality of ribs and the plurality of seams;

charging the collector with a first polarity;

providing a spinneret, the spinneret configured to dispense a polymer on the provided collector;

charging the spinneret to a second polarity opposite the first; and

dispensing the polymer on the collector via a focusing device, such that the polymer forms a plurality of fibers defining the structure, wherein the structure has at least two densities formed by the plurality of fibers.

2. A method in accordance with claim 1, further comprising applying at least one of a growth factor and a drug to the plurality of fibers.

3. A method in accordance with claim 1, further comprising chemically treating the plurality of fibers.

4. A method in accordance with claim 1, wherein providing the collector further comprises providing the collector including a plurality of features that are interconnected to form the predefined pattern.

5. A method in accordance with claim 4, wherein providing the collector further comprise providing the collector including at least one surface positioned within the interconnected features.