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(54) Title: BIOABSORBABLE BIOMEDICAL IMPLANTS

(57) Abstract: A bioabsorbable biomedical implant is disclosed. The implant includes a tubular scaffold comprising a plurality of interconnected polymer struts. The interconnected polymer struts defines a plurality of deformable cells. The polymer struts have an average thickness of no more than 150 µm. Methods for making the bioabsorbable biomedical implant, including the methods for making the fiber-reinforced polymer composite materials for the tubular scaffold, are also disclosed.

**BIOABSORBABLE BIOMEDICAL IMPLANTS****CROSS-REFERENCE PARAGRAPH**

[0001] This application claims the benefit of U.S. Provisional Application No. 61/823,755, filed May 15, 2013, the content of which is hereby incorporated by reference in its entirety.

**BACKGROUND**

[0002] The present disclosure relates to bioabsorbable stents made of polymeric composite materials and method of manufacturing the bioabsorbable stents.

**SUMMARY OF THE DISCLOSURE**

[0003] According to one aspect of the present disclosure, a biomedical implant is disclosed as including a tubular scaffold comprising a plurality of interconnected polymer struts. The interconnected polymer struts defines a plurality of deformable cells. The polymer struts have an average thickness of no more than 150  $\mu\text{m}$ . Also provided is a biomedical implant, comprising: a tubular scaffold comprising a plurality of polymer struts, wherein the polymer struts are interconnected and define a plurality of deformable cells, wherein the polymer struts have an average thickness of no more than 150  $\mu\text{m}$ , and wherein the polymer struts comprise a fiber-reinforced polymer composite material. In some embodiments, the tubular scaffold maintains at least 50% of its nominal luminal cross sectional area under a pressure load of 50mmHg. In another embodiment, the tubular scaffold maintains at least 80% of its nominal luminal cross sectional area under a pressure load of 50mmHg. In some embodiments, the tubular scaffold maintains at least 50% of its nominal luminal cross sectional area under a pressure load of 50mmHg upon 3 months of exposure to saline *in vitro*. In another embodiment, the tubular scaffold maintains at least 50% of its deployed luminal cross sectional area under a pressure load of 50mmHg upon 3 months *in vivo*. In some embodiments, the tubular scaffold maintains at least 50% of its nominal luminal cross sectional area under a pressure load of 50mmHg upon 6 months of exposure to saline *in vitro*. In another embodiment, the tubular scaffold maintains at least 50% of its nominal luminal cross sectional area under a pressure load of 50mmHg upon 6 months *in vivo*. In some embodiments, at least 80% of the polymer struts are bioabsorbed within 2 years after deployment *in vivo*. In another embodiment, at least 80% of the polymer struts are bioabsorbed within 1 year after deployment *in vivo*. In some embodiments, the polymer struts have an average thickness of no more than 120  $\mu\text{m}$ . In another embodiment, the polymer struts have an average thickness of no more than 90  $\mu\text{m}$ . In some embodiments, the polymer struts have anisotropic elastic modulus. In a refinement, the polymer struts have an average longitudinal (i.e. along the axis of the polymer struts) elastic modulus and an average

lateral elastic modulus, the average longitudinal elastic modulus being greater than the average lateral elastic modulus. In a further refinement, the average longitudinal elastic modulus is at least three times the average lateral elastic modulus. In another further refinement, the average longitudinal elastic modulus is at least five times the average lateral elastic modulus. In yet another further refinement, the average longitudinal elastic modulus is at least ten times the average lateral elastic modulus. In some embodiments, the polymer struts include reinforcement fibers that are longitudinally (i.e. along the axis of the polymer struts) aligned. In some embodiments, more than 50% of the reinforcement fibers in the polymer struts are longitudinally aligned. In another embodiment, more than 70% of the reinforcement fibers in the polymer struts are longitudinally aligned. In another embodiment, more than 90% of the reinforcement fibers in the polymer struts are longitudinally aligned. In some embodiments, the polymer struts have an average deformation angle of at least 60 degrees. In another embodiment, the polymer struts have an average deformation angle of at least 45 degrees. In some embodiments, the polymer struts comprises a fiber-reinforced polymer composite material. In some embodiments, the fiber-reinforced polymer composite material comprises a bioabsorbable polymer material and a reinforcement fiber material. In some embodiments, the reinforcement fiber material is carbon fiber material, carbon nanotube material, bioabsorbable glass material, or combinations thereof. In some embodiments, the carbon nanotube material is a multi-wall carbon nanotube material. In some embodiments, the reinforcement fiber material comprises one or more surface functionalities to facilitate intermolecular interaction between the bioabsorbable polymer material and the reinforcement fiber material. In some embodiments, the one or more surface functionalities are selected from -COOH, -OH, or combination thereof. In some embodiments, the reinforcement fiber material comprising one or more surface functionalities is multi-wall carbon nanotube material. In some embodiments, the reinforcement fiber material is distributed throughout the polymer struts. In some embodiments, the fiber-reinforced polymer composite material has a tensile modulus that is at least five times of a tensile modulus of the bioabsorbable polymer. In some embodiments, the fiber-reinforced polymer composite material has a tensile modulus that is at least three times of a tensile modulus of the bioabsorbable polymer. In some embodiments, the fiber-reinforced polymer composite material has a tensile modulus that is at least two times of a tensile modulus of the bioabsorbable polymer. In some embodiments, the fiber-reinforced polymer composite material has a tensile strength that is at least five times of a tensile strength of the bioabsorbable polymer. In some embodiments, the fiber-reinforced polymer composite material has a tensile strength that is at least three times of a tensile strength of the bioabsorbable polymer. In some embodiments, the fiber-reinforced polymer composite material has a tensile strength that is at least two times of a tensile strength of the bioabsorbable polymer. In some embodiments, the fiber-reinforced polymer composite material comprises from 0.1 wt% to 15 wt% of the reinforcement fiber material. In some embodiments, the fiber-reinforced polymer composite material comprises from 0.1 wt% to 10 wt% of the reinforcement fiber material. In some embodiments, the fiber-reinforced polymer composite material comprises from 0.1 wt% to 5 wt% of the reinforcement fiber material. In some embodiments, the fiber-reinforced polymer composite material comprises from 0.1 wt% to 1.5 wt% of the

reinforcement fiber material. In some embodiments, the bioabsorbable polymer material is selected from the group consisting of polylactides (PLA); poly(lactide-co-glycolide) (PLGA); polyanhydrides; polyorthoesters; poly(N-(2-hydroxypropyl) methacrylamide); poly(dl-lactide) (DLPLA); poly(l-lactide) (LPLA); poly(d-lactide) (DPLA); polyglycolide (PGA); poly(dioxanone) (PDO); poly(glycolide-co-trimethylene carbonate) (PGA-TMC); poly(l-lactide-co-glycolide) (PGA-LPLA); poly(dl-lactide-co-glycolide) (PGA-DLPLA); poly(l-lactide-co-dl-lactide) (LPLA-DLPLA); poly(glycolide-co-trimethylene carbonate-co-dioxanone) (PDO-PGA-TMC), poly(lactic acid-co-caprolactone) (PLACL), and mixtures or co-polymers thereof. In one refinement, the bioabsorbable polymer material is PLGA. In a further refinement, the PLGA has a ratio of lactic acid monomer to glycolic acid monomer ranging from 72:28 to 78:22. In another further refinement, the PLGA has a ratio of lactic acid monomer to glycolic acid monomer ranging from 62:38 to 68:32. In another further refinement, the PLGA has a ratio of lactic acid monomer to glycolic acid monomer ranging from 47:53 to 53:47. In another further refinement, the PLGA has a weight average molecular weight of about 8,000 Dalton to about 12,000 Dalton. In another further refinement, the PLGA has a weight average molecular weight of about 12,000 Dalton to about 16,000 Dalton. In another further refinement, the PLGA has a weight average molecular weight of up to about 90,000 Dalton. In another refinement, the bioabsorbable polymer material is PLA or LPLA. In another refinement, the bioabsorbable polymer material is PGA. In some embodiment, the bioabsorbable polymer material (e.g. PLGA, LPLA, PLA, PGA) has a weight average molecular weight of at least 90,000 Dalton, and optionally at least 100,000 Dalton. In some embodiments, the polymer struts include a polymer material selected from the group consisting of polycarboxylic acids, cellulosic polymers, proteins, polypeptides, polyvinylpyrrolidone, maleic anhydride polymers, polyamides, polyvinyl alcohols, polyethylene oxides, glycosaminoglycans, polysaccharides, polyesters, aliphatic polyesters, polyurethanes, polystyrenes, copolymers, silicones, silicone containing polymers, polyalkyl siloxanes, polyorthoesters, polyanhydrides, copolymers of vinyl monomers, polycarbonates, polyethylenes, polypropylenes, polylactic acids, polylactides, polyglycolic acids, polyglycolides, polylactide-co-glycolides, polycaprolactones, poly( $\epsilon$ -caprolactone)s, polyhydroxybutyrate valerates, polyacrylamides, polyethers, polyurethane dispersions, polyacrylates, acrylic latex dispersions, polyacrylic acid, polyalkyl methacrylates, polyalkylene-co-vinyl acetates, polyalkylenes, aliphatic polycarbonates, polyhydroxyalkanoates, polytetrahaloalkylenes, poly(phosphonates), polytetrahaloalkylenes, poly(phosphonates), and mixtures, combinations, and copolymers thereof. In some embodiments, the tubular scaffold is expandable from an undeployed diameter to a nominal diameter without affecting the structural integrity of the tubular scaffold. In a refinement, the tubular scaffold is further expandable from the nominal diameter to an over-deployed diameter without affecting the structural integrity of the tubular scaffold. In a further refinement, the over-deployed diameter is about 1.0 mm greater than the nominal diameter. In another further refinement, the over-deployed diameter is about 0.5 mm greater than the nominal diameter. In one refinement, the tubular scaffold is expandable by an inflatable balloon positioned within the tubular scaffold. In a further refinement, the tubular scaffold has a nominal diameter of 2.25 mm at nominal balloon pressure. In another further refinement, the tubular scaffold has

a nominal diameter of 2.5 mm at nominal balloon pressure. In another further refinement, the tubular scaffold has a nominal diameter of 3.0 mm at nominal balloon pressure. In another further refinement, the tubular scaffold has a nominal diameter of 3.5 mm at nominal balloon pressure. In another further refinement, the tubular scaffold has a nominal diameter of 4.0 mm at nominal balloon pressure. In another further refinement, the tubular scaffold has a nominal diameter of 4.5 mm at nominal balloon pressure. In one refinement, the polymer struts comprise a shape-memory polymer and wherein tubular scaffold is self-expandable. In a further refinement, the tubular scaffold is self-expandable upon change in temperature. In another further refinement, the tubular scaffold is self-expandable upon change in crystallinity of the shape-memory polymer. In some embodiments, the tubular scaffold is formed from a plurality of sinusoidal polymer fibers each including a plurality of struts. In a refinement, the sinusoidal polymer fibers are interconnected at a plurality of connecting points. In some embodiments, the tubular scaffold is formed from a single polymer fiber including a plurality of struts. In a refinement, the single polymer fiber comprises a plurality of sinusoidal sections interconnected at a plurality of connecting points. In some embodiments, the biomedical implant further includes a pharmaceutical agent incorporated to the tubular scaffold. In a refinement, the pharmaceutical agent is a macrolide immunosuppressant. In a further refinement, the macrolide immunosuppressant is rapamycin or a derivative, a prodrug, a hydrate, an ester, a salt, a polymorph, a derivative or an analog thereof. In another further refinement, the macrolide immunosuppressant is selected from the group consisting of rapamycin, 40-O-(2-Hydroxyethyl)rapamycin, (everolimus), 40-O-Benzyl-rapamycin, 40-O-(4'-Hydroxymethyl)benzyl-rapamycin, 40-O-[4'-(1,2-Dihydroxyethyl)]benzyl-rapamycin, 40-O-Allyl-rapamycin, 40-O-[3'-(2,2-Dimethyl-1,3-dioxolan-4(S)-yl)-prop-2'-en-1'-yl]-rapamycin, (2':E,4'S)-40-O-(4',5'-Dihydroxypent-2'-en-1'-yl)-rapamycin, 40-O-(2-Hydroxy)ethoxycarbonylmethyl-rapamycin, 40-O-(3-Hydroxy)propyl-rapamycin, 40-O-(6-Hydroxy)hexyl-rapamycin, 40-O-[2-(2-Hydroxy)ethoxy]ethyl-rapamycin, 40-O-[(3S)-2,2-Dimethyldioxolan-3-yl]methyl-rapamycin, 40-O-[(2S)-2,3-Dihydroxyprop-1-yl]-rapamycin, 40-O-(2-Acetoxy)ethyl-rapamycin, 40-O-(2-Nicotinoyloxy)ethyl-rapamycin, 40-O-[2-(N-Morpholino)acetoxy]ethyl-rapamycin, 40-O-(2-N-Imidazolylacetoxy)ethyl-rapamycin, 40-O-[2-(N-Methyl-N'-piperazinyl)acetoxy]ethyl-rapamycin, 39-O-Desmethyl-39,40-O,O-ethylene-rapamycin, (26R)-26-Dihydro-40-O-(2-hydroxy)ethyl-rapamycin, 28-O-Methyl-rapamycin, 40-O-(2-Aminoethyl)-rapamycin, 40-O-(2-Acetaminoethyl)-rapamycin, 40-O-(2-Nicotinamidoethyl)-rapamycin, 40-O-(2-(N-Methyl-imidazo-2'-yl)carbethoxamido)ethyl-rapamycin, 40-O-(2-Ethoxycarbonylaminoethyl)-rapamycin, 40-O-(2-Tolylsulfonamidoethyl)-rapamycin, 40-O-[2-(4',5'-Dicarboethoxy-1',2',3'-triazol-1'-yl)-ethyl]-rapamycin, 42-Epi-(tetrazolyl)rapamycin (tacrolimus), and 42-[3-hydroxy-2-(hydroxymethyl)-2-methylpropanoate] rapamycin. In one refinement, the pharmaceutical agent is rapamycin. In one refinement, the pharmaceutical agent is impregnated in at least a portion of the tubular scaffold. In a further refinement, the pharmaceutical agent is impregnated in the polymer struts. In a further refinement, the pharmaceutical agent is evenly distributed throughout the polymer struts. In one refinement, at least a portion of the tubular scaffold is covered with a coating comprising the pharmaceutical agent. In a further refinement, the coating further comprises a coating

polymer. In a further refinement, at least 90% of the surface area of the pharmaceutical agent is encapsulated in the coating polymer. In a further refinement, the coating polymer comprises a bioabsorbable polymer. In a further refinement, the bioabsorbable polymer is selected from the group consisting of polylactides (PLA); poly(lactide-co-glycolide) (PLGA); polyanhydrides; polyorthoesters; poly(N-(2-hydroxypropyl) methacrylamide); poly(dl-lactide) (DLPLA); poly(l-lactide) (LPLA); polyglycolide (PGA); poly(dioxanone) (PDO); poly(glycolide-co-trimethylene carbonate) (PGA-TMC); poly(l-lactide-co-glycolide) (PGA-LPLA); poly(dl-lactide-co-glycolide) (PGA-DLPLA); poly(l-lactide-co-dl-lactide) (LPLA-DLPLA); poly(glycolide-co-trimethylene carbonate-co-dioxanone) (PDO-PGA-TMC), polyarginine, and mixtures or co-polymers thereof. In a further refinement, the biodegradable polymer is selected from the group consisting of PLGA, polyarginine, and mixtures thereof. In some embodiments, the biomedical implant is a vascular stent. In another embodiment, the biomedical implant is a coronary artery stent. In another embodiment, the biomedical implant is a peripheral artery stent. In another embodiment, the biomedical implant is a non-vascular stent. In a refinement, the non-vascular stent is selected from esophageal stent, biliary stent, duodenal stent, colonic stent, and pancreatic stent. According to another aspect of the present disclosure, a method of forming a biomedical implant is disclosed. The method includes the steps of forming one or more polymer fibers comprising a bioabsorbable polyester material and a reinforcement fiber material; and interconnecting the polymer fibers to form a tubular scaffold, the tubular scaffold comprising a plurality of interconnected polymer struts to define a plurality of deformable cells, wherein the polymer struts have an average thickness of no more than 150  $\mu\text{m}$ . In some embodiments, the tubular scaffold maintains at least 50% of its nominal luminal cross sectional area under a pressure load of at least 50mmHg. In some embodiments, the tubular scaffold maintains at least 80% of its nominal luminal cross sectional area under a pressure load of at least 50mmHg. In some embodiments, the reinforcement fiber material is carbon fiber material, carbon nanotube material, bioabsorbable glass material, or combinations thereof. In some embodiments, the carbon nanotube material is a multi-wall carbon nanotube material. In some embodiments, the reinforcement fiber material comprises one or more surface functionalities to facilitate intermolecular interaction between the bioabsorbable polymer material and the reinforcement fiber material. In some embodiments, the one or more surface functionalities are selected from -COOH, -OH, or combination thereof. In some embodiments, the reinforcement fiber material comprising one or more surface functionalities is multi-wall carbon nanotube material. In some embodiments, the polymer fibers comprise from 0.1 wt% to 15 wt% of the reinforcement fiber material. In some embodiments, the polymer fibers comprise from 0.1 wt% to 10 wt% of the reinforcement fiber material. In some embodiments, the polymer fibers comprise from 0.1 wt% to 5 wt% of the reinforcement fiber material. In some embodiments, the polymer fibers comprise from 0.1 wt% to 1.5 wt% of the reinforcement fiber material.

**[0004]** In some embodiments, the polyester is selected from the group consisting of polylactides (PLA); poly(lactide-co-glycolide) (PLGA); polyanhydrides; polyorthoesters; poly(N-(2-hydroxypropyl) methacrylamide); poly(dl-lactide) (DLPLA); poly(l-lactide) (LPLA); poly(d-lactide) (DPLA);

polyglycolide (PGA); poly(dioxanone) (PDO); poly(glycolide-co-trimethylene carbonate) (PGA-TMC); poly(l-lactide-co-glycolide) (PGA-LPLA); poly(dl-lactide-co-glycolide) (PGA-DLPLA); poly(l-lactide-co-dl-lactide) (LPLA-DLPLA); poly(glycolide-co-trimethylene carbonate-co-dioxanone) (PDO-PGA-TMC), poly(lactic acid-co-caprolactone) (PLACL), and mixtures or co-polymers thereof. In some embodiments, the polyester is PLGA. In some embodiments, the polyester is PLA or LPLA. According to another aspect of the present disclosure, another method of making a bioabsorbable tubular scaffold is disclosed. The method includes the steps of forming a composition comprising a bioabsorbable polyester material and a reinforcement fiber material; extruding the composition to form a polymer tube, wherein the polymer tube has an average wall thickness of no more than 150  $\mu\text{m}$ ; and removing a portion of the polymer tube to form a scaffold comprising interconnected struts. In some embodiments, the tubular scaffold maintains at least 50% of its nominal luminal cross sectional area under a pressure load of at least 50mmHg. In some embodiments, the tubular scaffold maintains at least 80% of its nominal luminal cross sectional area under a pressure load of at least 50mmHg. In some embodiments, the reinforcement fiber material is carbon fiber material, carbon nanotube material, bioabsorbable glass material, or combinations thereof. In some embodiments, the carbon nanotube material is a multi-wall carbon nanotube material. In some embodiments, the reinforcement fiber material comprises one or more surface functionalities to facilitate intermolecular interaction between the bioabsorbable polymer material and the reinforcement fiber material. In some embodiments, the one or more surface functionalities are selected from -COOH, -OH, or combination thereof. In some embodiments, the reinforcement fiber material comprising one or more surface functionalities is multi-wall carbon nanotube material. In some embodiments, the polymer tube comprises from 0.1 wt% to 15 wt% of the reinforcement fiber material. In some embodiments, the polymer tube comprises from 0.1 wt% to 10 wt% of the reinforcement fiber material. In some embodiments, the polymer tube comprises from 0.1 wt% to 5 wt% of the reinforcement fiber material. In some embodiments, the polymer tube comprises from 0.1 wt% to 1.5 wt% of the reinforcement fiber material. In some embodiments, the polyester is selected from the group consisting of polylactides (PLA); poly(lactide-co-glycolide) (PLGA); polyanhydrides; polyorthoesters; poly(N-(2-hydroxypropyl) methacrylamide); poly(dl-lactide) (DLPLA); poly(l-lactide) (LPLA); poly(d-lactide) (DPLA); polyglycolide (PGA); poly(dioxanone) (PDO); poly(glycolide-co-trimethylene carbonate) (PGA-TMC); poly(l-lactide-co-glycolide) (PGA-LPLA); poly(dl-lactide-co-glycolide) (PGA-DLPLA); poly(l-lactide-co-dl-lactide) (LPLA-DLPLA); poly(glycolide-co-trimethylene carbonate-co-dioxanone) (PDO-PGA-TMC), poly(lactic acid-co-caprolactone) (PLACL), and mixtures or co-polymers thereof. In some embodiments, the polyester is PLGA. In some embodiments, the polyester is PLA or LPLA. In some embodiments, the removing is selected from laser-cutting, photochemical etching, and water-jetting.

**INCORPORATION BY REFERENCE**

[0005] All publications and patent applications mentioned in this specification are herein incorporated by reference to the same extent as if each individual publication or patent application was specifically and individually indicated to be incorporated by reference.

**DETAILED DESCRIPTION OF THE DISCLOSURE**

[0006] The present disclosure is explained in greater detail below. This description is not intended to be a detailed catalog of all the different ways in which the present disclosure may be implemented, or all the features that may be added to the present disclosure. For example, features illustrated with respect to one embodiment may be incorporated into other embodiments, and features illustrated with respect to a particular embodiment may be deleted from that embodiment. In addition, numerous variations and additions to the various embodiments suggested herein will be apparent to those skilled in the art in light of the instant disclosure, which do not depart from the present disclosure. Hence, the following specification is intended to illustrate some particular embodiments of the present disclosure, and not to exhaustively specify all permutations, combinations and variations thereof.

**Bioabsorbable Biomedical Implant**

[0007] Bioabsorbable biomedical implants, such as stents made of polymers without metal structural reinforcements, provide several desirable features over metal-based biomedical implants. Yet, the development of bioabsorbable polymer stents remains challenging to this date. As bioabsorbable polymer materials used to make the polymer stents are generally weaker than metals (e.g. steel), polymer stents with structural strength and integrity similar to metal stents need to be made of polymer struts with average thickness much greater than that of the metal struts (e.g. greater or significantly greater than 150  $\mu\text{m}$ ).

[0008] It is contemplated in the present disclosure that the increased strut thickness, while improving the structural strength and integrity of the stents, may adversely affect one or more desirable characteristics of the polymer stent. For example, the thicker struts may result in a stent with larger overall stent profile and less flexibility, and hence more difficult to navigate within blood vessels before deployment. The thicker struts may also lead to lower deformability that limits range of deployment (e.g. less than 10% overexpansion above nominal diameter, or less than about 0.5 mm in a vascular stent). In addition, the thicker struts may take longer to be fully dissolved or degraded, such as between three to five years.

[0009] According to one aspect of the present disclosure, a biomedical implant is disclosed as including a tubular scaffold comprising a plurality of interconnected polymer struts. The interconnected polymer struts defines a plurality of deformable cells. The polymer struts have an average thickness of no more than 150  $\mu\text{m}$ .

**[0010] Average Strut Thickness**

[0011] In some embodiments, the polymer struts have an average thickness of no more than 150  $\mu\text{m}$ . In another embodiment, the polymer struts have an average thickness of no more than 140  $\mu\text{m}$ . In another

embodiment, the polymer struts have an average thickness of no more than 130  $\mu\text{m}$ . In another embodiment, the polymer struts have an average thickness of no more than 120  $\mu\text{m}$ . In another embodiment, the polymer struts have an average thickness of no more than 110  $\mu\text{m}$ . In another embodiment, the polymer struts have an average thickness of no more than 100  $\mu\text{m}$ . In another embodiment, the polymer struts have an average thickness of no more than 90  $\mu\text{m}$ . In another embodiment, the polymer struts have an average thickness of no more than 80  $\mu\text{m}$ . In another embodiment, the polymer struts have an average thickness of no more than 70  $\mu\text{m}$ . In another embodiment, the polymer struts have an average thickness of no more than 60  $\mu\text{m}$ . In another embodiment, the polymer struts have an average thickness of no more than 50  $\mu\text{m}$ .

**[0012]** In some embodiments, the polymer struts have an average thickness of from 50  $\mu\text{m}$  to about 150  $\mu\text{m}$ . In some embodiments, the polymer struts have an average thickness of from 60  $\mu\text{m}$  to about 150  $\mu\text{m}$ . In some embodiments, the polymer struts have an average thickness of from 70  $\mu\text{m}$  to about 150  $\mu\text{m}$ . In some embodiments, the polymer struts have an average thickness of from 80  $\mu\text{m}$  to about 150  $\mu\text{m}$ . In some embodiments, the polymer struts have an average thickness of from 90  $\mu\text{m}$  to about 150  $\mu\text{m}$ . In some embodiments, the polymer struts have an average thickness of from 100  $\mu\text{m}$  to about 150  $\mu\text{m}$ . In some embodiments, the polymer struts have an average thickness of from 110  $\mu\text{m}$  to about 150  $\mu\text{m}$ . In some embodiments, the polymer struts have an average thickness of from 120  $\mu\text{m}$  to about 150  $\mu\text{m}$ .

**[0013]** In some embodiments, the polymer struts have an average thickness of from 50  $\mu\text{m}$  to about 120  $\mu\text{m}$ . In some embodiments, the polymer struts have an average thickness of from 60  $\mu\text{m}$  to about 120  $\mu\text{m}$ . In some embodiments, the polymer struts have an average thickness of from 70  $\mu\text{m}$  to about 120  $\mu\text{m}$ . In some embodiments, the polymer struts have an average thickness of from 80  $\mu\text{m}$  to about 120  $\mu\text{m}$ . In some embodiments, the polymer struts have an average thickness of from 90  $\mu\text{m}$  to about 120  $\mu\text{m}$ .

**[0014]** In some embodiments, the polymer struts have an average thickness of from 50  $\mu\text{m}$  to about 100  $\mu\text{m}$ . In some embodiments, the polymer struts have an average thickness of from 60  $\mu\text{m}$  to about 100  $\mu\text{m}$ . In some embodiments, the polymer struts have an average thickness of from 70  $\mu\text{m}$  to about 100  $\mu\text{m}$ . In some embodiments, the polymer struts have an average thickness of from 80  $\mu\text{m}$  to about 100  $\mu\text{m}$ . In some embodiments, the polymer struts have an average thickness of from 90  $\mu\text{m}$  to about 100  $\mu\text{m}$ .

**[0015]** In some embodiments, the polymer struts have an average thickness of from 50  $\mu\text{m}$  to about 90  $\mu\text{m}$ . In some embodiments, the polymer struts have an average thickness of from 60  $\mu\text{m}$  to about 90  $\mu\text{m}$ . In some embodiments, the polymer struts have an average thickness of from 70  $\mu\text{m}$  to about 90  $\mu\text{m}$ . In some embodiments, the polymer struts have an average thickness of from 80  $\mu\text{m}$  to about 90  $\mu\text{m}$ .

**[0016] Structural Strength and Integrity**

**[0017]** The structural strength and integrity of the disclosed bioabsorbable biomedical implants can be characterized by one or combinations of the following methods.

**[0018] Radial Strength Testing**

[0019] This test is conducted to determine and graphically represent the change in stent internal diameter as a function of circumferential pressure and to determine the pressure at which deformation is no longer completely reversible for the disclosed stent. The stents are deployed to nominal pressure and removed from the delivery system. The stents are placed into a sleeve approximately 1mm larger than the stent diameter. A vacuum is then applied and outer diameter measurements taken at various pressures. The bioabsorbable implants according to the present disclosure should maintain a minimum of at least 50 percent of the original stent diameter after a 50 mm Hg pressure is applied. Some bioabsorbable implants according to the present disclosure should maintain a minimum of at least 80 percent of the original stent diameter after a 50 mm Hg pressure is applied.

[0020] Stent Recoil Testing

[0021] This test was conducted to quantify the amount of elastic recoil. The stent delivery system is inflated to nominal pressure (9ATM) and the stent is removed allowing for recoil to occur. The inner diameter at each end of the stent is recorded. Recoil is calculated subtracting the recoiled stent inner diameter from the pre-recoil inner diameter.

[0022] Stent Expansion Testing

[0023] This test is conducted to determine if the plastic deformation experienced by the stent when expanded from the compressed profile to the final maximum deployed diameter (i.e. over-deployed diameter) can produce crack initiation for the disclosed stent. The sample stents are deployed to their largest possible diameters by inflating each delivery system to balloon failure. Each stent is examined at 45X magnification for potential cracks.

[0024] Maximum Pressure (burst test) Testing

[0025] This test is conducted to demonstrate that the delivery system (with mounted stent) will not experience balloon, shaft, proximal adaptation or proximal/distal seal loss of integrity at or below the pressure required to expand the stent to its labeled diameter. Stent delivery systems that had been subjected to all manufacturing and sterilization procedures were pressurized to 90psi with pressure held for 15 seconds and released for 3 seconds. The cycle was then repeated, increasing inflation pressure by 15psi each cycle until failure.

[0026] In some embodiments, the tubular scaffold maintains at least 50% of its nominal luminal cross sectional area under a pressure load of 50mmHg. In another embodiment, the tubular scaffold maintains at least 60% of its nominal luminal cross sectional area under a pressure load of 50mmHg. In another embodiment, the tubular scaffold maintains at least 70% of its nominal luminal cross sectional area under a pressure load of 50mmHg. In another embodiment, the tubular scaffold maintains at least 80% of its nominal luminal cross sectional area under a pressure load of 50mmHg. In another embodiment, the tubular scaffold maintains at least 90% of its nominal luminal cross sectional area under a pressure load of 50mmHg. In another embodiment, the tubular scaffold maintains at least 95% of its nominal luminal cross sectional area under a pressure load of 50mmHg.

[0027] In some embodiments, the tubular scaffold maintains at least 50% of its nominal luminal cross sectional area under a pressure load of 50mmHg upon 2 months of exposure to saline *in vitro*. In another

embodiment, the tubular scaffold maintains at least 50% of its nominal luminal cross sectional area under a pressure load of 50mmHg upon 2 month *in vivo*.

[0028] In some embodiments, the tubular scaffold maintains at least 50% of its nominal luminal cross sectional area under a pressure load of 50mmHg upon 3 months of exposure to saline *in vitro*. In another embodiment, the tubular scaffold maintains at least 50% of its nominal luminal cross sectional area under a pressure load of 50mmHg upon 3 month *in vivo*.

[0029] In some embodiments, the tubular scaffold maintains at least 50% of its nominal luminal cross sectional area under a pressure load of 50mmHg upon 4 months of exposure to saline *in vitro*. In another embodiment, the tubular scaffold maintains at least 50% of its nominal luminal cross sectional area under a pressure load of 50mmHg upon 4 month *in vivo*.

[0030] In some embodiments, the tubular scaffold maintains at least 50% of its nominal luminal cross sectional area under a pressure load of 50mmHg upon 6 months of exposure to saline *in vitro*. In another embodiment, the tubular scaffold maintains at least 50% of its nominal luminal cross sectional area under a pressure load of 50mmHg upon 6 month *in vivo*.

[0031] **Reinforcement Fiber Materials**

[0032] In some embodiments, the polymer struts comprises a fiber-reinforced polymer composite material. In a refinement, the fiber-reinforced polymer composite material comprises a bioabsorbable polymer material and a reinforcement fiber material. In a further refinement, the reinforcement fiber material is carbon fiber material or carbon nanotube material.

[0033] In some embodiments, the carbon nanotube material is a multi-wall carbon nanotube material.

[0034] In some embodiments, the reinforcement fiber material is distributed throughout the polymer struts.

[0035] Carbon Fiber

[0036] Carbon fiber (sometimes also referred to as graphite fiber, carbon graphite or CF), is a material consisting of fibers about 5-10  $\mu\text{m}$  in diameter and composed mostly of carbon atoms. The carbon atoms are bonded together in crystals that are more or less aligned parallel to the long axis of the fiber. The crystal alignment gives the fiber high strength-to-volume ratio (making it strong for its size). Several thousand carbon fibers are bundled together to form a tow, which may be used by itself or woven into a fabric.

[0037] Each carbon filament thread is a bundle of many thousand carbon filaments. A single such filament is a thin tube with a diameter of 5-8 micrometers and consists almost exclusively of carbon. The earliest generation of carbon fibers (e.g. T300, HTA and AS4) had diameters of 7-8 micrometers. Later fibers (e.g. IM6 or IM600) have diameters that are approximately 5 micrometers.

[0038] The atomic structure of carbon fiber is similar to that of graphite, consisting of sheets of carbon atoms (graphene sheets) arranged in a regular hexagonal pattern. The difference lies in the way these sheets interlock. Graphite is a crystalline material in which the sheets are stacked parallel to one another in regular fashion. The intermolecular forces between the sheets are relatively weak Van der Waals forces, giving graphite its soft and brittle characteristics. Depending upon the precursor to make the

fiber, carbon fiber may be turbostratic or graphitic, or have a hybrid structure with both graphitic and turbostratic parts present. In turbostratic carbon fiber the sheets of carbon atoms are haphazardly folded, or crumpled, together. Carbon fibers derived from Polyacrylonitrile (PAN) are turbostratic, whereas carbon fibers derived from mesophase pitch are graphitic after heat treatment at temperatures exceeding 2200 C. Turbostratic carbon fibers tend to have high tensile strength, whereas heat-treated mesophase-pitch-derived carbon fibers have high Young's modulus (i.e., high stiffness or resistance to extension under load) and high thermal conductivity. Major manufacturers of carbon fibers include Hexcel, SGL Carbon, Toho Tenax, Toray Industries and Zoltek. Manufacturers typically make different grades of fibers for different applications.

[0039] Carbon fibers are sometimes combined with other materials to form a composite. When combined with a plastic resin and wound or molded it forms carbon fiber reinforced plastic which has a high strength-to-weight ratio. However, the carbon-fiber reinforced polymer composite also has a high rigidity and sometime a tendency to be brittle, thereby limiting its use in devices and apparatus where deformability is desirable or mandatory, such as in deformable medical implants. It is contemplated that the technical features disclosed herein, whether alone or in various combinations, enables the development of a fiber-reinforced polymer composite material that has improved mechanical strength (e.g. tensile modulus and tensile strength) and yet has sufficient deformability for application in deformable medical implants, such as stents. It is further contemplated that the technical features disclosed herein, whether alone or in various combinations, enables the development of a fiber-reinforcement polymer composite material that is at least substantially bioabsorbable within a desirable period of time.

[0040] Carbon Nanotube

[0041] Carbon nanotubes (CNTs) are allotropes of carbon with a cylindrical nanostructure. Nanotubes have been constructed with length-to-diameter ratio of up to 132,000,000:1, significantly larger than for any other material. These cylindrical carbon molecules have unusual properties, which are valuable for nanotechnology, electronics, optics and other fields of materials science and technology. In particular, owing to their extraordinary thermal conductivity and mechanical and electrical properties, carbon nanotubes find applications as additives to various structural materials.

[0042] Nanotubes are categorized as single-walled nanotubes (SWNTs) and multi-walled nanotubes (MWNTs). Individual nanotubes naturally align themselves into "ropes" held together by van der Waals forces, more specifically, pi-stacking. Multi-walled nanotubes (MWNT) consist of multiple rolled layers (concentric tubes) of graphene. There are two models that can be used to describe the structures of multi-walled nanotubes. In the Russian Doll model, sheets of graphite are arranged in concentric cylinders, e.g., a (0,8) single-walled nanotube (SWNT) within a larger (0,17) single-walled nanotube. In the Parchment model, a single sheet of graphite is rolled in around itself, resembling a scroll of parchment or a rolled newspaper. The interlayer distance in multi-walled nanotubes is close to the distance between graphene layers in graphite, approximately 3.4 Å. The Russian Doll structure is observed more commonly. Its individual shells can be described as SWNTs, which can be metallic or semiconducting.

[0043] Carbon nanotubes have generally very high the strength and stiffness. They are sometimes combined with other materials to form a composite. As such, carbon nanotube reinforced polymer composite also has a high rigidity and sometime a tendency to be brittle, thereby limiting its use in devices and apparatus where deformability is desirable or mandatory, such as in deformable medical implants. It is contemplated that the technical features disclosed herein, whether alone or in various combinations, enables the development of a fiber-reinforced polymer composite material that has improved mechanical strength (e.g. tensile modulus and tensile strength) and yet has sufficient deformability for application in deformable medical implants, such as stents. It is further contemplated that the technical features disclosed herein, whether alone or in various combinations, enables the development of a fiber-reinforcement polymer composite material that is at least substantially bioabsorbable within a desirable period of time.

[0044] Bioabsorbable Glass

[0045] Another reinforcement fiber material suitable for the present disclosure is bioabsorbable glass material. In some embodiments, the bioabsorbable glass material is a spun or drawn glass fiber having the required tensile strength and resorption properties. As such, the glass fibers reinforce the bioabsorbable polymer matrix as the bioabsorbable polymer and the reinforcement glass fiber are gradually reduced in strength and elastic modulus, such as through slow, steady bioabsorption.

[0046] As a non-limiting example, the bioabsorbable glass material includes a binary mixture of calcium oxide (CaO) and phosphorous pentoxide ( $P_2O_5$ ); although, other ingredients such as calcium fluoride ( $CaF_2$ ), water ( $H_2O$ ), and other oxides containing cations such as magnesium, zinc, strontium, sodium, potassium, lithium and aluminum may also be incorporated in small amounts. In terms of the binary mixture, the preferred Ca:P mole ratio is 0.25 to 0.33. Preferably, the glass comprises by weight 5-50% CaO, 50-95%  $P_2O_5$ , 0-5%  $CaF_2$ , 0-5%  $H_2O$ , and 0-10% XO, wherein X is a single magnesium, zinc or strontium ion or two sodium, potassium, lithium or aluminum ions and O is a single oxygen ion except when X is aluminum, in which case it is three oxygen ions. More preferably, the calcium oxide (CaO) is present by weight in the amount of 15-25%; the phosphorous pentoxide ( $P_2O_5$ ) is present by weight in the amount of 65-90%; and either calcium fluoride ( $CaF_2$ ) or water ( $H_2O$ ) is present by weight in the amount of 0.1-4%.

[0047] Surface Modification

[0048] In some embodiments, the reinforcement fiber material comprises one or more surface functionalities to facilitate intermolecular interaction between the bioabsorbable polymer material and the reinforcement fiber material. In some embodiment, the reinforcement fibers are chemically modified to include the surface functionalities. Without wishing to be bound by any particular theory, it is contemplated that the surface functionalities contribute to desirable reinforcement fiber orientation, desirable reinforcement fiber distribution or dispersion, and/or other technical features of the present disclosure.

[0049] In some embodiments, the one or more surface functionalities are selected from -COOH, -OH, or combination thereof. In some embodiments, the reinforcement fiber material comprising one or more surface functionalities is multi-wall carbon nanotube material.

[0050] A non-limiting example of chemically modifying multi-wall carbon nanotube to include -COOH is provided in Li Buay Koh, Isabel Rodriguezb, Subbu S. Venkatramana. A novel nanostructured poly(lactic-co-glycolic-acid)-multi-walled carbon nanotube composite for blood-contacting applications: Thrombogenicity studies. Acta Biomaterialia Volume 5, Issue 9, November 2009, Pages 341 1-3422.

[0051] A non-limiting example of chemically modifying multi-wall carbon nanotube to include -COOH or -OH is provided in Wu, C. S. & Liao, H.T. (2007). Study on the preparation and characterization of biodegradable polylactide/multi-walled carbon nanotubes nanocomposites. Polymer, Vol.48, No. 15, (July 2007), pp. 4449-4458.

[0052] The contents of those articles are incorporated herein in their entirety. Moreover, other method of adding surface functionalities to reinforcement fibers can be used in light of the technical feature disclosed herein.

[0053] Method of Making Fiber-Reinforced Polymer Composite Material

[0054] Non-limiting examples of methods of making the fiber reinforced polymer composite materials, especially bioabsorbable polymer composite materials, are provided below.

[0055] Chlopek, J.; Morawska-Chochol, A.; Bajor, G.; Adwent, M.; Cieslik-Bielecka, A.; Cieslik, M.; Sabat, D. The influence of carbon fibres on the resorption time and mechanical properties of the lactide-glycolide co-polymer. J. Biomater. Sci. Polym. Ed. 2007, 18, 1355-1368.

[0056] Li Buay Koh, Isabel Rodriguezb, Subbu S. Venkatramana. A novel nanostructured poly(lactic-co-glycolic-acid)-multi-walled carbon nanotube composite for blood-contacting applications: Thrombogenicity studies. Acta Biomaterialia Volume 5, Issue 9, November 2009, Pages 341 1-3422.

[0057] Wu, C. S. & Liao, H.T. (2007). Study on the preparation and characterization of biodegradable polylactide/multi-walled carbon nanotubes nanocomposites. Polymer, Vol.48, No. 15, (July 2007), pp. 4449-4458.

[0058] Hualin Zhang. Electrospun poly (lactic-co-glycolic acid)/multiwalled carbon nanotubes composite scaffolds for guided bone tissue regeneration. Journal of Bioactive and Compatible Polymers 26(4) 347-362 2011

[0059] The contents of those articles are incorporated herein in their entirety. Moreover, other method of making the fiber reinforced polymer composite materials can be used in light of the technical feature disclosed herein.

[0060] Tensile Modulus

[0061] In some embodiments, the inclusion of the reinforcement fiber material significantly increases tensile modulus of the fiber-reinforced polymer composite material. In some embodiments, the fiber-reinforced polymer composite material has a tensile modulus that is at least ten times of a tensile modulus of the bioabsorbable polymer. In some embodiments, the fiber-reinforced polymer composite material has a tensile modulus that is at least nine times of a tensile modulus of the bioabsorbable

polymer. In some embodiments, the fiber-reinforced polymer composite material has a tensile modulus that is at least eight times of a tensile modulus of the bioabsorbable polymer. In some embodiments, the fiber-reinforced polymer composite material has a tensile modulus that is at least seven times of a tensile modulus of the bioabsorbable polymer. In some embodiments, the fiber-reinforced polymer composite material has a tensile modulus that is at least six times of a tensile modulus of the bioabsorbable polymer. In some embodiments, the fiber-reinforced polymer composite material has a tensile modulus that is at least five times of a tensile modulus of the bioabsorbable polymer. In some embodiments, the fiber-reinforced polymer composite material has a tensile modulus that is at least four times of a tensile modulus of the bioabsorbable polymer. In some embodiments, the fiber-reinforced polymer composite material has a tensile modulus that is at least three times of a tensile modulus of the bioabsorbable polymer. In some embodiments, the fiber-reinforced polymer composite material has a tensile modulus that is at least two times of a tensile modulus of the bioabsorbable polymer. In some embodiments, the fiber-reinforced polymer composite material has a tensile modulus that is at least 1.5 times of a tensile modulus of the bioabsorbable polymer.

**[0062]** Tensile Strength

**[0063]** In some embodiments, the inclusion of the reinforcement fiber material significantly increases tensile strength of the fiber-reinforced polymer composite material. In some embodiments, the fiber-reinforced polymer composite material has a tensile strength that is at least ten times of a tensile strength of the bioabsorbable polymer. In some embodiments, the fiber-reinforced polymer composite material has a tensile strength that is at least nine times of a tensile strength of the bioabsorbable polymer. In some embodiments, the fiber-reinforced polymer composite material has a tensile strength that is at least eight times of a tensile strength of the bioabsorbable polymer. In some embodiments, the fiber-reinforced polymer composite material has a tensile strength that is at least seven times of a tensile strength of the bioabsorbable polymer. In some embodiments, the fiber-reinforced polymer composite material has a tensile strength that is at least six times of a tensile strength of the bioabsorbable polymer. In some embodiments, the fiber-reinforced polymer composite material has a tensile strength that is at least five times of a tensile strength of the bioabsorbable polymer. In some embodiments, the fiber-reinforced polymer composite material has a tensile strength that is at least four times of a tensile strength of the bioabsorbable polymer. In some embodiments, the fiber-reinforced polymer composite material has a tensile strength that is at least three times of a tensile strength of the bioabsorbable polymer. In some embodiments, the fiber-reinforced polymer composite material has a tensile strength that is at least two times of a tensile strength of the bioabsorbable polymer. In some embodiments, the fiber-reinforced polymer composite material has a tensile strength that is at least 1.5 times of a tensile strength of the bioabsorbable polymer.

**[0064]** Content of Reinforcement Fiber

**[0065]** In some embodiments, the fiber-reinforced polymer composite material comprises from 0.1 wt% to 15 wt% of the reinforcement fiber material. In some embodiments, the fiber-reinforced polymer composite material comprises from 0.1 wt% to 10 wt% of the reinforcement fiber material. In some

embodiments, the fiber-reinforced polymer composite material comprises from 0.1 wt% to 5 wt% of the reinforcement fiber material. In some embodiments, the fiber-reinforced polymer composite material comprises from 0.1 wt% to 4 wt% of the reinforcement fiber material. In some embodiments, the fiber-reinforced polymer composite material comprises from 0.1 wt% to 3 wt% of the reinforcement fiber material. In some embodiments, the fiber-reinforced polymer composite material comprises from 0.1 wt% to 2 wt% of the reinforcement fiber material. In some embodiments, the fiber-reinforced polymer composite material comprises from 0.1 wt% to 1.5 wt% of the reinforcement fiber material. In some embodiments, the fiber-reinforced polymer composite material comprises from 0.1 wt% to 1 wt% of the reinforcement fiber material.

**[0066]** In some embodiments, the fiber-reinforced polymer composite material comprises from 0.1 wt% to 0.9 wt% of the reinforcement fiber material. In some embodiments, the fiber-reinforced polymer composite material comprises from 0.1 wt% to 0.9 wt% of the reinforcement fiber material. In some embodiments, the fiber-reinforced polymer composite material comprises from 0.1 wt% to 0.8 wt% of the reinforcement fiber material. In some embodiments, the fiber-reinforced polymer composite material comprises from 0.1 wt% to 0.7 wt% of the reinforcement fiber material. In some embodiments, the fiber-reinforced polymer composite material comprises from 0.1 wt% to 0.6 wt% of the reinforcement fiber material.

**[0067]** In some embodiments, the fiber-reinforced polymer composite material comprises from 0.2 wt% to 0.9 wt% of the reinforcement fiber material. In some embodiments, the fiber-reinforced polymer composite material comprises from 0.2 wt% to 0.9 wt% of the reinforcement fiber material. In some embodiments, the fiber-reinforced polymer composite material comprises from 0.2 wt% to 0.8 wt% of the reinforcement fiber material. In some embodiments, the fiber-reinforced polymer composite material comprises from 0.2 wt% to 0.7 wt% of the reinforcement fiber material. In some embodiments, the fiber-reinforced polymer composite material comprises from 0.2 wt% to 0.6 wt% of the reinforcement fiber material.

**[0068] Reinforcement Fiber Orientation**

**[0069] Strut-Longitudinal Orientation**

**[0070]** In some embodiments, each polymer strut includes reinforcement fibers that are longitudinally aligned along a center axis of the polymer strut. In some embodiments, more than 50% of reinforcement fibers are longitudinally aligned along the center axes of the polymer struts. In some embodiments, more than 55% of reinforcement fibers are longitudinally aligned along the center axes of the polymer struts. In some embodiments, more than 60% of reinforcement fibers are longitudinally aligned along the center axes of the polymer struts. In some embodiments, more than 65% of reinforcement fibers are longitudinally aligned along the center axes of the polymer struts. In some embodiments, more than 70% of reinforcement fibers are longitudinally aligned along the center axes of the polymer struts. In some embodiments, more than 75% of reinforcement fibers are longitudinally aligned along the center axes of the polymer struts. In some embodiments, more than 80% of reinforcement fibers are longitudinally aligned along the center axes of the polymer struts. In some embodiments, more than 85% of

reinforcement fibers are longitudinally aligned along the center axes of the polymer struts. In some embodiments, more than 90% of reinforcement fibers are longitudinally aligned along the center axes of the polymer struts. In some embodiments, more than 95% of reinforcement fibers are longitudinally aligned along the center axes of the polymer struts.

[0071] As a result of the strut-longitudinal reinforcement fiber orientation, the polymer struts have anisotropic elastic modulus. In some embodiments, the polymer struts have an average longitudinal elastic modulus along the center axes of the polymer struts and an average lateral elastic modulus orthogonal to the center axes of the polymer struts, the average longitudinal elastic modulus being greater than the average lateral elastic modulus.

[0072] In one embodiment, the average longitudinal elastic modulus is at least 2 times the average lateral elastic modulus. In another embodiment, the average longitudinal elastic modulus is at least 3 times the average lateral elastic modulus. In another embodiment, the average longitudinal elastic modulus is at least 4 times the average lateral elastic modulus. In another embodiment, the average longitudinal elastic modulus is at least 5 times the average lateral elastic modulus. In another embodiment, the average longitudinal elastic modulus is at least 6 times the average lateral elastic modulus. In another embodiment, the average longitudinal elastic modulus is at least 7 times the average lateral elastic modulus. In another embodiment, the average longitudinal elastic modulus is at least 8 times the average lateral elastic modulus. In another embodiment, the average longitudinal elastic modulus is at least 9 times the average lateral elastic modulus. In another embodiment, the average longitudinal elastic modulus is at least 10 times the average lateral elastic modulus.

[0073] Scaffold-Axial Orientation

[0074] In one embodiment, the tubular scaffold includes reinforcement fibers that are axially aligned along a center axis of the tubular scaffold. In some embodiment, more than 50% of reinforcement fibers are axially aligned along a center axis of the tubular scaffold. In some embodiment, more than 55% of reinforcement fibers are axially aligned along a center axis of the tubular scaffold. In some embodiment, more than 60% of reinforcement fibers are axially aligned along a center axis of the tubular scaffold. In some embodiment, more than 65% of reinforcement fibers are axially aligned along a center axis of the tubular scaffold. In some embodiment, more than 70% of reinforcement fibers are axially aligned along a center axis of the tubular scaffold. In some embodiment, more than 75% of reinforcement fibers are axially aligned along a center axis of the tubular scaffold. In some embodiment, more than 80% of reinforcement fibers are axially aligned along a center axis of the tubular scaffold. In some embodiment, more than 85% of reinforcement fibers are axially aligned along a center axis of the tubular scaffold. In some embodiment, more than 90% of reinforcement fibers are axially aligned along a center axis of the tubular scaffold. In some embodiment, more than 95% of reinforcement fibers are axially aligned along a center axis of the tubular scaffold.

[0075] As a result of the scaffold-axial reinforcement fiber orientation, the tubular scaffold has anisotropic elastic modulus. In some embodiments, the tubular scaffold has an average axial elastic modulus along a center axis of the tubular scaffold and an average circumferential elastic modulus

orthogonally surrounding a center axis of the tubular scaffold, the average axial elastic modulus being greater than the average circumferential elastic modulus.

[0076] In one embodiment, the average axial elastic modulus is at least 2 times the average circumferential elastic modulus. In another embodiment, the average axial elastic modulus is at least 3 times the average circumferential elastic modulus. In another embodiment, the average axial elastic modulus is at least 4 times the average circumferential elastic modulus. In another embodiment, the average axial elastic modulus is at least 5 times the average circumferential elastic modulus. In another embodiment, the average axial elastic modulus is at least 6 times the average circumferential elastic modulus. In another embodiment, the average axial elastic modulus is at least 7 times the average circumferential elastic modulus. In another embodiment, the average axial elastic modulus is at least 8 times the average circumferential elastic modulus. In another embodiment, the average axial elastic modulus is at least 9 times the average circumferential elastic modulus. In another embodiment, the average axial elastic modulus is at least 10 times the average circumferential elastic modulus.

[0077] Scaffold- Circumferential Orientation

[0078] In one embodiment, the tubular scaffold includes reinforcement fibers that are circumferential aligned, i.e. orthogonally surrounding a center axis of the tubular scaffold. In some embodiments, more than 50% of reinforcement fibers are circumferential aligned. In some embodiments, more than 55% of reinforcement fibers are circumferential aligned. In some embodiments, more than 60% of reinforcement fibers are circumferential aligned. In some embodiments, more than 65% of reinforcement fibers are circumferential aligned. In some embodiments, more than 70% of reinforcement fibers are circumferential aligned. In some embodiments, more than 75% of reinforcement fibers are circumferential aligned. In some embodiments, more than 80% of reinforcement fibers are circumferential aligned. In some embodiments, more than 85% of reinforcement fibers are circumferential aligned. In some embodiments, more than 90% of reinforcement fibers are circumferential aligned. In some embodiments, more than 95% of reinforcement fibers are circumferential aligned.

[0079] As a result of the scaffold-circumferential reinforcement fiber orientation, the tubular scaffold has anisotropic elastic modulus. For example, the tubular scaffold has an average axial elastic modulus along a center axis of the tubular scaffold and an average radial elastic modulus orthogonal to a center axis of the tubular scaffold, the average circumferential elastic modulus being greater than the average axial elastic modulus.

[0080] In one embodiment, the average circumferential elastic modulus is at least 2 times the average axial elastic modulus. In another embodiment, the average circumferential elastic modulus is at least 3 times the average axial elastic modulus. In another embodiment, the average circumferential elastic modulus is at least 4 times the average axial elastic modulus. In another embodiment, the average circumferential elastic modulus is at least 5 times the average axial elastic modulus. In another embodiment, the average circumferential elastic modulus is at least 6 times the average axial elastic modulus. In another embodiment, the average circumferential elastic modulus is at least 7 times the

average axial elastic modulus. In another embodiment, the average circumferential elastic modulus is at least 8 times the average axial elastic modulus. In another embodiment, the average circumferential elastic modulus is at least 9 times the average axial elastic modulus. In another embodiment, the average circumferential elastic modulus is at least 10 times the average axial elastic modulus.

**[0081] Bioabsorbable Polymer Materials**

**[0082]** In some embodiments, the polymer struts comprises a gel-spun polymer material. In a refinement, the polymer struts are not structurally reinforced with a metal material. In a further refinement, the gel-spun polymer material is selected from the group consisting of polylactides (PLA); poly(lactide-co-glycolide) (PLGA); polyanhydrides; polyorthoesters; poly(N-(2-hydroxypropyl) methacrylamide); poly(dl-lactide) (DLPLA); poly(l-lactide) (LPLA); poly(d-lactide) (DPLA); polyglycolide (PGA); poly(dioxanone) (PDO); poly(glycolide-co-trimethylene carbonate) (PGA-TMC); poly(l-lactide-co-glycolide) (PGA-LPLA); poly(dl-lactide-co-glycolide) (PGA-DLPLA); poly(l-lactide-co-dl-lactide) (LPLA-DLPLA); poly(glycolide-co-trimethylene carbonate-co-dioxanone) (PDO-PGA-TMC), poly(lactic acid-co-caprolactone) (PLACL), and mixtures or co-polymers thereof.

**[0083]** In one refinement, the gel-spun polymer material is PLGA. In a further refinement, the PLGA has a ratio of lactic acid monomer to glycolic acid monomer ranging from 82:18 to 88:12. In a further refinement, the PLGA has a ratio of lactic acid monomer to glycolic acid monomer ranging from 72:28 to 78:22. In another further refinement, the PLGA has a ratio of lactic acid monomer to glycolic acid monomer ranging from 62:38 to 68:32. In another further refinement, the PLGA has a ratio of lactic acid monomer to glycolic acid monomer ranging from 47:53 to 53:47. In another further refinement, the PLGA has a ratio of lactic acid monomer to glycolic acid monomer of 50:50.

**[0084]** In another further refinement, the PLGA has a weight average molecular weight of about 8,000 Dalton to about 12,000 Dalton. In another further refinement, the PLGA has a weight average molecular weight of about 12,000 Dalton to about 16,000 Dalton. In another further refinement, the PLGA has a weight average molecular weight of up to about 90,000 Dalton. In another refinement, the gel-spun polymer material is PLA or LPLA. In another refinement, the gel-spun polymer material is PGA. In some embodiment, the gel spun polymer material (e.g. PLGA, LPLA, PLA, PGA) has a weight average molecular weight of at least 90,000 Dalton, and optionally at least 100,000 Dalton

**[0085]** In some embodiments, the polymer struts include a polymer material selected from the group consisting of polycarboxylic acids, cellulosic polymers, proteins, polypeptides, polyvinylpyrrolidone, maleic anhydride polymers, polyamides, polyvinyl alcohols, polyethylene oxides, glycosaminoglycans, polysaccharides, polyesters, aliphatic polyesters, polyurethanes, polystyrenes, copolymers, silicones, silicone containing polymers, polyalkyl siloxanes, polyorthoesters, polyanhydrides, copolymers of vinyl monomers, polycarbonates, polyethylenes, polypropytenes, polylactic acids, polylactides, polyglycolic acids, polyglycolides, polylactide-co-glycolides, polycaprolactones, poly(e-caprolactone)s, polyhydroxybutyrate valerates, polyacrylamides, polyethers, polyurethane dispersions, polyacrylates, acrylic latex dispersions, polyacrylic acid, polyalkyl methacrylates, polyalkylene-co-vinyl acetates,

polyalkylenes, aliphatic polycarbonates polyhydroxyalkanoates, polytetrahaloalkylenes, poly(phosphasones), polytetrahaloalkylenes, poly(phosphasones), and mixtures, combinations, and copolymers thereof.

**[0086] Deformation Angle**

**[0087]** Further, as a result of the polymer chain orientation, the polymer struts have an average deformation angle, i.e the average angle between the polymer struts when deployed minus the average angle between the polymer struts when undeployed. In some embodiments, the polymer struts have an average deformation angle of at least 90 degrees. In another embodiment, the polymer struts have an average deformation angle of at least 85 degrees. In another embodiment, the polymer struts have an average deformation angle of at least 80 degrees. In another embodiment, the polymer struts have an average deformation angle of at least 75 degrees. In another embodiment, the polymer struts have an average deformation angle of at least 70 degrees. In another embodiment, the polymer struts have an average deformation angle of at least 65 degrees. In another embodiment, the polymer struts have an average deformation angle of at least 60 degrees. In another embodiment, the polymer struts have an average deformation angle of at least 55 degrees. In another embodiment, the polymer struts have an average deformation angle of at least 50 degrees. In another embodiment, the polymer struts have an average deformation angle of at least 45 degrees. In another embodiment, the polymer struts have an average deformation angle of at least 40 degrees. In another embodiment, the polymer struts have an average deformation angle of at least 30 degrees. Without wishing to be bound by any particular theory, it is contemplated that the configuration of the polymer struts according to the specified deformation angle improves the deformability of the polymer stent made of chain-oriented polymers.

**[0088] Stent Deployment**

**[0089]** In some embodiments, the tubular scaffold is expandable from an undeployed diameter to a nominal diameter without affecting the structural integrity of the tubular scaffold. In a refinement, the tubular scaffold is further expandable from the nominal diameter to an over-deployed diameter without affecting the structural integrity of the tubular scaffold.

**[0090]** In a further refinement, the over-deployed diameter is about 1.0 mm greater than the nominal diameter. In another further refinement, the over-deployed diameter is about 0.9 mm greater than the nominal diameter. In another further refinement, the over-deployed diameter is about 0.8 mm greater than the nominal diameter. In another further refinement, the over-deployed diameter is about 0.7 mm greater than the nominal diameter. In another further refinement, the over-deployed diameter is about 0.6 mm greater than the nominal diameter. In another further refinement, the over-deployed diameter is about 0.5 mm greater than the nominal diameter. In another further refinement, the over-deployed diameter is about 0.4 mm greater than the nominal diameter. In another further refinement, the over-deployed diameter is about 0.3 mm greater than the nominal diameter. In another further refinement, the over-deployed diameter is about 0.2 mm greater than the nominal diameter.

**[0091]** In one refinement, the tubular scaffold is expandable by an inflatable balloon positioned within the tubular scaffold. In a further refinement, the tubular scaffold has a deployed diameter of 2.25 mm at

nominal balloon pressure. In another further refinement, the tubular scaffold has a deployed diameter of 2.5 mm at nominal balloon pressure. In another further refinement, the tubular scaffold has a deployed diameter of 3.0 mm at nominal balloon pressure. In another further refinement, the tubular scaffold has a deployed diameter of 3.5 mm at nominal balloon pressure. In another further refinement, the tubular scaffold has a deployed diameter of 4.0 mm at nominal balloon pressure. In another further refinement, the tubular scaffold has a deployed diameter of 4.5 mm at nominal balloon pressure. The nominal balloon pressure may be dependent on the material and design of the balloon. As a non-limiting example, the nominal balloon pressure is 6 atmospheres. As another example, the nominal balloon pressure is 9 atmosphere.

**[0092]** In one refinement, the polymer struts comprise a shape-memory polymer and wherein tubular scaffold is self-expandable. In a further refinement, the tubular scaffold is self-expandable upon change in temperature. In another further refinement, the tubular scaffold is self-expandable upon change in crystallinity of the shape-memory polymer.

**[0093]** In some embodiments, the tubular scaffold is formed from a plurality of sinusoidal polymer fibers each including a plurality of struts. In a refinement, the sinusoidal polymer fibers are interconnected at a plurality of connecting points.

**[0094]** In some embodiments, the tubular scaffold is formed from a single polymer fiber including a plurality of struts. In a refinement, the single polymer fiber comprises a plurality of sinusoidal sections interconnected at a plurality of connecting points.

**[0095]** Many methods for forming wire- or filament-based stents can be used to make the bioabsorbable stents disclosed herein. For example, the methods for forming Wallstent (Boston Scientific), S7 (Medtronic), AngioStent (AngioDynamics), Strecker (Boston Scientific), Expander (Medicorp), Horizon Prostatic (Endocare), Endocoil (InStent), etc, can be used to in light of the present disclosure.

**[0096] Drug Incorporation**

**[0097]** In some embodiments, the biomedical implant further includes a pharmaceutical agent incorporated to the tubular scaffold. In a refinement, the pharmaceutical agent is a macrolide immunosuppressant. In a further refinement, the macrolide immunosuppressant is rapamycin or a derivative, a prodrug, a hydrate, an ester, a salt, a polymorph, a derivative or an analog thereof. In another further refinement, the macrolide immunosuppressant is selected from the group consisting of rapamycin, 40-O-(2-Hydroxyethyl)rapamycin (everolimus), 40-O-Benzyl-rapamycin, 40-O-(4'-Hydroxymethyl)benzyl-rapamycin, 40-O-[4'-(1,2-Dihydroxyethyl)]benzyl-rapamycin, 40-O-Allyl-rapamycin, 40-O-[3'-(2,2-Dimethyl-1,3-dioxolan-4(S)-yl)-prop-2'-en-1'-yl]-rapamycin, (2':E,4'S)-40-O-(4',5'-Dihydroxypent-2'-en-1'-yl)-rapamycin, 40-O-(2-Hydroxy)ethoxycarbonylmethyl-rapamycin, 40-O-(3-Hydroxy)propyl-rapamycin, 40-O-(6-Hydroxy)hexyl-rapamycin, 40-O-[2-(2-Hydroxy)ethoxy]ethyl-rapamycin, 40-O-[(3S)-2,2-Dimethyldioxolan-3-yl]methyl-rapamycin, 40-O-[(2S)-2,3-Dihydroxyprop-1-yl]-rapamycin, 40-O-(2-Acetoxy)ethyl-rapamycin, 40-O-(2-Nicotinoyloxy)ethyl-rapamycin, 40-O-[2-(N-Morpholino)acetoxy]ethyl-rapamycin, 40-O-(2-N-Imidazolylacetoxy)ethyl-rapamycin, 40-O-[2-(N-Methyl-N'-piperazinyl)acetoxy]ethyl-rapamycin, 39-O-

Desmethyl-39,40-O,O-ethylene-rapamycin, (26R)-26-Dihydro-40-O-(2-hydroxy)ethyl-rapamycin, 28-O-Methyl-rapamycin, 40-O-(2-Aminoethyl)-rapamycin, 40-O-(2-Acetaminoethyl)-rapamycin, 40-O-(2-Nicotinamidoethyl)-rapamycin, 40-O-(2-(N-Methyl-imidazo-2'-ylcarbethoxamido)ethyl)-rapamycin, 40-O-(2-Ethoxycarbonylaminoethyl)-rapamycin, 40-O-(2-Tolylsulfonamidoethyl)-rapamycin, 40-O-[2-(4',5'-Dicarboethoxy-1',2',3'-triazol-1'-yl)-ethyl]-rapamycin, 42-Epi-(tetrazolyl)rapamycin (tacrolimus), and 42-[3-hydroxy-2-(hydroxymethyl)-2-methylpropanoate]rapamycin. In one refinement, the pharmaceutical agent is rapamycin.

**[0098]** In one refinement, the pharmaceutical agent is impregnated in at least a portion of the tubular scaffold. In a further refinement, the pharmaceutical agent is impregnated in the polymer struts. In a further refinement, the pharmaceutical agent is evenly distributed throughout the polymer struts.

**[0099]** In some embodiment, the pharmaceutical agent is impregnated in the fiber-reinforced polymer composite material before composite material forms the polymer struts or tubular scaffold. In some embodiments, the pharmaceutical agent is impregnated in the bioabsorbable polymer before the impregnated polymer is combined with the reinforcement fiber to form the fiber-reinforced polymer composite material. In some embodiment, the pharmaceutical agent is combined with the bioabsorbable polymer and reinforcement fiber in the process of forming the fiber-reinforced polymer composite material.

**[00100]** In one refinement, at least a portion of the tubular scaffold is covered with a coating comprising the pharmaceutical agent. In a further refinement, the coating further comprises a coating polymer. In a further refinement, at least 90% of the surface area of the pharmaceutical agent is encapsulated in the coating polymer. In a further refinement, at least 85% of the surface area of the pharmaceutical agent is encapsulated in the coating polymer. In a further refinement, at least 80% of the surface area of the pharmaceutical agent is encapsulated in the coating polymer. In a further refinement, at least 75% of the surface area of the pharmaceutical agent is encapsulated in the coating polymer. In a further refinement, at least 70% of the surface area of the pharmaceutical agent is encapsulated in the coating polymer. In a further refinement, at least 65% of the surface area of the pharmaceutical agent is encapsulated in the coating polymer. In a further refinement, at least 60% of the surface area of the pharmaceutical agent is encapsulated in the coating polymer. In a further refinement, at least 55% of the surface area of the pharmaceutical agent is encapsulated in the coating polymer. In a further refinement, at least 50% of the surface area of the pharmaceutical agent is encapsulated in the coating polymer.

**[00101]** In a further embodiment, the pharmaceutical agent is impregnated in at least a portion of the tubular scaffold (e.g. evenly distributed throughout the tubular scaffold) and at least a portion of the tubular scaffold is covered with a coating comprising the pharmaceutical agent, such as in the manner discussed in the paragraph above.

**[00102]** In a further refinement, the coating polymer comprises a bioabsorbable polymer. In a further refinement, the bioabsorbable polymer is selected from the group consisting of polylactides (PLA); poly(lactide-co-glycolide) (PLGA); polyanhydrides; polyorthoesters; poly(N-(2-hydroxypropyl) methacrylamide); poly(DL-lactide) (DLPLA); poly(L-lactide) (LPLA); polyglycolide (PGA);

poly(dioxanone) (PDO); poly(glycolide-co-trimethylene carbonate) (PGA-TMC); poly(l-lactide-co-glycolide) (PGA-LPLA); poly(dl-lactide-co-glycolide) (PGA-DLPLA); poly(l-lactide-co-dl-lactide) (LPLA-DLPLA); poly(glycolide-co-trimethylene carbonate-co-dioxanone) (PDO-PGA-TMC), polyarginine, and mixtures or co-polymers thereof. In a further refinement, the biodegradable polymer is selected from the group consisting of PLGA, polyarginine, and mixtures thereof.

[00103] In some embodiments, the biomedical implant is a vascular stent. In another embodiment, the biomedical implant is a coronary artery stent. In another embodiment, the biomedical implant is a peripheral artery stent. In another embodiment, the biomedical implant is a non-vascular stent. In a refinement, the non-vascular stent is selected from esophageal stent, biliary stent, duodenal stent, colonic stent, and pancreatic stent.

#### **Manufacturing of Bioabsorbable Stent**

[00104] According to another aspect of the present disclosure, a method of forming a biomedical implant is disclosed. The method includes the steps of forming one or more polymer fibers comprising a bioabsorbable polyester material and a reinforcement fiber material; and interconnecting the polymer fibers to form a tubular scaffold, the tubular scaffold comprising a plurality of interconnected polymer struts to define a plurality of deformable cells, wherein the polymer struts have an average thickness of no more than 150  $\mu\text{m}$ .

[00105] According to another aspect of the present disclosure, another method of making a bioabsorbable tubular scaffold is disclosed. The method includes the steps of forming a composition comprising a bioabsorbable polyester material and a reinforcement fiber material; extruding the composition to form a polymer tube, wherein the polymer tube has an average wall thickness of no more than 150  $\mu\text{m}$ ; and removing a portion of the polymer tube to form a scaffold comprising interconnected struts.

#### **[00106] Manufacturing of Tubular Scaffold**

##### **[00107] Tubular Scaffold Made from Polymer Fiber(s)**

[00108] According to another aspect of the present disclosure, a method of forming a biomedical implant is disclosed. The method includes the steps of forming one or more polymer fibers comprising a bioabsorbable polyester material and a reinforcement fiber material; and interconnecting the polymer fibers to form a tubular scaffold, the tubular scaffold comprising a plurality of interconnected polymer struts to define a plurality of deformable cells, wherein the polymer struts have an average thickness of no more than 150  $\mu\text{m}$ .

[00109] In some embodiments, the tubular scaffold maintains at least 50% of its nominal luminal cross sectional area under a pressure load of at least 50mmHg. In some embodiments, the tubular scaffold maintains at least 80% of its nominal luminal cross sectional area under a pressure load of at least 50mmHg.

[00110] In some embodiments, the reinforcement fiber material is a carbon fiber material or a carbon nanotube material. In some embodiments, the carbon nanotube material is a multi-wall carbon nanotube material.

[00111] In some embodiments, the polymer fibers comprise from 0.1 wt% to 15 wt% of the reinforcement fiber material. In some embodiments, the polymer fibers comprise from 0.1 wt% to 10 wt% of the reinforcement fiber material. In some embodiments, the polymer fibers comprise from 0.1 wt% to 5 wt% of the reinforcement fiber material. In some embodiments, the polymer fibers comprise from 0.1 wt% to 1.5 wt% of the reinforcement fiber material.

[00112] In some embodiments, the polyester is selected from the group consisting of polylactides (PLA); poly(lactide-co-glycolide) (PLGA); polyanhydrides; polyorthoesters; poly(N-(2-hydroxypropyl) methacrylamide); poly(dl-lactide) (DLPLA); poly(l-lactide) (LPLA); poly(d-lactide) (DPLA); polyglycolide (PGA); poly(dioxanone) (PDO); poly(glycolide-co-trimethylene carbonate) (PGA-TMC); poly(l-lactide-co-glycolide) (PGA-LPLA); poly(dl-lactide-co-glycolide) (PGA-DLPLA); poly(l-lactide-co-dl-lactide) (LPLA-DLPLA); poly(glycolide-co-trimethylene carbonate-co-dioxanone) (PDO-PGA-TMC), poly(lactic acid-co-caprolactone) (PLACL), and mixtures or co-polymers thereof.

[00113] In some embodiments, the polyester is PLGA. In some embodiments, the polyester is PLA or LPLA.

[00114] Tubular Scaffold Made with Polymer Tubes

[00115] According to another aspect of the present disclosure, another method of making a bioabsorbable tubular scaffold is disclosed. The method includes the steps of forming a composition comprising a bioabsorbable polyester material and a reinforcement fiber material; extruding the composition to form a polymer tube, wherein the polymer tube has an average wall thickness of no more than 150  $\mu\text{m}$ ; and removing a portion of the polymer tube to form a scaffold comprising interconnected struts.

[00116] In some embodiments, the tubular scaffold maintains at least 50% of its nominal luminal cross sectional area under a pressure load of at least 50mmHg. In some embodiments, the tubular scaffold maintains at least 80% of its nominal luminal cross sectional area under a pressure load of at least 50mmHg.

[00117] In some embodiments, the reinforcement fiber material is a carbon fiber material or a carbon nanotube material. In some embodiments, the carbon nanotube material is a multi-wall carbon nanotube material.

[00118] In some embodiments, the polymer tube comprises from 0.1 wt% to 15 wt% of the reinforcement fiber material. In some embodiments, the polymer tube comprises from 0.1 wt% to 10 wt% of the reinforcement fiber material. In some embodiments, the polymer tube comprises from 0.1 wt% to 5 wt% of the reinforcement fiber material. In some embodiments, the polymer tube comprises from 0.1 wt% to 1.5 wt% of the reinforcement fiber material.

[00119] In some embodiments, the polyester is selected from the group consisting of polylactides (PLA); poly(lactide-co-glycolide) (PLGA); polyanhydrides; polyorthoesters; poly(N-(2-hydroxypropyl) methacrylamide); poly(dl-lactide) (DLPLA); poly(l-lactide) (LPLA); poly(d-lactide) (DPLA); polyglycolide (PGA); poly(dioxanone) (PDO); poly(glycolide-co-trimethylene carbonate) (PGA-TMC); poly(l-lactide-co-glycolide) (PGA-LPLA); poly(dl-lactide-co-glycolide) (PGA-DLPLA); poly(l-lactide-

co-dl-lactide) (LPLA-DLPLA); poly(glycolide-co-trimethylene carbonate-co-dioxanone) (PDO-PGA-TMC), poly(lactic acid-co-caprolactone) (PLACL), and mixtures or co-polymers thereof.

[00120] In some embodiments, the polyester is PLGA. In some embodiments, the polyester is PLA or LPLA.

[00121] In some embodiments, the removing is selected from laser-cutting, photochemical etching, and water-jetting.

**[00122] Coating Of Tubular Scaffold.**

[00123] Provided herein are methods for coating the tubular scaffold (also referred to as substrate in this section) with a pharmaceutical or biological agent in powder form. Conventional processes for spray coating stents may also be used. For example, the drug and coating polymer may be dissolved in a suitable solvent or mutual solvent before spray coating can occur. Provided herein are methods for depositing a coating polymer and a pharmaceutical or biological agent in powder form onto the substrate. The coating process provides a cost-effective, efficient method for depositing a combination of an inert polymer or polymers and a pharmaceutical or biological agent or agents, onto parts or all surfaces of a substrate, to form a coating that is of a pre-determined, desired thickness, conformal, substantially defect-free, and uniform and the composition of the coating can be regulated. In particular, the coating process addresses the problem of existing coating processes, which do not allow for structural and morphological preservation of the agents deposited during the coating process.

[00124] One aspect of the invention entails the deposition of the pharmaceutical or biological agents as dry powder. Dry powder spraying is well known in the art, and dry powder spraying coupled with electrostatic capture has been described, for example in US Patents 5,470,603; 6,319,541; or 6,372,246. The deposition of the polymer can be performed in any number of standard procedures, as the morphology of the polymer, so long as it provides coatings possessing the desired properties (e.g. thickness, conformity, defect-free, uniformity etc), is of less importance. The function of the polymer is primarily one of inert carrier matrix for the active components of the coating.

[00125] One aspect of the coating process is the combination of two or more of the dry powder, RESS and SEDS spraying techniques.

[00126] Another aspect of the coating process involves the dry powder spraying of a pharmaceutical agent, in a preferred particle size and morphology, into the same capture vessel as a polymer that is also dry powder sprayed, whereby the spraying of the agent and the polymer is sequential or simultaneous.

[00127] Another specific aspect of the coating process involves the dry powder spraying of an active biological agent, in a preferred particle size and possessing a particular activity, into the same capture vessel as a polymer that is also dry powder sprayed, whereby the spraying of the agent and the polymer is sequential or simultaneous.

[00128] Yet another aspect of the coating process involves the dry powder spraying of a pharmaceutical agent, in a preferred particle size and morphology, into the same capture vessel as a polymer that is sequentially or simultaneously sprayed by the RESS spray process.

[00129] Yet another aspect of the coating process involves the dry powder spraying of an active biological agent, in a preferred particle size and possessing a particular activity, into the same capture vessel as a polymer that is sequentially or simultaneously sprayed by the RESS spray process.

[00130] Yet another aspect of the coating process involves the dry powder spraying of a pharmaceutical agent, in a preferred particle size and morphology, into the same capture vessel as a polymer that is sequentially or simultaneously sprayed by the SEDS spray process.

[00131] Yet another aspect of the coating process involves the dry powder spraying of an active biological agent, in a preferred particle size and possessing a particular activity, into the same capture vessel as a polymer that is sequentially or simultaneously sprayed by the SEDS spray process.

[00132] In some embodiments, the RESS or the SEDS process used in forming the coating is performed with electrically charging the substrate. In some embodiments, the e-RESS or the e-SEDS process used in forming the coating is performed by creating an electrical potential between the substrate and the coating apparatus used in process. In some embodiment, the RESS or the SEDS process used in forming the coating is performed without electrically charging the substrate.

[00133] In further aspects of the coating process the substrates that have been coated with pharmaceutical or biological agents and polymers, as described in the above embodiments are then subjected to a sintering process. The sintering process takes place under benign conditions, which do not affect the structural and morphological integrity of the pharmaceutical and biological agents, and refers to a process by which the co-deposited pharmaceutical agent or biological agent-polymer matrix, becomes continuous and adherent to the substrate. This is achieved by treating the coated substrate with a compressed gas, compressed liquid or supercritical fluid at conditions such that it is a poor solvent of the polymers, a weak solvent of the polymers or a non-solvent for the polymers, the pharmaceutical agents and the biological agents, but an agent suitable for the treatment of polymer particles to form continuous polymer coatings. The sintering process takes place under conditions (e.g. mild temperatures), and using benign fluids (e.g. supercritical carbon dioxide) which will not affect the structural and morphological integrity of the pharmaceutical and biological agents. Other sintering processes, which do not affect the structural and morphological integrity of the pharmaceutical and biological agents may also be contemplated by the present invention.

[00134] In further aspects of the coating process, it is desirable to create coatings such that release of an active substance occurs with a predetermined elution profile when placed in the desired elution media. Coating properties can be modified in a variety of different ways in order to provide desirable elution profiles.

[00135] The chemical composition of the coating polymers can be varied, to provide greater or lesser amounts of coating polymers that will allow or restrict the elution of active substance. For example, if the intended elution media contain water, a higher content of coating polymers that swell in water, will allow for a faster elution of active substance. Conversely, a higher content of coating polymers that do not swell in aqueous media will result in a slower elution rate.

[00136] The coating properties can also be controlled by alternating coating polymer layers. Layers of coating polymers of different properties are deposited on the substrate in a sequential manner. By modifying the nature of the polymer deposited in each layer (e.g., depositing layers of different polymers) the elution profile of the coating is altered. The number of layers and the sequence in their deposition provide additional avenues for the design of coatings having controlled elution profiles.

[00137] The coating properties can also be modified by control of the macro and/or micro-structure of the polymer coating (diffusion pathways). This may be achieved by varying the coating process(es) or by using different sintering conditions.

[00138] The coating process provides several approaches for controlling the elution of a drug or several drugs. For example, In some embodiments, controlled elution is achieved by the segregation of different coating polymers (e.g. PEVA / PBMA). In another embodiment, control of elution is achieved by controlling the conditions during the sintering process such that controlled incomplete sintering of the polymer matrix is obtained, whereby the coating would retain some of the particle-like structure of the polymer particles as deposited. Incomplete sintering would provide pores/voids in the coating and allow additional pathways for elution of the drug, including drug elution around the polymer(s) instead of, or in addition to, elution through the polymer(s). The size of the pores or voids obtained through incomplete sintering of the polymer matrix may be obtained through several methods. For example, the rate of depressurization of a vessel in which the sintering process is carried out provides one avenue for controlling pore size. The size of the cavities or pores in the coating can be controlled by employing a porogen as an excipient and subsequent removal of at least a portion of the porogen, for example by treatment with a solvent of the porogen. Preferably, the porogen solvent comprises a densified gas (e.g.; carbon). In some embodiments the porogen is an SOA or other such hydrophobically derivatized carbohydrate. Removal of at least a portion of the porogen is preferably carried out during the sintering process.

[00139] In some aspects of the invention, the active substance elution profile is controllable by altering the coating polymer particle size. The method by which the polymer particles are deposited onto the substrate is thus varied to provide the desired elution rate. For example, for polymers released simultaneously through the same nozzle, RESS release from a supercritical solution would typically result in small polymer particles; RESS-like release from a mixture in a compressed gas usually generates larger polymer particles. Using the SEDS process can result in variable polymer particle size, depending on the particular SEDS conditions employed.

[00140] In further aspects of the coating process, the active substance elution profile is controllable by altering the coating polymer particle shape. One way to achieve variation in polymer particle shape is to alter the initial concentration of the polymers. At lower initial concentrations, polymers are deposited as small particles. At increased concentrations, larger particles are formed. At higher concentrations, the formed particles become elongated, until at high concentrations the elongated features become fiber-like and eventually become continuous fibers.

[00141] In yet other aspects of the coating process, the active substance elution profile is controllable by creating discrete domains of chemically different polymers. As described above, chemically different polymers will allow or restrict the elution of active substance in different elution media. By changing the position of such polymers in discrete macroscopic domains within the coating, the elution profiles will be adjustable. For example during a process whereby two different polymers are released sequentially through the same nozzle, particles of either polymer could be deposited to position them, for example, closer to the outside, the inside or the middle of the coating on the substrate. In another embodiment, the two polymers may be released simultaneously through two different nozzles at differing and/or alternating deposition rates, resulting in a similar effect. In a further embodiment, the deposition of eluting and non-eluting polymers is alternated to result in a fluctuating type of release. In yet other embodiments, the polymers are deposited to provide for a pulsatile release of active substance. Separation of the polymer(s) providing different domains for drug diffusion is achieved, for example, by subsequent spray of the polymers through same nozzle or by using multiple nozzles. Also, as described above, controlling the elution of the active substance may be achieved by layering of different polymers across the depth of the coating. A combination of domain separation and cross-depth layering is also contemplated for the design of coatings having controlled elution properties.

[00142] The deposition of active substance during any of these processes may be constant to provide even distribution throughout the coating, or the spraying of the active substance may be varied to result in differing amounts of active substance in the differing polymeric domains within the coating.

[00143] In further aspects of the coating process, the active substance elution profile is controllable by varying the coating sintering conditions. For example, incomplete sintering will create open spaces, or pores in the interstitial spaces between the polymer particles, which will enable faster eluting of active substance from the coating. Another way to utilize the sintering conditions for elution control would be to deliberately create irregular coatings by foaming during the sintering process. Rapid pressure release of a CO<sub>2</sub>- or isobutylene-impregnated polymer film induces formation of foamed polymers which would create a coating with increased porosity and be very 'open' to diffusion/elution. Thus the elution profile would be controllable by manipulating the foaming conditions, which in turn controls the pore density and size.

[00144] Another advantage of the coating process is the ability to create a stent with a controlled (dialed-in) drug-elution profile. Via the ability to have different materials in each layer of the laminate structure and the ability to control the location of drug(s) independently in these layers, the method enables a stent that could release drugs at very specific elution profiles, programmed sequential and/or parallel elution profiles. Also, the present invention allows controlled elution of one drug without affecting the elution of a second drug (or different doses of the same drug).

[00145] The embodiments incorporating a stent form or framework provide the ability to radiographically monitor the stent in deployment. In an alternative embodiment, the inner-diameter of the stent can be masked (e.g. by a non-conductive mandrel). Such masking would prevent additional layers from being on the interior diameter (abluminal) surface of the stent. The resulting configuration may be desirable to

provide preferential elution of the drug toward the vessel wall (luminal surface of the stent) where the therapeutic effect of anti-restenosis is desired, without providing the same antiproliferative drug(s) on the abluminal surface, where they may retard healing, which in turn is suspected to be a cause of late-stage safety problems with current DESs.

[00146] The coating process allows for employing a platform combining layer formation methods based on compressed fluid technologies; electrostatic capture and sintering methods. The platform results in drug eluting stents having enhanced therapeutic and mechanical properties. The coating process is particularly advantageous in that it employs optimized laminate polymer technology. In particular, the coating process allows the formation of discrete layers of specific drug platforms.

[00147] The coating process provided herein the drugs and polymers are coated on the stent framework in discrete steps, which can be carried out simultaneously or alternately. This allows discrete deposition of the active agent (e.g.; a drug) within a polymer matrix thereby allowing the placement of more than one drug on a single medical device with or without an intervening polymer layer. For example, the present platform provides a dual drug eluting stent.

[00148] Some of the advantages provided by the coating process include employing compressed fluids (e.g., supercritical fluids, for example RESS based methods); solvent free deposition methodology; a platform that allows processing at lower temperatures thereby preserving the qualities of the active agent and the polymer matrix; the ability to incorporate two, three or more drugs while minimizing deleterious effects from direct interactions between the various drugs and/or their excipients during the fabrication and/or storage of the drug eluting stents; a dry deposition; enhanced adhesion and mechanical properties of the layers on the stent framework; precision deposition and rapid batch processing; and ability to form intricate structures.

[00149] The coating process may provide a multi-drug delivery platform which produces strong, resilient and flexible drug eluting stents including an anti-restenosis drug (e.g.; a limus or taxol) and anti-thrombosis drug (e.g.; heparin or an analog thereof) and well characterized bioabsorbable polymers. The drug eluting stents provided herein minimize potential for thrombosis, in part, by reducing or totally eliminating thrombogenic polymers and reducing or totally eliminating residual drugs that could inhibit healing.

### **Definitions**

[00150] As used in the present specification, the following words and phrases are generally intended to have the meanings as set forth below, except to the extent that the context in which they are used indicates otherwise.

[00151] The terms "bioabsorbable," "biodegradable," "bioerodible," "bioresorbable," and "resorbable" are art-recognized synonyms. These terms are used herein interchangeably. Bioabsorbable polymers typically differ from non-bioabsorbable polymers in that the former may be absorbed (e.g.; degraded) during use. In certain embodiments, such use involves *in vivo* use, such as *in vivo* therapy, and in other certain embodiments, such use involves *in vitro* use. In general, degradation attributable to biodegradability involves the degradation of a bioabsorbable polymer into its component subunits, or

digestion, e.g., by a biochemical process, of the polymer into smaller, non-polymeric subunits. In certain embodiments, biodegradation may occur by enzymatic mediation, degradation in the presence of water (hydrolysis) and/or other chemical species in the body, or both. The bioabsorbability of a polymer may be indicated in-vitro as described herein or by methods known to one of skill in the art. An in-vitro test for bioabsorbability of a polymer does not require living cells or other biologic materials to indicate bioabsorption properties (e.g. degradation, digestion). Thus, resorbtion, resorption, absorption, absorbtion, erosion may also be used synonymously with the terms "bioabsorbable," "biodegradable," "bioerodible," and "bioresorbable." Mechanisms of degradation of a bioabsorbable polymer may include, but are not limited to, bulk degradation, surface erosion, and combinations thereof.

**[00152]** As used herein, the term "biodegradation" encompasses both general types of biodegradation. The degradation rate of a biodegradable polymer often depends in part on a variety of factors, including the chemical identity of the linkage responsible for any degradation, the molecular weight, crystallinity, biostability, and degree of cross-linking of such polymer, the physical characteristics (e.g., shape and size) of the implant, and the mode and location of administration. For example, the greater the molecular weight, the higher the degree of crystallinity, and/or the greater the biostability, the biodegradation of any bioabsorbable polymer is usually slower.

**[00153]** "Degradation" as used herein refers to the conversion or reduction of a chemical compound to one less complex, e.g., by splitting off one or more groups of atoms. Degradation of the coating may reduce the coating's cohesive and adhesive binding to the device, thereby facilitating transfer of the coating to the intervention site

**[00154]** "Pharmaceutical agent" as used herein refers to any of a variety of drugs or pharmaceutical compounds that can be used as active agents to prevent or treat a disease (meaning any treatment of a disease in a mammal, including preventing the disease, i.e. causing the clinical symptoms of the disease not to develop; inhibiting the disease, i.e. arresting the development of clinical symptoms; and/or relieving the disease, i.e. causing the regression of clinical symptoms). It is possible that the pharmaceutical agents of the invention may also comprise two or more drugs or pharmaceutical compounds. Pharmaceutical agents, include but are not limited to antirestenotic agents, antidiabetics, analgesics, antiinflammatory agents, antirheumatics, antihypotensive agents, antihypertensive agents, psychoactive drugs, tranquilizers, antiemetics, muscle relaxants, glucocorticoids, agents for treating ulcerative colitis or Crohn's disease, antiallergics, antibiotics, antiepileptics, anticoagulants, antimycotics, antitussives, arteriosclerosis remedies, diuretics, proteins, peptides, enzymes, enzyme inhibitors, gout remedies, hormones and inhibitors thereof, cardiac glycosides, immunotherapeutic agents and cytokines, laxatives, lipid-lowering agents, migraine remedies, mineral products, otologicals, anti parkinson agents, thyroid therapeutic agents, spasmolytics, platelet aggregation inhibitors, vitamins, cytostatics and metastasis inhibitors, phytopharmaceuticals, chemotherapeutic agents and amino acids. Examples of suitable active ingredients are acarbose, antigens, beta-receptor blockers, non-steroidal antiinflammatory drugs [NSAIDs], cardiac glycosides, acetylsalicylic acid, virustatics, aclarubicin, acyclovir, cisplatin, actinomycin, alpha- and beta-sympatomimetics, (dmeprazole, allopurinol, alprostadil, prostaglandins,

amantadine, ambroxol, amlodipine, methotrexate, S-aminosalicylic acid, amitriptyline, amoxicillin, anastrozole, atenolol, azathioprine, balsalazide, beclomethasone, betahistine, bezafibrate, bicalutamide, diazepam and diazepam derivatives, budesonide, bufexamac, buprenorphine, methadone, calcium salts, potassium salts, magnesium salts, candesartan, carbamazepine, captopril, cephalosporins, cetirizine, chenodeoxycholic acid, ursodeoxycholic acid, theophylline and theophylline derivatives, trypsin, cimetidine, clarithromycin, clavulanic acid, clindamycin, clobutinol, clonidine, cotrimoxazole, codeine, caffeine, vitamin D and derivatives of vitamin D, colestyramine, cromoglicic acid, coumarin and coumarin derivatives, cysteine, cytarabine, cyclophosphamide, ciclosporin, cyproterone, cytarabine, dapiprazole, desogestrel, desonide, dihydralazine, diltiazem, ergot alkaloids, dimenhydrinate, dimethyl sulphoxide, dimeticone, domperidone and domperidan derivatives, dopamine, doxazosin, doxorubizin, doxylamine, dapiprazole, benzodiazepines, diclofenac, glycoside antibiotics, desipramine, econazole, ACE inhibitors, enalapril, ephedrine, epinephrine, epoetin and epoetin derivatives, morphinans, calcium antagonists, irinotecan, modafinil, orlistat, peptide antibiotics, phenytoin, riluzoles, risedronate, sildenafil, topiramate, macrolide antibiotics, oestrogen and oestrogen derivatives, progestogen and progestogen derivatives, testosterone and testosterone derivatives, androgen and androgen derivatives, etenzamide, etofenamate, etofibrate, fenofibrate, etofylline, etoposide, famciclovir, famotidine, felodipine, fenofibrate, fentanyl, fenticonazole, gyrase inhibitors, fluconazole, fludarabine, fluarizine, fluorouracil, fluoxetine, flurbiprofen, ibuprofen, flutamide, fluvastatin, follitropin, formoterol, fosfomicin, furosemide, fusidic acid, gallopamil, ganciclovir, gemfibrozil, gentamicin, ginkgo, Saint John's wort, glibenclamide, urea derivatives as oral antidiabetics, glucagon, glucosamine and glucosamine derivatives, glutathione, glycerol and glycerol derivatives, hypothalamus hormones, goserelin, gyrase inhibitors, guanethidine, halofantrine, haloperidol, heparin and heparin derivatives, hyaluronic acid, hydralazine, hydrochlorothiazide and hydrochlorothiazide derivatives, salicylates, hydroxyzine, idarubicin, ifosfamide, imipramine, indometacin, indoramine, insulin, interferons, iodine and iodine derivatives, isoconazole, isoprenaline, glucitol and glucitol derivatives, itraconazole, ketoconazole, ketoprofen, ketotifen, lacidipine, lansoprazole, levodopa, levomethadone, thyroid hormones, lipoic acid and lipoic acid derivatives, lisinopril, lisuride, lofepramine, lomustine, loperamide, loratadine, maprotiline, mebendazole, mebeverine, meclozine, mefenamic acid, mefloquine, meloxicam, mepindolol, meprobamate, meropenem, mesalazine, mesuximide, metamizole, metformin, methotrexate, methylphenidate, methylprednisolone, metixene, metoclopramide, metoprolol, metronidazole, mianserin, miconazole, minocycline, minoxidil, misoprostol, mitomycin, mizolastine, moexipril, morphine and morphine derivatives, evening primrose, nalbuphine, naloxone, tilidine, naproxen, narcotine, natamycin, neostigmine, nicergoline, nicethamide, nifedipine, niflumic acid, nimodipine, nimorazole, nimustine, nisoldipine, adrenaline and adrenaline derivatives, norfloxacin, novamine sulfone, noscapine, nystatin, ofloxacin, olanzapine, olsalazine, omeprazole, omoconazole, ondansetron, oxaceprol, oxacillin, oxiconazole, oxymetazoline, pantoprazole, paracetamol, paroxetine, penciclovir, oral penicillins, pentazocine, pentifylline, pentoxifylline, perphenazine, pethidine, plant extracts, phenazone, pheniramine, barbituric acid derivatives, phenylbutazone, phenytoin, pimozide, pindolol, piperazine,

piracetam, pirenzepine, piribedil, piroxicam, pramipexole, pravastatin, prazosin, procaine, promazine, propiverine, propranolol, propyphenazone, prostaglandins, protionamide, proxyphylline, quetiapine, quinapril, quinaprilat, ramipril, ranitidine, reproterol, reserpine, ribavirin, rifampicin, risperidone, ritonavir, ropinirole, roxatidine, roxithromycin, ruscogenin, rutoside and rutoside derivatives, sabadilla, salbutamol, salmeterol, scopolamine, selegiline, sertaconazole, sertindole, sertraline, silicates, sildenafil, simvastatin, sitosterol, sotalol, spaglumic acid, sparfloxacin, spectinomycin, spiramycin, spirapril, spironolactone, stavudine, streptomycin, sucralfate, sufentanil, sulbactam, sulphonamides, sulfasalazine, sulphiride, sultamicillin, sultiam, sumatriptan, suxamethonium chloride, tacrine, tacrolimus, taliolol, tamoxifen, taurolidine, tazarotene, temazepam, teniposide, tenoxicam, terazosin, terbinafine, terbutaline, terfenadine, terlipressin, tertatolol, tetracyclins, teryzoline, theobromine, theophylline, butizine, thiamazole, phenothiazines, thiotepa, tiagabine, tiapride, propionic acid derivatives, ticlopidine, timolol, tinidazole, tioconazole, tioguanine, tioxelone, tiropramide, tizanidine, tolazoline, tolbutamide, tolcapone, tolnaftate, tolperisone, toptecan, torasemide, antioestrogens, tramadol, tramazoline, trandolapril, tranlycypromine, trapidil, trazodone, triamcinolone and triamcinolone derivatives, triamterene, trifluoperidol, trifluridine, trimethoprim, trimipramine, tripeleminamine, triprolidine, trifosfamide, tromantadine, trometamol, tropalpin, troxerutine, tulobuterol, tyramine, tyrothricin, urapidil, ursodeoxycholic acid, chenodeoxycholic acid, valaciclovir, valproic acid, vancomycin, vecuronium chloride, Viagra, venlafaxine, verapamil, vidarabine, vigabatrin, viloazine, vinblastine, vincamine, vincristine, vindesine, vinorelbine, vinpocetine, viquidil, warfarin, xantinol nicotinate, xipamide, zafirlukast, zalcitabine, zidovudine, zolmitriptan, Zolpidem, zopiclone, zotipine and the like. See, e.g., US Patent No. 6,897,205; see also US Patent No. 6,838,528; US Patent No. 6,497,729.

**[00155]** Examples of therapeutic agents employed in conjunction with the invention include, rapamycin, 40-O-(2-Hydroxyethyl)rapamycin (everolimus), 40-O-Benzyl-rapamycin, 40-O-(4'-Hydroxymethyl)benzyl-rapamycin, 40-O-[4'-(1,2-Dihydroxyethyl)]benzyl-rapamycin, 40-O-Allyl-rapamycin, 40-O-[3'-(2,2-Dimethyl-1,3-dioxolan-4(S)-yl)-prop-2'-en-1'-yl]-rapamycin, (2':E,4'S)-40-O-(4',5'-Dihydroxypent-2'-en-1'-yl)-rapamycin, 40-O-(2-Hydroxy)ethoxycarbonylmethyl-rapamycin, 40-O-(3-Hydroxy)propyl-rapamycin, 40-O-(6-Hydroxy)hexyl-rapamycin, 40-O-[2-(2-Hydroxy)ethoxy]ethyl-rapamycin, 40-O-[(3S)-2,2-Dimethyldioxolan-3-yl]methyl-rapamycin, 40-O-[(2S)-2,3-Dihydroxyprop-1-yl]-rapamycin, 40-O-(2-Acetoxy)ethyl-rapamycin, 40-O-(2-Nicotinoyloxy)ethyl-rapamycin, 40-O-[2-(N-Morpholino)acetoxy]ethyl-rapamycin, 40-O-(2-N-Imidazolylacetoxy)ethyl-rapamycin, 40-O-[2-(N-Methyl-N'-piperazinyloxy)acetoxy]ethyl-rapamycin, 39-O-Desmethyl-39,40-O,O-ethylene-rapamycin, (26R)-26-Dihydro-40-O-(2-hydroxy)ethyl-rapamycin, 28-O-Methyl-rapamycin, 40-O-(2-Aminoethyl)-rapamycin, 40-O-(2-Acetaminoethyl)-rapamycin, 40-O-(2-Nicotinamidoethyl)-rapamycin, 40-O-(2-(N-Methyl-imidazo-2'-yl)carbethoxamido)ethyl)-rapamycin, 40-O-(2-Ethoxycarbonylaminoethyl)-rapamycin, 40-O-(2-Tolylsulfonamidoethyl)-rapamycin, 40-O-[2-(4',5'-Dicarboethoxy-1',2',3'-triazol-1'-yl)-ethyl]-rapamycin, 42-Epi-(tetrazolyl)rapamycin (tacrolimus), and 42-[3-hydroxy-2-(hydroxymethyl)-2-methylpropanoate]rapamycin (temsirolimus).

[00156] The active ingredients may, if desired, also be used in the form of their pharmaceutically acceptable salts or derivatives (meaning salts which retain the biological effectiveness and properties of the compounds of this invention and which are not biologically or otherwise undesirable), and in the case of chiral active ingredients it is possible to employ both optically active isomers and racemates or mixtures of diastereoisomers.

[00157] "Stability" as used herein refers to the stability of the drug in a polymer coating deposited on a substrate in its final product form (e.g., stability of the drug in a coated stent). The term stability will define 5% or less degradation of the drug in the final product form.

[00158] "Active biological agent" as used herein refers to a substance, originally produced by living organisms, that can be used to prevent or treat a disease (meaning any treatment of a disease in a mammal, including preventing the disease, i.e. causing the clinical symptoms of the disease not to develop; inhibiting the disease, i.e. arresting the development of clinical symptoms; and/or relieving the disease, i.e. causing the regression of clinical symptoms). It is possible that the active biological agents of the invention may also comprise two or more active biological agents or an active biological agent combined with a pharmaceutical agent, a stabilizing agent or chemical or biological entity. Although the active biological agent may have been originally produced by living organisms, those of the present invention may also have been synthetically prepared, or by methods combining biological isolation and synthetic modification. By way of a non-limiting example, a nucleic acid could be isolated from a biological source, or prepared by traditional techniques, known to those skilled in the art of nucleic acid synthesis. Furthermore, the nucleic acid may be further modified to contain non-naturally occurring moieties. Non-limiting examples of active biological agents include peptides, proteins, enzymes, glycoproteins, nucleic acids (including deoxyribonucleotide or ribonucleotide polymers in either single or double stranded form, and unless otherwise limited, encompasses known analogues of natural nucleotides that hybridize to nucleic acids in a manner similar to naturally occurring nucleotides), antisense nucleic acids, fatty acids, antimicrobials, vitamins, hormones, steroids, lipids, polysaccharides, carbohydrates and the like. They further include, but are not limited to, antirestenotic agents, antidiabetics, analgesics, antiinflammatory agents, antirheumatics, antihypotensive agents, antihypertensive agents, psychoactive drugs, tranquilizers, antiemetics, muscle relaxants, glucocorticoids, agents for treating ulcerative colitis or Crohn's disease, antiallergics, antibiotics, antiepileptics, anticoagulants, antimycotics, antitussives, arteriosclerosis remedies, diuretics, proteins, peptides, enzymes, enzyme inhibitors, gout remedies, hormones and inhibitors thereof, cardiac glycosides, immunotherapeutic agents and cytokines, laxatives, lipid-lowering agents, migraine remedies, mineral products, otologicals, anti parkinson agents, thyroid therapeutic agents, spasmolytics, platelet aggregation inhibitors, vitamins, cytostatics and metastasis inhibitors, phytopharmaceuticals and chemotherapeutic agents. Preferably, the active biological agent is a peptide, protein or enzyme, including derivatives and analogs of natural peptides, proteins and enzymes.

[00159] "Activity" as used herein refers to the ability of a pharmaceutical or active biological agent to prevent or treat a disease (meaning any treatment of a disease in a mammal, including preventing the disease, i.e. causing the clinical symptoms of the disease not to develop; inhibiting the disease, i.e.

arresting the development of clinical symptoms; and/or relieving the disease, i.e. causing the regression of clinical symptoms). Thus the activity of a pharmaceutical or active biological agent should be of therapeutic or prophylactic value.

[00160] "Secondary, tertiary and quaternary structure " as used herein are defined as follows. The active biological agents of the present invention will typically possess some degree of secondary, tertiary and/or quaternary structure, upon which the activity of the agent depends. As an illustrative, non-limiting example, proteins possess secondary, tertiary and quaternary structure. Secondary structure refers to the spatial arrangement of amino acid residues that are near one another in the linear sequence. The  $\alpha$ -helix and the  $\beta$ -strand are elements of secondary structure. Tertiary structure refers to the spatial arrangement of amino acid residues that are far apart in the linear sequence and to the pattern of disulfide bonds. Proteins containing more than one polypeptide chain exhibit an additional level of structural organization. Each polypeptide chain in such a protein is called a subunit. Quaternary structure refers to the spatial arrangement of subunits and the nature of their contacts. For example hemoglobin consists of two  $\alpha$  and two  $\beta$  chains. It is well known that protein function arises from its conformation or three dimensional arrangement of atoms (a stretched out polypeptide chain is devoid of activity). Thus one aspect of the present invention is to manipulate active biological agents, while being careful to maintain their conformation, so as not to lose their therapeutic activity.

[00161] "Polymer" as used herein, refers to a series of repeating monomeric units that have been cross-linked or polymerized. Any suitable polymer can be used to carry out the present invention. It is possible that the polymers of the invention may also comprise two, three, four or more different polymers. In some embodiments, of the invention only one polymer is used. In some preferred embodiments a combination of two polymers are used. Combinations of polymers can be in varying ratios, to provide coatings with differing properties. Those of skill in the art of polymer chemistry will be familiar with the different properties of polymeric compounds. Examples of polymers that may be used in the present invention include, but are not limited to polycarboxylic acids, cellulosic polymers, , proteins, polypeptides, polyvinylpyrrolidone, maleic anhydride polymers, polyamides, polyvinyl alcohols, polyethylene oxides, glycosaminoglycans, polysaccharides, polyesters, polyurethanes, polystyrenes, copolymers, silicones, polyorthoesters, polyanhydrides, copolymers of vinyl monomers, polycarbonates, polyethylenes, polypropylenes, polylactic acids, polyglycolic acids, polycaprolactones, polyhydroxybutyrate valerates, polyacrylamides, polyethers, polyurethane dispersions, polyacrylates, acrylic latex dispersions, polyacrylic acid, mixtures and copolymers thereof. The polymers of the present invention may be natural or synthetic in origin, including gelatin, chitosan, dextrin, cyclodextrin, Poly(urethanes), Poly(siloxanes) or silicones, Poly(acrylates) such as poly(methyl methacrylate), poly(butyl methacrylate), and Poly(2-hydroxy ethyl methacrylate), Poly(vinyl alcohol) Poly(olefins) such as poly(ethylene), poly(isoprene), halogenated polymers such as Poly(tetrafluoroethylene) - and derivatives and copolymers such as those commonly sold as Teflon® products, Poly(vinylidene fluoride), Poly(vinyl acetate), Poly(vinyl pyrrolidone),. Poly(acrylic acid), Polyacrylamide, Poly(ethylene -co-vinyl acetate), Poly(ethylene glycol), Poly(propylene glycol), Poly(methacrylic acid); etc. Suitable polymers

also include absorbable and/or resorbable polymers including the following, combinations, copolymers and derivatives of the following: Polylactides (PLA), Polyglycolides (PGA), Poly(lactide-co-glycolides) (PLGA), Polyanhydrides, Polyorthoesters, Poly(N-(2-hydroxypropyl) methacrylamide), Poly(l-aspartamide), etc.

**[00162]** "Therapeutically desirable morphology" as used herein refers to the gross form and structure of the pharmaceutical agent, once deposited on the substrate, so as to provide for optimal conditions of ex vivo storage, in vivo preservation and/or in vivo release. Such optimal conditions may include, but are not limited to increased shelf life, increased in vivo stability, good biocompatibility, good bioavailability or modified release rates. Typically, for the present invention, the desired morphology of a pharmaceutical agent would be crystalline or semi-crystalline or amorphous, although this may vary widely depending on many factors including, but not limited to, the nature of the pharmaceutical agent, the disease to be treated/prevented, the intended storage conditions for the substrate prior to use or the location within the body of any biomedical implant. Preferably at least 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, or 100%, of the pharmaceutical agent is in crystalline or semi-crystalline form.

**[00163]** "Stabilizing agent" as used herein refers to any substance that maintains or enhances the stability of the biological agent. Ideally these stabilizing agents are classified as Generally Regarded As Safe (GRAS) materials by the US Food and Drug Administration (FDA). Examples of stabilizing agents include, but are not limited to carrier proteins, such as albumin, gelatin, metals or inorganic salts. Pharmaceutically acceptable excipient that may be present can further be found in the relevant literature, for example in the Handbook of Pharmaceutical Additives: An International Guide to More Than 6000 Products by Trade Name, Chemical, Function, and Manufacturer; Michael and Irene Ash (Eds.); Gower Publishing Ltd.; Aldershot, Hampshire, England, 1995.

**[00164]** "Compressed fluid" as used herein refers to a fluid of appreciable density (e.g., >0.2 g/cc) that is a gas at standard temperature and pressure. "Supercritical fluid", "near-critical fluid", "near-supercritical fluid", "critical fluid", "densified fluid" or "densified gas" as used herein refers to a compressed fluid under conditions wherein the temperature is at least 80% of the critical temperature of the fluid and the pressure is at least 50% of the critical pressure of the fluid.

**[00165]** Examples of substances that demonstrate supercritical or near critical behavior suitable for the present invention include, but are not limited to carbon dioxide, isobutylene, ammonia, water, methanol, ethanol, ethane, propane, butane, pentane, dimethyl ether, xenon, sulfur hexafluoride, halogenated and partially halogenated materials such as chlorofluorocarbons, hydrochlorofluorocarbons, hydrofluorocarbons, perfluorocarbons (such as perfluoromethane and perfluoropropane, chloroform, trichloro-fluoromethane, dichloro-difluoromethane, dichloro-tetrafluoroethane) and mixtures thereof.

**[00166]** "Sintering" as used herein refers to the process by which parts of the matrix or the entire polymer matrix becomes continuous (e.g., formation of a continuous polymer film). As discussed below, the sintering process is controlled to produce a fully conformal continuous matrix (complete sintering) or to produce regions or domains of continuous coating while producing voids (discontinuities) in the matrix. As well, the sintering process is controlled such that some phase separation is obtained between polymer

different polymers (e.g., polymers A and B) and/or to produce phase separation between discrete polymer particles. Through the sintering process, the adhesions properties of the coating are improved to reduce flaking or detachment of the coating from the substrate during manipulation in use. As described below, in some embodiments, the sintering process is controlled to provide incomplete sintering of the polymer matrix. In embodiments involving incomplete sintering, a polymer matrix is formed with continuous domains, and voids, gaps, cavities, pores, channels or, interstices that provide space for sequestering a therapeutic agent which is released under controlled conditions. Depending on the nature of the polymer, the size of polymer particles and/or other polymer properties, a compressed gas, a densified gas, a near critical fluid or a super-critical fluid may be employed. In one example, carbon dioxide is used to treat a substrate that has been coated with a polymer and a drug, using dry powder and RESS electrostatic coating processes. In another example, isobutylene is employed in the sintering process. In other examples a mixture of carbon dioxide and isobutylene is employed.

[00167] When an amorphous material is heated to a temperature above its glass transition temperature, or when a crystalline material is heated to a temperature above a phase transition temperature, the molecules comprising the material are more mobile, which in turn means that they are more active and thus more prone to reactions such as oxidation. However, when an amorphous material is maintained at a temperature below its glass transition temperature, its molecules are substantially immobilized and thus less prone to reactions. Likewise, when a crystalline material is maintained at a temperature below its phase transition temperature, its molecules are substantially immobilized and thus less prone to reactions. Accordingly, processing drug components at mild conditions, such as the deposition and sintering conditions described herein, minimizes cross-reactions and degradation of the drug component. One type of reaction that is minimized by the processes of the invention relates to the ability to avoid conventional solvents which in turn minimizes autoxidation of drug, whether in amorphous, semi-crystalline, or crystalline form, by reducing exposure thereof to free radicals, residual solvents and autoxidation initiators.

[00168] "Rapid Expansion of Supercritical Solutions" or "RESS" as used herein involves the dissolution of a polymer into a compressed fluid, typically a supercritical fluid, followed by rapid expansion into a chamber at lower pressure, typically near atmospheric conditions. The rapid expansion of the supercritical fluid solution through a small opening, with its accompanying decrease in density, reduces the dissolution capacity of the fluid and results in the nucleation and growth of polymer particles. The atmosphere of the chamber is maintained in an electrically neutral state by maintaining an isolating "cloud" of gas in the chamber. Carbon dioxide or other appropriate gas is employed to prevent electrical charge is transferred from the substrate to the surrounding environment.

[00169] "Bulk properties" properties of a coating including a pharmaceutical or a biological agent that can be enhanced through the methods of the invention include for example: adhesion, smoothness, conformality, thickness, and compositional mixing.

[00170] The present invention provides several advantages which overcome or attenuate the limitations of current technology for bioabsorbable stents. For example, an inherent limitation of conventional

bioabsorbable polymeric materials relates to the difficulty in forming to a strong, flexible, deformable (e.g. balloon deployable) stent with low profile. The polymers generally lack the strength of high-performance metals. The present invention overcomes these limitations by creating a laminate structure in the essentially polymeric stent. Without wishing to be bound by any specific theory or analogy, the increased strength provided by the stents of the invention can be understood by comparing the strength of plywood vs. the strength of a thin sheet of wood.

[00171] Embodiments of the invention involving a thin metallic stent-framework provide advantages including the ability to overcome the inherent elasticity of most polymers. It is generally difficult to obtain a high rate (e.g., 100%) of plastic deformation in polymers (compared to elastic deformation where the materials have some 'spring back' to the original shape). Again, without wishing to be bound by any theory, the central metal stent framework (that would be too small and weak to serve as a stent itself) would act like wires inside of a plastic, deformable stent, basically overcoming any 'elastic memory' of the polymer.

### EXAMPLES

[00172] The following examples are given to enable those skilled in the art to more clearly understand and to practice the present invention. They should not be considered as limiting the scope of the invention, but merely as being illustrative and representative thereof. The following examples are provided to illustrate selected embodiments. They should not be considered as limiting the scope of the invention, but merely as being illustrative and representative thereof. Thus, the examples provided below, while illustrated with a particular medical device or active agent, are applicable to the range of medical devices and active agents described herein.

### POLYMER STENT

#### [00173] **Example 1 - Bioabsorbable Stent Formed from Polymer Tube**

[00174] In a non-limiting example, the tubular scaffold is made by laser-cutting a stent design from the polymer tube. In some embodiments, the stent design is cut from the polymer tube using a polymer-compatible laser, such as carbon dioxide laser beam or other suitable laser cutting technologies in light of the present disclosure. In another embodiment, the stent design is cut from the polymer tube by water jet cutting or abrasive water jet cutting. Alternatively, the tubular scaffold can be made through photochemical etching or chemical etching. Many slotted tube stent designs can be used to make the bioabsorbable stents disclosed herein. For example, suitable stent designs may include, but are not limited to, bStent2 by Medtronic; BiodivYsio by Biocompatibles Ltd.; Velocity, Palmaz-Schatz 153/154, Palmaz-Schatz Crown by Cordis; Express by Boston Scientific; JOSTENT Flex by JOMED; Multi-Link PENTA, Multi-Link Rx, and Multi-Link Vision by Guidant; and NIR and NIR Flex by Medinol. Other stent designs may also be used in light of the present disclosure.

#### [00175] **Example 2 - Bioabsorbable Stent Formed from Polymer Fibers**

[00176] In a non-limiting example, the tubular scaffold of the present disclosure is made by forming a continuous wave form that includes a plurality of struts and a plurality of crowns. Each crown is a curved portion or turn within the wave form that connects adjacent struts to define the continuous wave

form. In this example, the struts are substantially straight portions of the wave form. In other examples, the struts are slightly bent or have other shapes, such as a sinusoidal wave, for example. The wave form may be formed by a single polymer fiber or filament or a plurality of interconnected polymer fibers or filaments.

[00177] After the wave form is formed, the wave form is wrapped around a mandrel, a center axis of which defines the longitudinal axis of the tubular scaffold. The wave form may be wrapped at an angle that is not perpendicular to the longitudinal axis to form a plurality of helical turns that together generally form a helical coil in the shape of a helix.

[00178] The tubular scaffold also includes a plurality of connections that are configured to connect selected crowns of adjacent turns. In some embodiments, the tubular scaffold includes three connections per complete helix turn. In some embodiments, the tubular scaffold includes four connections per complete helix turn. In some embodiments, the tubular scaffold includes five connections per complete helix turn. Other connection numbers and configurations can also be used in light of the present disclosure. In a non-limiting example, the connections are created by fusing the selected crowns together. As used herein, "fusing" is defined as heating the target portions of materials to be fused together, with or without adding any additional material, to a level where the material in the target portions flow together, intermix with one another, and form a fusion when the materials cool down to, for example, room temperature.

[00179] Many methods for forming wire- or filament-based stents can be used to make the bioabsorbable stents disclosed herein. For example, the methods for forming Wallstent (Boston Scientific), S7 (Medtronic), AngioStent (AngioDynamics), Strecker (Boston Scientific), Expander (Medicorp), Horizon Prostatic (Endocare), Endocoil (InStent), etc, can be used to in light of the present disclosure.

#### [00180] Example 3 - Radial Strength Testing

[00181] This test is conducted to determine and graphically represent the change in stent internal diameter as a function of circumferential pressure and to determine the pressure at which deformation is no longer completely reversible for the disclosed stent. Fifteen (15) 3.0mm and fifteen (15) 4.0mm stents are subjected to all stent-manufacturing procedures. The stents are deployed to nominal pressure and removed from the delivery system. The stents are placed into a sleeve approximately 1mm larger than the stent diameter. A vacuum is then applied and outer diameter measurements taken at various pressures. All samples should maintain a minimum of at least 50 percent of the nominal stent diameter after a 50mm Hg pressure is applied.

#### [00182] Example 4 - Stent Recoil Testing

[00183] This test is conducted to quantify the amount of elastic recoil. Fifteen (15) stent delivery systems of each length and diameter are subjected to all manufacturing and sterilization procedures. The stent delivery system is inflated to nominal pressure (e.g. 9ATM) and the stent is removed allowing for recoil to occur. The inner diameter at each end of the stent is recorded. Recoil is calculated subtracting the recoiled stent inner diameter from the pre-recoil inner diameter. Average recoil may ranged from 0.002 to 0.004 inches.

**[00184] Example 5 - Stent Expansion Testing**

[00185] This test is conducted to determine if the plastic deformation experienced by the stent when expanded from the compressed profile to the final maximum deployed diameter can produce crack initiation for the disclosed stent. Fifteen (15) samples from each length and diameter are deployed to their largest possible diameters by inflating each delivery system to balloon failure. Each stent is examined at 45X magnification for potential cracks.

**[00186] Example 6 - Maximum Pressure (burst test) Testing**

[00187] This test is conducted to demonstrate that the delivery system (with mounted stent) will not experience balloon, shaft, proximal adaptation or proximal/distal seal loss of integrity at or below the pressure required to expand the stent to its labeled diameter. Stent delivery systems that had been subjected to all manufacturing and sterilization procedures are pressurized to 90psi with pressure held for 15 seconds and released for 3 seconds. The cycle is then repeated, increasing inflation pressure by 15psi each cycle until failure.

**[00188] Example 7 - Analysis of the Strut Thickness****[00189] Scanning Electron Microscopy (SEM)**

[00190] A sample coated stent described herein is obtained. Thickness of the device can be assessed using this analytical technique. The thickness of multiple struts were taken to ensure reproducibility and to characterize the coating and stent. The thickness of the coating was observed by SEM using a Hitachi S-4800 with an accelerating voltage of 800V. Various magnifications are used. SEM can provide top-down and cross-section images at various magnifications.

**[00191] Nano X-Ray Computer Tomography**

[00192] Another technique that may be used to view the physical structure of a device in 3-D is Nano X-Ray Computer Tomography (e.g. such as made by SkyScan).

**[00193] Example 8 - Determination of the Bioabsorbability of a Device**

[00194] Techniques presented with respect to showing Bioabsorbability of a polymer coating may be used to additionally and/or alternatively show the bioabsorbability of a device, for example, by GPC In-Vivo testing, HPLC In-Vivo Testing, GPC In-Vitro testing, HPLC In-Vitro Testing, SEM-FIB Testing, Raman Spectroscopy, SEM, and XPS as described herein with variations and adjustments which would be obvious to those skilled in the art. Another technique to view the physical structure of a device in 3-D is Nano X-Ray Computer Tomography (e.g. such as made by SkyScan), which could be used in an elution test and/or bioabsorbability test, as described herein to show the physical structure of the coating remaining on stents at each time point, as compared to a scan prior to elution/bioabsorbation..

**DRUG ELUTION POLYMER STENT****[00195] Example 11 - Determination of an Elution Profile****[00196] In Vitro**

[00197] In one method, a stent described herein is obtained. The elution profile is determined as follows: stents are placed in 16 mL test tubes and 15 mL of 10 mM PBS (pH 7.4) is pipetted on top. The tubes are capped and incubated at 37 C with end-over-end rotation at 8 rpm. Solutions are then collected at the

designated time points (e.g. Id, 7d, 14d, 21d, and 28d) (e.g. 1 week, 2 weeks, and 10 weeks) and replenished with fresh 1.5 ml solutions at each time point to prevent saturation. One mL of DCM is added to the collected sample of buffer and the tubes are capped and shaken for one minute and then centrifuged at 200.times.G for 2 minutes. The supernatant is discarded and the DCM phase is evaporated to dryness under gentle heat (40.degree. C.) and nitrogen gas. The dried DCM is reconstituted in 1 mL of 60:40 acetonitrile:water (v/v) and analyzed by HPLC. HPLC analysis is performed using Waters HPLC system (mobile phase 58:37:5 acetonitrile:water:methanol 1 mL/min, 20 uL injection, CI8 Novapak Waters column with detection at 232 nm).

**[00198]** In another method, the in vitro pharmaceutical agent elution profile is determined by a procedure comprising contacting the device with an elution media comprising ethanol (5%) wherein the pH of the media is about 7.4 and wherein the device is contacted with the elution media at a temperature of about 37.degree. C. The elution media containing the device is optionally agitating the elution media during the contacting step. The device is removed (and/or the elution media is removed) at least at designated time points (e.g. 1 h, 3 h, 5 h, 7 h, Id, and daily up to 28d) (e.g. 1 week, 2 weeks, and 10 weeks). The elution media is then assayed using a UV-Vis for determination of the pharmaceutical agent content. The elution media is replaced at each time point with fresh elution media to avoid saturation of the elution media. Calibration standards containing known amounts of drug were also held in elution media for the same durations as the samples and used at each time point to determine the amount of drug eluted at that time (in absolute amount and as a cumulative amount eluted).

**[00199]** In another method, the in vitro pharmaceutical agent elution profile is determined by a procedure comprising contacting the device with an elution media comprising ethanol (20%) and phosphate buffered saline (80%) wherein the pH of the media is about 7.4 and wherein the device is contacted with the elution media at a temperature of about 37.degree. C. The elution media containing the device is optionally agitating the elution media during the contacting step. The device is removed (and/or the elution media is removed) at least at designated time points (e.g. 1 h, 3 h, 5 h, 7 h, Id, and daily up to 28d) (e.g. 1 week, 2 weeks, and 10 weeks). The elution media is replaced periodically (at least at each time point, and/or daily between later time points) to prevent saturation; the collected media are pooled together for each time point. The elution media is then assayed for determination of the pharmaceutical agent content using HPLC. The elution media is replaced at each time point with fresh elution media to avoid saturation of the elution media. Calibration standards containing known amounts of drug are also held in elution media for the same durations as the samples and used at each time point to determine the amount of drug eluted at that time (in absolute amount and as a cumulative amount eluted). Where the elution method changes the drug over time, resulting in multiple peaks present for the drug when tested, the use of these calibration standards will also show this change, and allows for adding all the peaks to give the amount of drug eluted at that time period (in absolute amount and as a cumulative amount eluted).

**[00200]** To obtain an accelerated in-vitro elution profile, an accelerated elution buffer comprising 18% v/v of a stock solution of 0.067 mol/L  $\text{KH}_2\text{PO}_4$  and 82% v/v of a stock solution of 0.067 mol/L

Na2HP04 with a pH of 7.4 is used. Stents described herein are expanded and then placed in 1.5 ml solution of this accelerated elution in a 70 degree Celsius bath with rotation at 70 rpm. The solutions are then collected at the following time points: 0 min., 15 min., 30 min., 1 hr, 2 hr, 4 hr, 6 hr, 8 hr, 12 hr, 16 hr, 20 hr, 24 hr, 30 hr, 36 hr and 48 hr. Fresh accelerated elution buffer are added periodically at least at each time point to replace the incubated buffers that are collected and saved in order to prevent saturation. For time points where multiple elution media are used (refreshed between time points), the multiple collected solutions are pooled together for liquid extraction by dichloromethane.

Dichloromethane extraction and HPLC analysis is performed in the manner described previously.

#### [002011] In Vivo

[00202] Rabbit in vivo models as described above are euthanized at multiple time points. Stents are explanted from the rabbits. The explanted stents are placed in 16 mL test tubes and 15 mL of 10 mM PBS (pH 7.4) is pipette on top. One mL of DCM is added to the buffer and the tubes are capped and shaken for one minute and then centrifuged at 200.times.G for 2 minutes. The supernatant is discarded and the DCM phase is evaporated to dryness under gentle heat (40.degree. C.) and nitrogen gas. The dried DCM is reconstituted in 1 mL of 60:40 acetonitrile:water (v/v) and analyzed by HPLC. HPLC analysis is performed using Waters HPLC system (mobile phase 58:37:5 acetonitrile:water:methanol 1 mL/min, 20 uL injection, C18 Novapak Waters column with detection at 232 nm).

#### **[00203] Example 12 - Crystallinity of Drug**

[00204] The presence and or quantification of the active agent crystallinity can be determined from a number of characterization methods known in the art, but not limited to, XRPD, vibrational spectroscopy (FTIR, NIR, Raman), polarized optical microscopy, calorimetry, thermal analysis and solid-state NMR.

#### X-Ray Diffraction to Determine the Presence and/or Quantification of Active Agent Crystallinity

[00205] Active agent and polymer coated proxy substrates are prepared using 3 16L stainless steel coupons for X-ray powder diffraction (XRPD) measurements to determine the presence of crystallinity of the active agent. The coating on the coupons is equivalent to the coating on the stents described herein. Coupons of other materials described herein, such as cobalt-chromium alloys, may be similarly prepared and tested. Likewise, substrates such as stents, or other medical devices described herein may be prepared and tested. Where a coated stent is tested, the stent may be cut lengthwise and opened to lay flat in a sample holder.

[00206] For example XRPD analyses are performed using an X-ray powder diffractometer (for example, a Bruker D8 Advance X-ray diffractometer) using Cu Ka radiation. Diffractograms are typically collected between 2 and 40 degrees 2 theta. Where required low background XRPD sample holders are employed to minimize background noise.

[00207] The diffractograms of the deposited active agent are compared with diffractograms of known crystallized active agents, for example micronized crystalline sirolimus in powder form. XRPD patterns of crystalline forms show strong diffraction peaks whereas amorphous show diffuse and non-distinct patterns. Crystallinity is shown in arbitrary Intensity units.

[00208] A related analytical technique which may also be used to provide crystallinity detection is wide angle scattering of radiation (e.g.; Wide Angle X-ray Scattering or WAXS), for example, as described in F. Unger, et al., "Poly(ethylene carbonate): A thermoelastic and biodegradable biomaterial for drug eluting stent coatings?" Journal of Controlled Release, Volume 117, Issue 3, 312-321 (2007) for which the technique and variations of the technique specific to a particular sample would be obvious to one of skill in the art.

#### Raman Spectroscopy

[00209] Raman spectroscopy, a vibrational spectroscopy technique, can be useful, for example, in chemical identification, characterization of molecular structures, effects of bonding, identification of solid state form, environment and stress on a sample. Raman spectra can be collected from a very small volume ( $< 1 \mu\text{m}^3$ ); these spectra allow the identification of species present in that volume. Spatially resolved chemical information, by mapping or imaging, terms often used interchangeably, can be achieved by Raman microscopy.

[00210] Raman spectroscopy and other analytical techniques such as described in Balss, et al., "Quantitative spatial distribution of sirolimus and polymers in drug-eluting stents using confocal Raman microscopy" J. of Biomedical Materials Research Part A, 258-270 (2007), incorporated in its entirety herein by reference, and/or described in Belu et al., "Three-Dimensional Compositional Analysis of Drug Eluting Stent Coatings Using Cluster Secondary Ion Mass Spectroscopy" Anal. Chem. 80: 624-632 (2008) incorporated herein in its entirety by reference may be used.

[00211] For example, to test a sample using Raman microscopy and in particular confocal Raman microscopy, it is understood that to get appropriate Raman high resolution spectra sufficient acquisition time, laser power, laser wavelength, sample step size and microscope objective need to be optimized. For example a sample (a coated stent) is prepared as described herein. Alternatively, a coated coupon could be tested in this method. Maps are taken on the coating using Raman microscopy. A WITec CRM 200 scanning confocal Raman microscope using a Nd:YAG laser at 532 nm is applied in the Raman imaging mode. The laser light is focused upon the sample using a 100 $\times$  dry objective (numerical aperture 0.90), and the finely focused laser spot is scanned into the sample. As the laser scans the sample, over each 0.33 micron interval a Raman spectrum with high signal to noise is collected using 0.3 seconds of integration time. Each confocal cross-sectional image of the coatings displays a region 70  $\mu\text{m}$  wide by 10  $\mu\text{m}$  deep, and results from the gathering of 6300 spectra with a total imaging time of 32 min.

[00212] Multivariate analysis using reference spectra from samples of rapamycin (amorphous and crystalline) and polymer are used to deconvolve the spectral data sets, to provide chemical maps of the distribution.

#### Infrared (IR) Spectroscopy for In-Vitro Testing

[00213] Infrared (IR) Spectroscopy such as FTIR and ATR-IR are well utilized techniques that can be applied to show, for example, the quantitative drug content, the distribution of the drug in the sample coating, the quantitative polymer content in the coating, and the distribution of polymer in the coating. Infrared (IR) Spectroscopy such as FTIR and ATR-IR can similarly be used to show, for example, drug

crystallinity. The following table lists the typical IR materials for various applications. These IR materials are used for IR windows, diluents or ATR crystals.

MATERIAL	NACL	KBR	CSI	AGCL	GE	ZNSE	DIAMOND
Transmission range (cm-1)	40,000 ~625	40,000 ~400	40,000 ~200	25,000 ~360	5,500 ~625	20,000 ~454	40,000 ~2,500 & 1667-33
Water sol (g/100g, 25C)	35.7	53.5	44.4	Insol.	Insol.	Insol.	Insol.
Attacking materials	Wet Solvents	Wet Solvents	Wet Solvents	Ammonium Salts	H2SO4, aqua regin	Acids, strong alkalies, chlorinated solvents	K2Cr2Os, conc. H2SO4

[00214] In one test, a coupon of crystalline ZnSe is coated by the processes described herein, creating a PDPDP (Polymer, Drug, Polymer, Drug, Polymer) layered coating that is about 10 microns thick. The coated coupon is analyzed using FTIR. The resulting spectrum shows crystalline drug as determined by comparison to the spectrum obtained for the crystalline form of a drug standard (i.e. a reference spectrum).

#### Differential Scanning Calorimetry (DSC)

[00215] DSC can provide qualitative evidence of the crystallinity of the drug (e.g. rapamycin) using standard DSC techniques obvious to one of skilled in the art. Crystalline melt can be shown using this analytical method (e.g. rapamycin crystalline melting - at about 185 °C to 200 °C, and having a heat of fusion at or about 46.8 J/g). The heat of fusion decreases with the percent crystallinity. Thus, the degree of crystallinity could be determined relative to a pure sample, or versus a calibration curve created from a sample of amorphous drug spiked and tested by DSC with known amounts of crystalline drug. Presence (at least) of crystalline drug on a stent could be measured by removing (scraping or stripping) some drug from the stent and testing the coating using the DSC equipment for determining the melting temperature and the heat of fusion of the sample as compared to a known standard and/or standard curve.

#### Confocal Raman Microscopy

Confocal Raman Microscopy can provide nondestructive depth analysis and allows coating specific Raman spectral features to be obtained (Bugay *et al.*, "Raman Analysis of Pharmaceuticals," in *"Applications of Vibrational Spectroscopy in Pharmaceutical Research and Development," Ed. Pivonka, D. E., Chalmers, J. M., Griffiths, P. R. (2007) Wiley and Sons*). In confocal Raman microscopy an aperture is place in a focal place of the collected beam. This limitation defines a shallow portion of the depth of field and thereby provides definition of the z-axis spatial resolution for data collection. By adjusting the aperture and moving the focus within the sample, the sampling position within the sample

moves. Moving the sample focus from the top surface, deeper into the specimen facilitates nondestructive depth analysis.

**[00216] Example 13 - Coating Uniformity**

[00217] The ability to uniformly coat devices, e.g., pre- and post-expansion stents, and balloons, with controlled composition and thickness using electrostatic capture in a rapid expansion of supercritical solution (RESS) experimental series has been demonstrated.

Scanning Electron Microscopy (SEM)

[00218] Devices are observed by SEM using a Hitachi S-4800 with an accelerating voltage of 800V. Various magnifications are used to evaluate the integrity, especially at high strain regions. SEM can provide top-down and cross-section images at various magnifications. Coating uniformity and thickness can also be assessed using this analytical technique.

[00219] Pre- and post-inflation balloons, for example, may be observed by SEM using a Hitachi S-4800 with an accelerating voltage of 800V. Various magnifications may be used to evaluate the integrity of the layers, and or of the coating.

Scanning Electron Microscopy (SEM) with Focused Ion Beam (FIB)

[00220] Devices as described herein, and or produced by methods described herein are visualized using SEM-FIB analysis. Alternatively, a coated coupon could be tested in this method. Focused ion beam FIB is a tool that allows precise site-specific sectioning, milling and depositing of materials. FIB can be used in conjunction with SEM, at ambient or cryo conditions, to produce in-situ sectioning followed by high-resolution imaging. Cross-sectional FIB images may be acquired, for example, at 7000x and/or at 20000x magnification. An even coating of consistent thickness is visible.

Optical Microscopy

[00221] An optical microscope may be used to create and inspect the devices and to empirically survey the coating of the substrate (e.g. coating uniformity). Nanoparticles of the drug and/or the polymer can be seen on the surfaces of the substrate using this analytical method. Following sintering, the coatings can be see using this method to view the coating conformality and for evidence of crystallinity of the drug.

**[00222] Example 14 - Total Drug Content on Coated Stent (Used or Unused)**

[00223] Determination of the total content of the active agent in a coated substrate may be tested using techniques described herein as well as other techniques obvious to one of skill in the art, for example using GPC and HPLC techniques to extract the drug from the coated substrate and determine the total content of drug in the sample.

[00224] UV-VIS can be used to quantitatively determine the mass of rapamycin (or another active agent) coated onto the substrates. A UV-Vis spectrum of Rapamycin can be shown and a Rapamycin calibration curve can be obtained, (e.g.  $\lambda$  @ 277nm in ethanol). Rapamycin is then dissolved from the coated substrate in ethanol, and the drug concentration and mass calculated.

[00225] In one test, the total amount of rapamycin (or another active agent) present in units of micrograms per substrate is determined by reverse phase high performance liquid chromatography with

UV detection (RP-HPLC-UV). The analysis is performed with modifications of literature-based HPLC methods for rapamycin (or the other active agent) that would be obvious to a person of skill in the art. The average drug content of samples (n=10) from devices comprising stents and coatings as described herein, and/or methods described herein are tested.

[00226] Further understanding of the present invention may be gained through contemplation of the numbered embodiments below.

1. A biomedical implant, comprising:  
a tubular scaffold comprising a plurality of polymer struts, wherein the polymer struts are interconnected and define a plurality of deformable cells,  
wherein the polymer struts have an average thickness of no more than 150  $\mu\text{m}$ , and  
wherein the polymer struts comprise a fiber-reinforced polymer composite material.
2. The biomedical implant of embodiment 1, wherein the tubular scaffold maintains at least 50% of its nominal luminal cross sectional area under a pressure load of 50mmHg.
3. The biomedical implant of embodiment 1, wherein the tubular scaffold maintains at least 80% of its nominal luminal cross sectional area under a pressure load of 50mmHg.
4. The biomedical implant of embodiment 1, wherein the tubular scaffold maintains at least 50% of its nominal luminal cross sectional area under a pressure load of 50mmHg upon 3 months of exposure to saline *in vitro*.
5. The biomedical implant of embodiment 1, wherein the tubular scaffold maintains at least 50% of its nominal luminal cross sectional area under a pressure load of 50mmHg upon 3 months *in vivo*.
6. The biomedical implant of embodiment 1, wherein the tubular scaffold maintains at least 50% of its nominal luminal cross sectional area under a pressure load of 50mmHg upon 6 months of exposure to saline *in vitro*.
7. The biomedical implant of embodiment 1, wherein the tubular scaffold maintains at least 50% of its nominal luminal cross sectional area under a pressure load of 50mmHg upon 6 months *in vivo*.
8. The biomedical implant of embodiment 1, wherein at least 80% of the polymer struts are bioabsorbed within 2 years after deployment *in vivo*.
9. The biomedical implant of embodiment 1, wherein at least 80% of the polymer struts are bioabsorbed within 1 year after deployment *in vivo*.
10. The biomedical implant of embodiment 1, wherein the polymer struts have an average thickness of no more than 120  $\mu\text{m}$ .
11. The biomedical implant of embodiment 1, wherein the polymer struts have an average thickness of no more than 90  $\mu\text{m}$ .
12. The biomedical implant of embodiment 1, wherein the fiber-reinforced polymer composite material comprise a bioabsorbable polymer material and a reinforcement fiber material.

13. The biomedical implant of embodiment 12, wherein the reinforcement fiber material is carbon fiber material, carbon nanotube material, bioabsorbable glass material, or combinations thereof.
14. The biomedical implant of embodiment 13, wherein carbon nanotube material is a multi-wall carbon nanotube material.
15. The biomedical implant of embodiment 12, wherein the reinforcement fiber material is distributed throughout the polymer struts.
16. The biomedical implant of embodiment 12, wherein the fiber-reinforced polymer composite material has a tensile modulus that is at least five times of a tensile modulus of the bioabsorbable polymer.
17. The biomedical implant of embodiment 12, wherein the fiber-reinforced polymer composite material has a tensile modulus that is at least three times of a tensile modulus of the bioabsorbable polymer.
18. The biomedical implant of embodiment 12, wherein the fiber-reinforced polymer composite material has a tensile modulus that is at least two times of a tensile modulus of the bioabsorbable polymer.
19. The biomedical implant of embodiment 12, wherein the fiber-reinforced polymer composite material has a tensile strength that is at least five times of a tensile strength of the bioabsorbable polymer.
20. The biomedical implant of embodiment 12, wherein the fiber-reinforced polymer composite material has a tensile strength that is at least three times of a tensile strength of the bioabsorbable polymer.
21. The biomedical implant of embodiment 12, wherein the fiber-reinforced polymer composite material has a tensile strength that is at least two times of a tensile strength of the bioabsorbable polymer.
22. The biomedical implant of embodiment 12, wherein the fiber-reinforced polymer composite material comprises from 0.1 wt% to 15 wt% of the reinforcement fiber material.
23. The biomedical implant of embodiment 12, wherein the fiber-reinforced polymer composite material comprises from 0.1 wt% to 10 wt% of the reinforcement fiber material.
24. The biomedical implant of embodiment 12, wherein the fiber-reinforced polymer composite material comprises from 0.1 wt% to 5 wt% of the reinforcement fiber material.
25. The biomedical implant of embodiment 12, wherein the fiber-reinforced polymer composite material comprises from 0.1 wt% to 1.5 wt% of the reinforcement fiber material.
26. The biomedical implant of embodiment 12, wherein the bioabsorbable polymer material is selected from the group consisting of polylactides (PLA); poly(lactide-co-glycolide) (PLGA); polyanhydrides; polyorthoesters; poly(N-(2-hydroxypropyl) methacrylamide); poly(dl-lactide) (DLPLA); poly(l-lactide) (LPLA); poly(d-lactide) (DPLA); polyglycolide (PGA); poly(dioxanone) (PDO); poly(glycolide-co-trimethylene carbonate) (PGA-TMC); poly(l-

- lactide-co-glycolide) (PGA-LPLA); poly(dl-lactide-co-glycolide) (PGA-DLPLA); poly(l-lactide-co-dl-lactide) (LPLA-DLPLA); poly(glycolide-co-trimethylene carbonate-co-dioxanone) (PDO-PGA-TMC), poly(lactic acid-co-caprolactone) (PLACL), and mixtures or co-polymers thereof.
27. The biomedical implant of embodiment 26, wherein the bioabsorbable polymer material is PLGA.
  28. The biomedical implant of embodiment 27, wherein the PLGA has a ratio of lactic acid monomer to glycolic acid monomer ranging from 72:28 to 78:22.
  29. The biomedical implant of embodiment 27, wherein the PLGA has a ratio of lactic acid monomer to glycolic acid monomer ranging from 62:38 to 68:32.
  30. The biomedical implant of embodiment 27, wherein the PLGA has a ratio of lactic acid monomer to glycolic acid monomer ranging from 47:53 to 53:47.
  31. The biomedical implant of embodiment 27, wherein the PLGA has a weight average molecular weight of about 8,000 Dalton to about 12,000 Dalton.
  32. The biomedical implant of embodiment 27, wherein the PLGA has a weight average molecular weight of about 12,000 Dalton to about 16,000 Dalton.
  33. The biomedical implant of embodiment 26, wherein the bioabsorbable polymer material has a weight average molecular weight of at least 90,000 Dalton, and optionally at least 100,000 Dalton.
  34. The biomedical implant of embodiment 33, wherein the gel-spun polymer material is LPLA having a weight average molecular weight of at least 100,000 Dalton.
  35. The biomedical implant of embodiment 26, wherein the bioabsorbable polymer material is PLA, LPLA, or PGA.
  36. The biomedical implant of embodiment 12, wherein the polymer struts have anisotropic elastic modulus.
  37. The biomedical implant of embodiment 36, wherein the polymer struts have an average longitudinal elastic modulus and an average lateral elastic modulus, the average longitudinal elastic modulus being greater than the average lateral elastic modulus.
  38. The biomedical implant of embodiment 36, wherein the average longitudinal elastic modulus is at least three times the average lateral elastic modulus.
  39. The biomedical implant of embodiment 36, wherein the average longitudinal elastic modulus is at least five times the average lateral elastic modulus.
  40. The biomedical implant of embodiment 36, wherein the average longitudinal elastic modulus is at least ten times the average lateral elastic modulus.
  41. The biomedical implant of embodiment 12, wherein more than 50% of the reinforcement fiber material in the polymer struts are longitudinally aligned.

42. The biomedical implant of embodiment 12, wherein more than 70% of the reinforcement fiber material in the polymer struts are longitudinally aligned.
43. The biomedical implant of embodiment 12, wherein more than 90% of the reinforcement fiber material in the polymer struts are longitudinally aligned.
44. The biomedical implant of embodiment 1, wherein the polymer struts have an average deformation angle of at least 60 degrees.
45. The biomedical implant of embodiment 1, wherein the polymer struts have an average deformation angle of at least 45 degrees.
46. The biomedical implant of embodiment 1, wherein the polymer struts are not structurally reinforced with a metal material.
47. The biomedical implant of embodiment 1, wherein the polymer struts comprises a polymer material selected from the group consisting of polycarboxylic acids, cellulosic polymers, proteins, polypeptides, polyvinylpyrrolidone, maleic anhydride polymers, polyamides, polyvinyl alcohols, polyethylene oxides, glycosaminoglycans, polysaccharides, polyesters, aliphatic polyesters, polyurethanes, polystyrenes, copolymers, silicones, silicone containing polymers, polyalkyl siloxanes, polyorthoesters, polyanhydrides, copolymers of vinyl monomers, polycarbonates, polyethylenes, polypropytenes, polylactic acids, polylactides, polyglycolic acids, polyglycolides, polylactide-co-glycolides, polycaprolactones, poly( $\epsilon$ -caprolactone)s, polyhydroxybutyrate valerates, polyacrylamides, polyethers, polyurethane dispersions, polyacrylates, acrylic latex dispersions, polyacrylic acid, polyalkyl methacrylates, polyalkylene-co-vinyl acetates, polyalkylenes, aliphatic polycarbonates polyhydroxyalkanoates, polytetrahaloalkylenes, poly(phosphasones), polytetrahaloalkylenes, poly(phosphasones), and mixtures, combinations, and copolymers thereof.
48. The biomedical implant of embodiment 1, wherein the tubular scaffold is expandable from an undeployed diameter to a nominal diameter without affecting the structural integrity of the tubular scaffold
49. The biomedical implant of embodiment 48, wherein the tubular scaffold is further expandable from the nominal diameter to an over-deployed diameter without affecting the structural integrity of the tubular scaffold.
50. The biomedical implant of embodiment 49, wherein the over-deployed diameter is about 1.0 mm greater than the nominal diameter.
51. The biomedical implant of embodiment 49, wherein the over-deployed diameter is about 0.5 mm greater than the nominal diameter.
52. The biomedical implant of embodiment 48, wherein the tubular scaffold is expandable by an inflatable balloon positioned within the tubular scaffold.
53. The biomedical implant of embodiment 52, wherein the tubular scaffold has a nominal diameter of 2.25 mm at nominal balloon pressure.

54. The biomedical implant of embodiment 52, wherein the tubular scaffold has a nominal diameter of 2.5 mm at nominal balloon pressure.
55. The biomedical implant of embodiment 52, wherein the tubular scaffold has a nominal diameter of 3.0 mm at nominal balloon pressure.
56. The biomedical implant of embodiment 52, wherein the tubular scaffold has a nominal diameter of 3.5 mm at nominal balloon pressure.
57. The biomedical implant of embodiment 52, wherein the tubular scaffold has a deployed diameter of 4.0 mm at nominal balloon pressure.
58. The biomedical implant of embodiment 52, wherein the tubular scaffold has a nominal diameter of 4.5 mm at nominal balloon pressure.
59. The biomedical implant of embodiment 48, wherein the polymer struts comprise a shape-memory polymer and wherein tubular scaffold is self-expandable.
60. The biomedical implant of embodiment 59, wherein the tubular scaffold is self-expandable upon change in temperature.
61. The biomedical implant of embodiment 59, wherein the tubular scaffold is self-expandable upon change in crystallinity of the shape-memory polymer.
62. The biomedical implant of embodiment 1, wherein the tubular scaffold is formed from a plurality of sinusoidal polymer fibers comprising the plurality of polymer struts.
63. The biomedical implant of embodiment 62, wherein the sinusoidal polymer fibers are interconnected at a plurality of connecting points.
64. The biomedical implant of embodiment 1, wherein the tubular scaffold is formed from a single polymer fiber.
65. The biomedical implant of embodiment 64, wherein the single polymer fiber comprises a plurality of sinusoidal sections interconnected at a plurality of connecting points.
66. The biomedical implant of embodiment 1, further comprising a pharmaceutical agent incorporated to the tubular scaffold.
67. The biomedical implant of embodiment 66, wherein the pharmaceutical agent is a macrolide immunosuppressant.
68. The biomedical implant of embodiment 67, wherein the macrolide immunosuppressant is rapamycin or a derivative, a prodrug, a hydrate, an ester, a salt, a polymorph, a derivative or an analog thereof.
69. The biomedical implant of embodiment 67, wherein the macrolide immunosuppressant is selected from the group consisting of rapamycin, 40-O-(2-Hydroxyethyl)rapamycin (everolimus), 40-O-Benzyl-rapamycin, 40-O-(4'-Hydroxymethyl)benzyl-rapamycin, 40-O-[4'-(1,2-Dihydroxyethyl)]benzyl-rapamycin, 40-O-Allyl-rapamycin, 40-O-[3'-(2,2-Dimethyl-1,3-dioxolan-4(S)-yl)-prop-2'-en-1'-yl] -rapamycin, (2':E,4'S)-40-O-(4',5'-Dihydroxypent-2'-en-1'-yl)-rapamycin, 40-O-(2-Hydroxy)ethoxycarbonylmethyl-rapamycin, 40-O-(3-Hydroxy)propyl-rapamycin, 40-O-(6-Hydroxy)hexyl-rapamycin, 40-O-[2-(2-

Hydroxy)ethoxy]ethyl-rapamycin, 40-O-[(3S)-2,2-Dimethyldioxolan-3-yl]methyl-rapamycin, 40-O-[(2S)-2,3-Dihydroxyprop-1-yl]-rapamycin, 40-O-(2-Acetoxy)ethyl-rapamycin, 40-O-(2-Nicotinoyloxy)ethyl-rapamycin, 40-O-[2-(N-Morpholino)acetoxy]ethyl-rapamycin, 40-O-(2-N-Imidazolylacetoxy)ethyl-rapamycin, 40-O-[2-(N-Methyl-N'-piperazinyl)acetoxy]ethyl-rapamycin, 39-O-Desmethyl-39,40-O,O-ethylene-rapamycin, (26R)-26-Dihydro-40-O-(2-hydroxy)ethyl-rapamycin, 28-O-Methyl-rapamycin, 40-O-(2-Aminoethyl)-rapamycin, 40-O-(2-Acetaminoethyl)-rapamycin, 40-O-(2-Nicotinamidoethyl)-rapamycin, 40-O-(2-(N-Methyl-imidazo-2'-ylcarbethoxamido)ethyl)-rapamycin, 40-O-(2-Ethoxycarbonylaminoethyl)-rapamycin, 40-O-(2-Tolylsulfonamidoethyl)-rapamycin, 40-O-[2-(4',5'-Dicarboethoxy-1',2',3'-triazol-1'-yl)-ethyl]-rapamycin, 42-Epi-(tetrazolyl)rapamycin (tacrolimus), and 42-[3-hydroxy-2-(hydroxymethyl)-2-methylpropanoate]rapamycin.

70. The biomedical implant of embodiment 67, wherein the pharmaceutical agent is rapamycin.
71. The biomedical implant of embodiment 66, wherein the pharmaceutical agent is impregnated in at least a portion of the tubular scaffold.
72. The biomedical implant of embodiment 71, wherein the pharmaceutical agent is impregnated in the polymer struts.
73. The biomedical implant of embodiment 72, wherein the pharmaceutical agent is evenly distributed throughout the polymer struts.
74. The biomedical implant of embodiment 66, wherein at least a portion of the tubular scaffold is covered with a coating comprising the pharmaceutical agent.
75. The biomedical implant of embodiment 74, wherein the coating further comprises a coating polymer.
76. The biomedical implant of embodiment 75, wherein at least 90% of the surface area of the pharmaceutical agent is encapsulated in the coating polymer.
77. The biomedical implant of embodiment 75, wherein the coating polymer comprises a bioabsorbable polymer.
78. The biomedical implant of embodiment 77, wherein the bioabsorbable polymer is selected from the group consisting of polylactides (PLA); poly(lactide-co-glycolide) (PLGA); polyanhydrides; polyorthoesters; poly(N-(2-hydroxypropyl) methacrylamide); poly(dl-lactide) (DLPLA); poly(l-lactide) (LPLA); polyglycolide (PGA); poly(dioxanone) (PDO); poly(glycolide-co-trimethylene carbonate) (PGA-TMC); poly(l-lactide-co-glycolide) (PGA-LPLA); poly(dl-lactide-co-glycolide) (PGA-DLPLA); poly(l-lactide-co-dl-lactide) (LPLA-DLPLA); poly(glycolide-co-trimethylene carbonate-co-dioxanone) (PDO-PGA-TMC), polyarginine, and mixtures or co-polymers thereof.
79. The biomedical implant of embodiment 77, wherein the biodegradable polymer is selected from the group consisting of PLGA, polyarginine, and mixtures thereof.
80. The biomedical implant of embodiment 1, wherein the biomedical implant is a vascular stent.

81. The biomedical implant of embodiment 80, wherein the biomedical implant is a coronary artery stent.
82. The biomedical implant of embodiment 80, wherein the biomedical implant is a peripheral artery stent.
83. The biomedical implant of embodiment 1, wherein the biomedical implant is a non-vascular stent.
84. The biomedical implant of embodiment 83, wherein the non-vascular stent is selected from esophageal stent, biliary stent, duodenal stent, colonic stent, and pancreatic stent.
85. A method of forming a biomedical implant, comprising:
  - forming one or more polymer fibers comprising a bioabsorbable polyester material and a reinforcement fiber material; and
  - interconnecting the polymer fibers to form a tubular scaffold, the tubular scaffold comprising a plurality of interconnected polymer struts to define a plurality of deformable cells, wherein the polymer struts have an average thickness of no more than 150  $\mu\text{m}$ .
86. The method of embodiment 85, wherein the tubular scaffold maintains at least 50% of its nominal luminal cross sectional area under a pressure load of at least 50mmHg.
87. The method of embodiment 85, wherein the tubular scaffold maintains at least 80% of its nominal luminal cross sectional area under a pressure load of at least 50mmHg.
88. The method of embodiment 85, wherein the reinforcement fiber material is carbon fiber material, carbon nanotube material, bioabsorbable glass material, or combinations thereof.
89. The method of embodiment 88, wherein the carbon nanotube material is a multi-wall carbon nanotube material.
90. The method of embodiment 85, wherein the polymer fibers comprise from 0.1 wt% to 15 wt% of the reinforcement fiber material.
91. The method of embodiment 85, wherein the polymer fibers comprise from 0.1 wt% to 10 wt% of the reinforcement fiber material.
92. The method of embodiment 85, wherein the polymer fibers comprise from 0.1 wt% to 5 wt% of the reinforcement fiber material.
93. The method of embodiment 85, wherein the polymer fibers comprise from 0.1 wt% to 1.5 wt% of the reinforcement fiber material.
94. The method of embodiment 85, wherein the polyester is selected from the group consisting of polylactides (PLA); poly(lactide-co-glycolide) (PLGA); polyanhydrides; polyorthoesters; poly(N-(2-hydroxypropyl) methacrylamide); poly(dl-lactide) (DLPLA); poly(l-lactide) (LPLA); poly(d-lactide) (DPLA); polyglycolide (PGA); poly(dioxanone) (PDO); poly(glycolide-co-trimethylene carbonate) (PGA-TMC); poly(l-lactide-co-glycolide) (PGA-LPLA); poly(dl-lactide-co-glycolide) (PGA-DLPLA); poly(l-lactide-co-dl-lactide) (LPLA-DLPLA); poly(glycolide-co-trimethylene carbonate-co-dioxanone) (PDO-PGA-TMC), poly(lactic acid-co-caprolactone) (PLACL), and mixtures or co-polymers thereof.

95. The method of embodiment 85, wherein the polyester is PLGA.
96. The method of embodiment 85, wherein the polyester is PLA or LPLA.
97. A method of making a bioabsorbable tubular scaffold, the method comprising forming a composition comprising a bioabsorbable polyester material and a reinforcement fiber material;  
extruding the composition to form a polymer tube, wherein the polymer tube has an average wall thickness of no more than 150  $\mu\text{m}$ ; and  
removing a portion of the polymer tube to form a scaffold comprising interconnected struts.
98. The method of embodiment 97, wherein the tubular scaffold maintains at least 50% of its nominal luminal cross sectional area under a pressure load of at least 50mmHg.
99. The method of embodiment 97, wherein the tubular scaffold maintains at least 80% of its nominal luminal cross sectional area under a pressure load of at least 50mmHg.
100. The method of embodiment 97, wherein the reinforcement fiber material is carbon fiber material, carbon nanotube material, bioabsorbable glass material, or combinations thereof.
101. The method of embodiment 100, wherein the carbon nanotube material is a multi-wall carbon nanotube material.
102. The method of embodiment 97, wherein the polymer tube comprises from 0.1 wt% to 15 wt% of the reinforcement fiber material.
103. The method of embodiment 97, wherein the polymer tube comprises from 0.1 wt% to 10 wt% of the reinforcement fiber material.
104. The method of embodiment 97, wherein the polymer tube comprises from 0.1 wt% to 5 wt% of the reinforcement fiber material.
105. The method of embodiment 97, wherein the polymer tube comprises from 0.1 wt% to 1.5 wt% of the reinforcement fiber material.
106. The method of embodiment 97, wherein the polyester is selected from the group consisting of polylactides (PLA); poly(lactide-co-glycolide) (PLGA); polyanhydrides; polyorthoesters; poly(N-(2-hydroxypropyl) methacrylamide); poly(dl-lactide) (DLPLA); poly(l-lactide) (LPLA); poly(d-lactide) (DPLA); polyglycolide (PGA); poly(dioxanone) (PDO); poly(glycolide-co-trimethylene carbonate) (PGA-TMC); poly(l-lactide-co-glycolide) (PGA-LPLA); poly(dl-lactide-co-glycolide) (PGA-DLPLA); poly(l-lactide-co-dl-lactide) (LPLA-DLPLA); poly(glycolide-co-trimethylene carbonate-co-dioxanone) (PDO-PGA-TMC), poly(lactic acid-co-caprolactone) (PLACL), and mixtures or co-polymers thereof.
107. The method of embodiment 97, wherein the polyester is PLGA.
108. The method of embodiment 97, wherein the polyester is PLA or LPLA.
109. The method of embodiment 97, wherein the removing is selected from laser-cutting, photochemical etching, and water-jetting.

110. The biomedical implant of embodiment 13, wherein the reinforcement fiber material comprises one or more surface functionalities to facilitate intermolecular interaction between the bioabsorbable polymer material and the reinforcement fiber material.
111. The biomedical implant of embodiment 13, wherein the one or more surface functionalities are selected from -COOH, -OH, or combination thereof.
112. The biomedical implant of embodiment 13, wherein the reinforcement fiber material is multi-wall carbon nanotube material.
113. The method of embodiment 88, wherein the reinforcement fiber material comprises one or more surface functionalities to facilitate intermolecular interaction between the bioabsorbable polymer material and the reinforcement fiber material.
114. The method of embodiment 88, wherein the one or more surface functionalities are selected from -COOH, -OH, or combination thereof.
115. The method of embodiment 88, wherein the reinforcement fiber material is multi-wall carbon nanotube material.
116. The method of embodiment 100, wherein the reinforcement fiber material comprises one or more surface functionalities to facilitate intermolecular interaction between the bioabsorbable polymer material and the reinforcement fiber material.
117. The method of embodiment 100, wherein the one or more surface functionalities are selected from -COOH, -OH, or combination thereof.
118. The method of embodiment 100, wherein the reinforcement fiber material is multi-wall carbon nanotube material.

[00227] While preferred embodiments of the present invention have been shown and described herein, it will be obvious to those skilled in the art that such embodiments are provided by way of example only. Numerous variations, changes, and substitutions will now occur to those skilled in the art without departing from the invention. It should be understood that various alternatives to the embodiments of the invention described herein may be employed in practicing the invention. It is intended that the following claims define the scope of the invention and that methods and structures within the scope of these claims and their equivalents be covered thereby.

## CLAIMS

1. A biomedical implant, comprising:  
a tubular scaffold comprising a plurality of polymer struts, wherein the polymer struts are interconnected and define a plurality of deformable cells,  
wherein the polymer struts have an average thickness of no more than 150  $\mu\text{m}$ , and  
wherein the polymer struts comprise a fiber-reinforced polymer composite material, the fiber-reinforced polymer composite material comprising a bioabsorbable polymer material and a reinforcement fiber material a bioabsorbable polymer material and a reinforcement fiber material.
2. The biomedical implant of claim 1, wherein the reinforcement fiber material is carbon fiber, carbon nanotube, bioabsorbable glass, or combinations thereof.
3. The biomedical implant of any one of claims 1-2, wherein the reinforcement fiber material is carbon fiber.
4. The biomedical implant of any one of claims 1-3, wherein the reinforcement fiber material is distributed throughout the polymer struts.
5. The biomedical implant of any one of claims 1-4, wherein the fiber-reinforced polymer composite material has a tensile modulus that is at least five times, at least three times, or at least two times of a tensile modulus of the bioabsorbable polymer.
6. The biomedical implant of any one of claims 1-5, wherein the fiber-reinforced polymer composite material has a tensile strength that is at least five times, at least three times, or at least two times of a tensile strength of the bioabsorbable polymer.
7. The biomedical implant of any one of claims 1-6, wherein the fiber-reinforced polymer composite material comprises from 0.1 wt% to 15 wt% of the reinforcement fiber material.
8. The biomedical implant of any one of claims 1-7, wherein the bioabsorbable polymer material is selected from the group consisting of polylactides (PLA); poly(lactide-co-glycolide) (PLGA); polyanhydrides; polyorthoesters; poly(N-(2-hydroxypropyl) methacrylamide); poly(dl-lactide) (DLPLA); poly(l-lactide) (LPLA); poly(d-lactide) (DPLA); polyglycolide (PGA); poly(dioxanone) (PDO); poly(glycolide-co-trimethylene carbonate) (PGA-TMC); poly(l-lactide-co-glycolide) (PGA-LPLA); poly(dl-lactide-co-glycolide) (PGA-DLPLA); poly(l-lactide-co-dl-lactide) (LPLA-DLPLA); poly(glycolide-co-trimethylene carbonate-co-dioxanone) (PDO-PGA-TMC), poly(lactic acid-co-caprolactone) (PLACL), and mixtures or co-polymers thereof.
9. The biomedical implant of any one of claims 1-8, wherein the bioabsorbable polymer material is **PLGA**.
10. The biomedical implant of any one of claims 1-9, wherein the polymer struts have anisotropic elastic modulus.

11. The biomedical implant of any one of claims 1-10, wherein the polymer struts have an average longitudinal elastic modulus and an average lateral elastic modulus, the average longitudinal elastic modulus being greater than the average lateral elastic modulus.
12. The biomedical implant of claim 11, wherein the average longitudinal elastic modulus is at least three times, at least five times, or at least ten times the average lateral elastic modulus.
13. The biomedical implant of any one of claims 1-12, wherein more than 50%, more than 70%, or more than 90% of the reinforcement fiber material in the polymer struts are longitudinally aligned.
14. The biomedical implant of any one of claims 1-13, wherein the polymer struts are not structurally reinforced with a metal material.
15. The biomedical implant of any one of claims 1-14, further comprising a pharmaceutical agent incorporated to the tubular scaffold.
16. The biomedical implant of claim 15, wherein the pharmaceutical agent is rapamycin.
17. The biomedical implant of any one of claims 15, wherein the pharmaceutical agent is impregnated in the polymer struts.
18. The biomedical implant of claim 15, wherein at least a portion of the tubular scaffold is covered with a coating comprising the pharmaceutical agent.
19. A method of forming a biomedical implant, comprising:
  - forming one or more polymer fibers comprising a bioabsorbable polyester material and a reinforcement fiber material; and
  - interconnecting the polymer fibers to form a tubular scaffold, the tubular scaffold comprising a plurality of interconnected polymer struts to define a plurality of deformable cells, wherein the polymer struts have an average thickness of no more than 150  $\mu\text{m}$ ,
    - wherein the reinforcement fiber material is carbon fiber, carbon nanotube, bioabsorbable glass, or combinations thereof.
20. A method of making a bioabsorbable tubular scaffold, the method comprising
  - forming a composition comprising a bioabsorbable polyester material and a reinforcement fiber material;
  - extruding the composition to form a polymer tube, wherein the polymer tube has an average wall thickness of no more than 150  $\mu\text{m}$ ; and
  - removing a portion of the polymer tube to form a scaffold comprising interconnected struts,
    - wherein the reinforcement fiber material is carbon fiber, carbon nanotube, bioabsorbable glass, or combinations thereof.

**INTERNATIONAL SEARCH REPORT**

International application No.  
PCT/US14/381 17

<p>A. CLASSIFICATION OF SUBJECT MATTER  <b>IPC(8)</b> - A61F 2/00, 2/06, 2/82, 2/90, 2/92; A61L 31/12 (2014.01 )  <b>CPC</b> - A61F 2/92, 2250/0067; A61L 31/06, 31/148                      According to International Patent Classification (IPC) or to both national classification and IPC</p>													
<p>B. FIELDS SEARCHED</p> <p>Minimum documentation searched (classification system followed by classification symbols)                      IPC(8): A61F 2/00, 2/06, 2/82, 2/90, 2/92; A61L 31/12 (2014.01)                      CPC: A61F 2/92, 2250/0067; A61L 31/06, 31/148; USPC: 428/35.7; 623/1 .38, 1.44, 1.49</p> <p>Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched</p> <p>Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)                      MicroPatent (US-G, US-A, EP-A, EP-B, WO, JP-bib, DE-C.B, DE-A, DE-T, DE-U, GB-A, FR-A); Google; Google Scholar; Google Patent; ProQuest; PubMed/Medline; Search terms used: stent, struts, bioabsorbable, biodegradable, reinforced, "carbon fiber"</p>													
<p>C. DOCUMENTS CONSIDERED TO BE RELEVANT</p> <table border="1" style="width:100%; border-collapse: collapse;"> <thead> <tr> <th style="width:10%;">Category*</th> <th style="width:70%;">Citation of document, with indication, where appropriate, of the relevant passages</th> <th style="width:20%;">Relevant to claim No.</th> </tr> </thead> <tbody> <tr> <td>X - Y</td> <td>US 2010/0131044 A1 (PATEL, U) May 27, 2010; abstract; figures 1-2; paragraphs [0032], [0081], [0094]</td> <td>1-2, 3/1-2, 19 ----- 4/1-2, 4/3/1-2, 20</td> </tr> <tr> <td>Y</td> <td>US 2008/0065192 A1 (BERGLUND, J) March 13, 2008; abstract; paragraph [0033]</td> <td>4/1-2, 4/3/1-2</td> </tr> <tr> <td>Y</td> <td>US 8377356 B2 (HUANG, B et al.) February 19, 2013; figure 1; column 14, lines 55-60; column 19, lines 16-17; claim 1</td> <td>20</td> </tr> </tbody> </table>		Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.	X - Y	US 2010/0131044 A1 (PATEL, U) May 27, 2010; abstract; figures 1-2; paragraphs [0032], [0081], [0094]	1-2, 3/1-2, 19 ----- 4/1-2, 4/3/1-2, 20	Y	US 2008/0065192 A1 (BERGLUND, J) March 13, 2008; abstract; paragraph [0033]	4/1-2, 4/3/1-2	Y	US 8377356 B2 (HUANG, B et al.) February 19, 2013; figure 1; column 14, lines 55-60; column 19, lines 16-17; claim 1	20
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Y	US 2008/0065192 A1 (BERGLUND, J) March 13, 2008; abstract; paragraph [0033]	4/1-2, 4/3/1-2											
Y	US 8377356 B2 (HUANG, B et al.) February 19, 2013; figure 1; column 14, lines 55-60; column 19, lines 16-17; claim 1	20											
<p><input type="checkbox"/> Further documents are listed in the continuation of Box C. <input type="checkbox"/></p>													
<table border="0" style="width:100%;"> <tr> <td style="width:50%; vertical-align: top;"> <p>* Special categories of cited documents.</p> <p>"A" document defining the general state of the art which is not considered to be of particular relevance</p> <p>"E" earlier application or patent but published on or after the international filing date</p> <p>"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</p> <p>"O" document referring to an oral disclosure, use, exhibition or other means</p> <p>"P" document published prior to the international filing date but later than the priority date claimed</p> </td> <td style="width:50%; vertical-align: top;"> <p>"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</p> <p>"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone</p> <p>"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art</p> <p>"&amp;" document member of the same patent family</p> </td> </tr> </table>		<p>* Special categories of cited documents.</p> <p>"A" document defining the general state of the art which is not considered to be of particular relevance</p> <p>"E" earlier application or patent but published on or after the international filing date</p> <p>"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</p> <p>"O" document referring to an oral disclosure, use, exhibition or other means</p> <p>"P" document published prior to the international filing date but later than the priority date claimed</p>	<p>"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</p> <p>"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone</p> <p>"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art</p> <p>"&amp;" document member of the same patent family</p>										
<p>* Special categories of cited documents.</p> <p>"A" document defining the general state of the art which is not considered to be of particular relevance</p> <p>"E" earlier application or patent but published on or after the international filing date</p> <p>"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</p> <p>"O" document referring to an oral disclosure, use, exhibition or other means</p> <p>"P" document published prior to the international filing date but later than the priority date claimed</p>	<p>"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</p> <p>"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone</p> <p>"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art</p> <p>"&amp;" document member of the same patent family</p>												
<p>Date of the actual completion of the international search</p> <p>12 September 2014 (12.09.2014)</p>	<p>Date of mailing of the international search report</p> <p align="center"><b>07 OCT 2014</b></p>												
<p>Name and mailing address of the ISA/US</p> <p>Mail Stop PCT, Attn: ISA/US, Commissioner for Patents                      P.O. Box 1450, Alexandria, Virginia 22313-1450                      Facsimile No. 571-273-3201</p>	<p>Authorized officer:</p> <p align="center">Shane Thomas</p> <p>PCT Helpdesk: 571-272-4300                      PCT OSP: 571-272-7774</p>												

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US14/381 17

**Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)**

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

- 1.  Claims Nos.:  
because they relate to subject matter not required to be searched by this Authority, namely:
  
- 2.  Claims Nos.:  
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
  
- 3.  Claims Nos.: **5-18**  
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

**Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)**

This International Searching Authority found multiple inventions in this international application, as follows:

- 1.  As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
- 2.  As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
- 3.  As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
  
- 4.  No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

**Remark on Protest**

- The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- No protest accompanied the payment of additional search fees.