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(71) Applicant: XELTIS B.V. [NL/NL]; Postbus 80, NL-5600 AB Eindhoven (NL).

(72) Inventors: LAVRIJSEN, Tom; p/a Xeltis B.V., Postbus 80, NL-5600 AB Eindhoven (NL). NANDAKUMAR, Anandkumar; p/a Xeltis B.V., Postbus 80, NL-5600 AB Eindhoven (NL). COX, Martijn Antonius Johannes; p/a Xeltis B.V., Postbus 80, NL-5600 AB Eindhoven (NL).

(74) Agents: ALGEMEEN OCTROOI- EN MERKENBUREAU B.V. et al.; P.O. Box 645, NL-5600 AP Eindhoven (NL).

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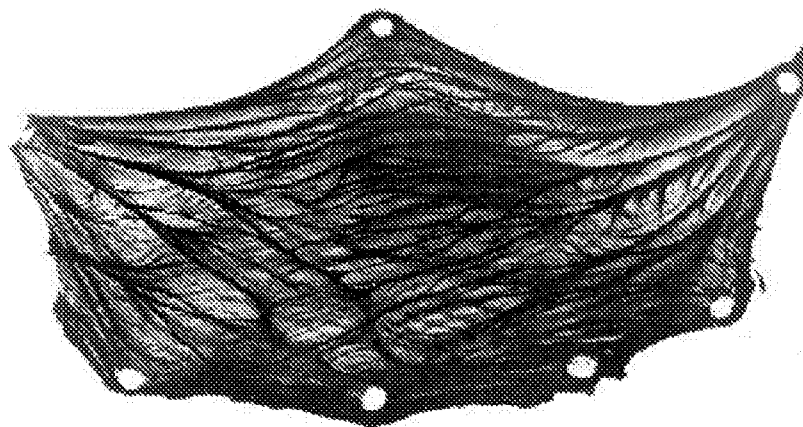


Fig. 1

(57) Abstract: A relatively new field of medicine - since the early 1990s - is the field of Regenerative Medicine. Regenerative Medicine is the process of creating living and functional tissues to repair, replace, or restore tissue or organ structure and function lost due to age, disease, damage, or congenital defects. This field of medicine uses new methods including (stem) cell therapy, development of medical devices and tissue engineering. The present invention lies in the field of regenerative medicine and relates to an implant comprising a matrix material, and a method for manufacturing an implant comprising matrix material. The invention further relates to a crimped implant.



Title: IMPLANT

The present invention relates to an implant comprising a matrix material, and a method for manufacturing an implant comprising matrix material. The invention  
5 further relates to a crimped implant.

A relatively new field of medicine – since the early 1990s – is the field of Regenerative Medicine. Regenerative Medicine is the process of creating living and functional tissues to repair, replace, or restore tissue or organ structure and function lost due to age, disease, damage, or congenital defects. This field of medicine uses new  
10 methods including (stem) cell therapy, development of medical devices and tissue engineering.

Over recent years continuous improvements in our healthcare have resulted in dramatic demographic changes, e.g. an increase in the average age of the population. These demographic changes are causing an increase in the prevalence of diseases associated with aging such as cardiovascular diseases. Many of these diseases  
15 arise from the loss or dysfunction of specific cell types in the human body, leading to permanently damaged tissues and organs.

Cardiovascular diseases are one of the biggest causes of deaths worldwide. One way to treat at least some of these diseases is by tissue engineering. Tissue engineering can be used for the replacement of cardiovascular tissues, such as  
20 arteries and heart valves. Currently used cardiovascular substitutes encounter risks due to coagulation, infections, degeneration, and no growth possibilities. Tissue engineering uses patient's own cells and a biodegradable polymer scaffold to make autologous tissue that is able to grow, adapt and repair. To ensure proper cell and tissue growth, the  
25 scaffolds must be highly porous and match the mechanical properties of the tissue. Electrospinning is a technique that produces polymer nanofibers using a high voltage electrostatic field. It results in a highly porous material consisting of nanofibers that resembles the extra cellular matrix of the tissue. Tissue engineering can for example be used for coronary bypass grafts, heart valve replacements, AV shunts for dialysis patients.

30 In the field of surgery minimal invasive surgery is preferred. However tissue engineered constructs can often only be implanted via normal surgical procedures since the constructs cannot be compressed to a size sufficiently small to facilitate minimal invasive surgery. Some artificial heart valves can now be crimped to a diameter of 18 French (6 mm) to allow for implantation via a small peripheral incision (e.g. transfemoral

or transjugular). However, many elderly patients in need of a replacement valves also suffer from stenotic and therefore narrowed arteries, which currently excludes them from the much preferred minimal invasive surgery. A reduction of 1 or 2 French in crimpable diameter already means a significant increase in the number of treatable patients.

5                   The technique of tissue engineering consists of constructing substitutes (e.g. biological substitutes) for diseased tissues. Tissue engineering makes use of natural or polymeric scaffolds that provide mechanical support and promote the re-growth of cells lost due to trauma or disease. A scaffold is a temporary structure used to support material (e.g. tissue) during the recovery thereof.

10                  Polymeric scaffolds can be constructed from biocompatible, non-toxic polymers. The choice of polymer and the technique used to make the scaffold effects the mechanical properties exhibited by the scaffold.

                  In the publication of Bouten et al, Advanced Drug Delivery Reviews, 2011, vol. 63, pp 221-241 synthetic polymers have been demonstrated to be good substrates for  
15                  valvular and vascular tissue engineering. For cardiac tissue engineering, the most commonly used biodegradable synthetic scaffold materials are polyglycolic acid (PGA), polylactic acid (PLA), polyhydroxybutyrates (PHB),  $\epsilon$ -polycaprolactone (PCL) or their co-polymers. No functioning implants were disclosed using the described synethetic scaffold materials.

20                  In the publication by Dankers et al in Nature Materials, 2005, Vol. 4, pp568-574 solution cast polymer films comprising 2-ureido-4[1H]-pyrimidinone (Upy) polymers were shown to be non-toxic when studied in vivo. However the use of UPy polymers as cardiovascular impant scaffolds was not shown.

                  In order to obtain a tissue engineered construct, a scaffold can be pre-  
25                  seeded in vitro with the appropriate cells prior to implantation. In most cases, as the formation and the remodeling of the newly formed tissue proceeds, degradation of the scaffold should slowly and steadily take place, leaving only new healthy tissue behind. With degradation is meant the breakdown of the material into smaller parts, e.g. chemical compounds and/or elements that can be eliminated from the body by means of excretion  
30                  in urine for example.

                  A drawback of growing a tissue construct in vitro is that the complete procedure including growing and implanting has to be conducted sterilely making it a costly and laborious procedure. In addition, regulatory guidelines on living tissues are complex, resulting in long and costly processes towards product approval.

Another option is to seed an implant with cells prior to implantation. This method requires the harvesting of cells from the subject to receive the implant, optionally growing the cells in vitro, and seeding the cells in the construct followed by implantation. This method has the same down sides as the previously described method.

5 It is an object of the present invention to provide for an implant which can be implanted via minimal invasive surgery.

It is an object of the present invention to provide for an implant which regenerates tissue in vivo.

10 It is further an object of the present invention to overcome one or more of the above mentioned draw backs associated with the prior art.

One or more of the above objects have been reached by the present invention. The inventors have surprisingly found that the above objects are reached with an implant comprising one or more supramolecular compounds and wherein the matrix material comprises a fibrous network and having a porosity of at least 60%, preferably a  
15 porosity of between 70% and 90%.

The present invention is illustrated in more detail in the following description and with reference to the drawings, in which:

Figure 1 shows native fiber orientations of a heart valve leaflet (Sauren(1981).

20 Figure 2 shows helical fiber orientation in blood vessel (Holzapfel, J.Elast., 2000).

Figure 3 shows results of valve testing at 120/80 mmHg on a PCL-bisurea valve at systemic conditions showing stable performance for 20 hours.

25 Figure 4 shows pictures of PCL-bisurea valves at start (two upper pictures) and after 20 hours (two lower pictures) of systemic conditions in a valve test, 20 hours (R11020).

Figure 5 shows results of valve testing at 50/25 mmHg on a PCL valve at systemic conditions showing a decreasing in performance within several hours.

30 Figure 6 shows pictures of PCL valves at start (two upper pictures) and after 20 hours (two lower pictures) at 50/25mmHg in a valve test, 20 hours (R11020).

Figure 7 shows Photograph (a) and schematic overview (b) of set-up for valve testing.

Figure 8 shows the uniaxial tensile test results for PCL and PCLbisurea electrospun scaffolds along (first figure) and perpendicular to (second figure) the main

fiber direction.

Figure 9 A shows the results of the uniaxial fatigue tests (10%, 2Hz,) on PCL and PCLbisurea. Figure 9 B shows comparative results of conduit fatigue testing conducted using PCLbisurea and PCL UPy implants.

5                    Figure 10 shows the results of the crimping tests on electrospun heart valve implants.

Figure 11 shows the different crimped states of 3D electrospun heart valves.

10                   Figure 12 shows the stents after different stages of crimping for 3D electrospun heart valves.

Figure 13 shows two pictures of DAPI staining of a PCL-bisurea implant in an ovine model.

15                   Figure 14 shows two SEM images of PCL and PCL-bisurea matrices  
In the present description and appended claims, the following terms are used, which are explained below.

A “polymer” is intended to also include homopolymer, copolymer or supramolecular polymer unless otherwise stated.

20                   A “supramolecular polymer” is a polymeric array of monomeric units that are brought together by reversible and highly directional secondary interactions, resulting in polymeric properties in dilute and concentrated solutions, as well as in the bulk. The monomeric units of the supramolecular polymers themselves do not possess a repetition of chemical fragments. The directionality and strength of the supramolecular bonding are important features of these systems, that can be regarded as polymers and behave according to well-established theories of polymer physics.

25                   A “supramolecular monomer compound” in this application is a compound which by virtue of reversible and highly directional secondary interactions (with other supramolecular monomer compounds) forms a supramolecular polymer.

30                   A supramolecular polymer is therefore composed of monomers, which monomers are designed in such a way that they autonomously self-assemble into the desired polymeric structure. This is in contrast to conventional polymerization reactions whereby monomers are linked via covalent bonds. As a result of the self-assembly, a (much) higher virtual molecular mass of the material is achieved. Examples of supramolecular polymers have been described in, for example, Science, 1997, 278, 1601.

A “contrast agent” is a substance used to enhance the contrast of

structures or fluids within the body in medical imaging.

A "scaffold" is a temporary structure used to support material (e.g. tissue) during the formation and/or recovery of said material.

5 A "structural component" is the part of the scaffold that is intended for the provision of structural properties.

An "imaging component" is the part of the scaffold that is intended for the provision of imaging properties.

A "biologically active component" is the part of the scaffold that is intended for the provision of biological activity.

10 A "substrate" is the material on which growing of cells takes place.

An implant is a medical device which can replace a dysfunctional or damaged biological structure, support a damaged biological structure, cover a damaged biological structure, or enhance an existing biological structure.

15 Backbone of a polymer is the backbone chain (also called main chain) is a series of covalently bonded atoms that together create the continuous chain of the polymer.

"Porosity" is measured for example by mercury porosimetry, fluid intrusion and gravimetry. "Pore size" the average size of openings (pores) in the matrix material. Porosity as mentioned in the specification is measured as follows:

20 The scaffold weight is measured using a balance. The dimensions (length and thickness for tubes, length, width and thickness for sheets) are also measured. The porosity is calculated using the following formula

$$\text{porosity} = (1 - \text{Density of scaffold} / \text{density of polymer}) \times 100 \%$$

25 where density of polymer varies based on the polymer used and density of scaffold is calculated as weight of scaffold/ volume of scaffold.

With "pores" is meant the inter-fiber spaces (that is, the pore size) in the matrix material. The pore size and porosity are properties of a scaffold that influence the attachment, proliferation, migration and/or differentiation of cells.

30 A minimally invasive procedure is a procedure (surgical or otherwise) that is less invasive than open surgery.

The inventors have surprisingly found that the above object is reached with an implant comprising a matrix material having a porosity of at least 60%. Said implant can be implanted in a subject (also called recipient of the implant) with a minimally invasive procedure. Due to the porosity of at least 60% the implant can be compressed

minimizing the size of the implant (also referred to as crimping). Since the size of the implant is reduced a smaller opening is required for implantation resulting in less discomfort to the recipient of the implant and minimizing recovery time of the recipient. Preferably the porosity is between 70% and 90%. Further a fibre structure with such a porosity allows for diffusion of nutrients into the matrix and for the ingrowth and/or infiltration of cells into the matrix.

The inventors have found that they can solve one of the major limitations currently associated with minimal invasive implantation of e.g. prosthetic heart valves by allowing crimping to a smaller size compared to existing transcatheter heart valves.

In an embodiment of the present invention the implant is a cardiovascular implant and preferably an implant chosen from the group consisting of a (blood) vessel, a heart valve, a cardiovascular patch or a valved conduit. It is beneficial for the recipient that an implant according to the present invention can be implanted by minimal invasive surgery. For these implants only a minor incision has to be made in order to facilitate implantation. Preferably the implant is applied to an object (i.e. a patient) via a small incision. Due to the high porosity of the implant the implant can be reduced at least 5 times in diameter size going from fully expanded towards fully crimped configuration and back.

In an embodiment of the present invention the implant is reinforced by at least one support structure, preferably the at least one support structure is chosen from the group consisting of a reinforcement ring, a suture ring or a stent structure, and is preferably biodegradable, preferably the implant consists of the reinforced matrix material. The presence of the support structure can for example be aimed at reinforcing the implant, allowing crimping of the implant during a minimally invasive procedure, allowing fixation of the implant at the correct anatomical position or allowing repeated puncturing of the implant with a needle. Suitable support structures are those widely known in the art and are for example used in artificial heart valves or as coronary stents or stents for other kinds of arteries. Reinforcements are for example described in US 4,626,255, US 6,338,740, US2004/0148018, US 3,570,014 and US 4,084,268.

In an embodiment of the present invention the implant has a matrix material which consists of a fibrous network. Said fibrous network is made up out of fibres. The fibers allow for the implant to have good structural integrity while maintaining its porosity and pores. Preferably the fibrous network are electro spun fibers. Electro-spinning is a technique using a metal target or mold, having either a flat, plate-like form or

a complex three-dimensional form, depending of the preform that is desired. Polymer fibers are deposited onto this mold by means of an electromagnetic field. The polymer fibers are generated from a solution of one or more polymers in one or more solvents. This technique of electro-spinning is known in the art and will not be further in detail in this specification. In Dutch patent NL 1026076 (corresponding to US 2008/0131965) the preparation of an article by means of electro-spinning of polymer microfibers is disclosed. The electrospinning setup used in the development of such a product is climate controlled and also allows for control of spinning area, nozzle speed, rotation of the collector and the possibility of the applying a small negative voltage (up to -4 kV). The humidity, temperature and other above mentioned factors can be used alone or in combination to alter various characteristics of the electrospun fibres. These include, but may not be limited to, fibre morphology, fibre diameter, fibre and pore size distribution, porosity and scaffold thickness.

In an embodiment of the present invention the fibres of the matrix material consists of one or more supramolecular polymers. By using these kinds of polymers the inventors have found that the implant can be implanted in a subject without having to seed the implant with cells prior to implantation. By using supramolecular compounds the inventors observed that cells attach, infiltrate and grow in vivo on and in the implant while the implant fulfills the function of the tissue to be replaced or repaired. Hence the implant can be implanted directly in the patient. The advantages of implanting a scaffold directly are a reduction in production time and cost, the scaffold can be stored for prolonged periods of time and it qualifies as a medical device meaning that regulatory approval can be obtained much faster. Hence, one or more of the important drawbacks of growing a tissue construct, or seeding cells, in vitro are overcome, while keeping the advantage and promise of regeneration, leaving only new healthy tissue behind.

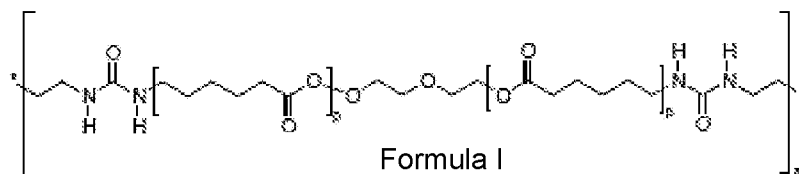
In an embodiment of the present invention the implant is biodegradable. This allows for the implant to be degraded after being implanted in the body. Hence the implant is replaced over time by tissue. The advantage is that the implant does not have to be removed surgically preventing further discomfort for the patient who received the implant.

The inventors found that if one or more supramolecular compounds have a backbone comprising or consisting of polycaprolactone (PCL) or a combination of PCL, caprolactone, poly lactic acid and/or lactic acid very good results are obtained with respect to the structural characteristics of the implant and with respect to biodegradability.

In an embodiment of the present invention the implant has a matrix material which comprises one or more supramolecular compounds wherein the one or more supramolecular compounds further comprise one or more groups chosen from UPy (ureido-pyrimidinone) and/or bisurea. A polycaprolactone polymer containing UPy-groups, is for example disclosed in patent application EP 1 687 378. Preferably the supramolecular compound is PCL-bisurea (also referred to as PCLbu). The present inventors have found that with these compounds good results can be obtained with respect to the in vivo growth of tissue in the implant as well as for structural characteristics of the implant. Good results are obtained with PCL-bisurea.

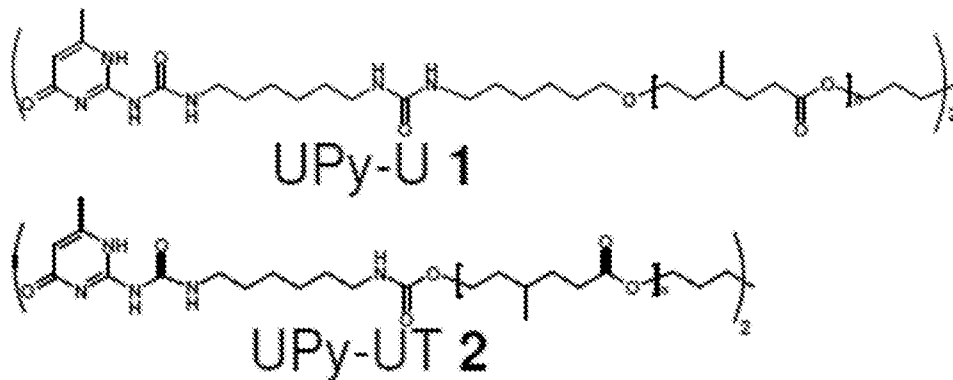
In an embodiment the one or more supramolecular compounds comprises at least PCL UPy, preferably the matrix material consists of PCL UPy. Especially good results are obtained with PCL-UPy.

A method for preparing PCL bis urea can be found in for example "Biomaterials by the supramolecular control of nanofibers by E. Wisse ISBN: 978-90-386-1094-8 chapter 2. The chemical formula of PCL-bis urea with a butyl spacer is shown in the Formula I below. Alternatively, no spacer or another alkyl spacer, e.g a hexyl spacer can also be used. The PCL acts as a soft-block while urea groups make up the hard block. The hydrogen bonding between the hard blocks results in reversible physical links.



Wherein p and n are integers and p and n > 1. The p and n values can be altered to yield different formulations of PCL bis urea which might result in different properties. The p value is dependent on the starting molecular weight of polycaprolactonediol while the n value relates to the number of chain extensions of the PCL bis urea. Preferably values of n can range from, 4 – 40.

A method for preparing PCL UPy can be found in for example "Biomaterials by the supramolecular control of nanofibers by E. Wisse ISBN: 978-90-386-1094-8 chapter 6. PCL-UPy polymers can be prepared, for example, as comprising the urea hydrogen bonding group (Upy-U 1) or the urethane hydrogen bonding group (Upy-U 2).



10 In an embodiment of the present invention the fibrous network comprises nano fibers and/or micro fibers, preferably the diameter of the micro fibers ranges from 3 to 20 micrometer and preferably from 5 to 10 micrometer. The advantage of this diameter is the excellent mechanical and structural stability of the implant, while providing a microstructure that is sufficiently porous to allow for cell ingrowth (Balguid, Strategies to optimize engineered tissue towards native human aortic valves, PhD thesis  
15 Eindhoven University of Technology, 2008 , ISBN 978-90-386-1185-3).

Nano fibres are fibres having a diameter of less 1 micrometer. The diameter of micro and nano fibres can be obtained by measuring the diameter under a microscope.

20 In an embodiment of the present invention the matrix material comprises pores having a diameter ranging from 1-300 micrometer and preferably ranging from 5-100 micrometer. The advantage of these pore sizes is that it allows the passage of the cells to be cultured and hence a good infiltration of cells into the complete thickness of the preform, which is required to ensure formation of tissue throughout the complete preform.  
25 The requirements of the pore size depend on the size of the cells to be cultured and can be selected according to this size. The size of human cells is generally larger than the size of animal cells, hence the differentiation between the most preferred pore sizes when using either animal or human cells.

30 In a preferred embodiment of the present invention the matrix material forms a layer having a thickness of at least 100  $\mu\text{m}$  and maximally 3000  $\mu\text{m}$ , preferably the thickness is between 200 and 1000  $\mu\text{m}$ . In case the implant consists of matrix material, the implant has a thickness of at least 100  $\mu\text{m}$  and maximally 3000  $\mu\text{m}$ , preferably the thickness is between 200 and 1000  $\mu\text{m}$ . The inventors have found that with the defined thicknesses implants are obtained with good structural properties so that

these implants can fulfill the desired function when implanted in a subject while resulting in tissue growth and obtaining tissue of good quality.

In an embodiment of the present invention the implant has a linear elastic stiffness ranging from 0.1-50 MPa and preferably from 0.1-10 MPa. The inventors have found that these ranges provide the combination of strength and flexibility that is required to withstand the hemodynamics of the human cardiovascular system. Previously published results on native and tissue engineered materials report stiffness values in this range as well (Non-invasive assessment of leaflet deformation and mechanical properties in heart valve tissue engineering by Kortsmits, ISBN: 978-90-386-2002-2 (2009), Stradins et al. (2004), Clark, (1973)).

In an embodiment of the present invention the implant has an (linear) elastic regime of at least 30%, and preferably at least 45% and more preferred at least 60% (Linear elastic stiffness has been measured using standard uniaxial tensile tests (for a description see ISO 13934-1:1999 Textiles -- Tensile properties of fabrics -- Part 1: Determination of maximum force and elongation at maximum force using the strip method)). This ensures that an implant according to the present invention does not show plastic deformation or breakage within a physiological strain region (strain exerted in the body on the implant). For example, for native heart valves, physiological strains have been reported of ~60% (Billiar & Sacks, (2000), Driessen et al., 2005)). Current bioprosthetic valves already fail to comply with these values, showing maximal strains during diastolic pressurization of glutaraldehyde treated porcine valves of 2-4% and 3-10% in circumferential and radial direction, respectively (Adamczyk & Vesely, 2002), and an average strain value of 4-10% in the heart valve leaflets (Sun et al., 2005). Furthermore, chemically fixed anisotropic tissue was described to become more isotropic (Zioupou et al., 1994) and less compliant than fresh tissue (Broom et al., 1982; Schoen et al., 1997; Billiar & Sacks, 2000) due to chemical crosslinking. Commercially available polymers that were shown to have a short elastic regime in a uniaxial tensile test, also showed insufficient performance in an in vitro valve testing set-up. Thus, for the implant to be used in the body and fulfill the function of the tissue to be replaced or repaired an extended elastic regime is important.

In an embodiment of the present invention the implant, the fibers (of the matrix material) have a preferred orientation direction. Preferably the fibers in the implant are arranged in such a way that when the implant is implanted the fibres are arranged substantially perpendicular to the blood stream.

Preferably the preferred fiber alignment is circumferential around an imaginary axis of the implant wherein the axis points in the direction of bloodflow in case of a tubular implant. In case of a heart valve leaflet the fibers are preferably arranged in the same fashion as depicted in figure 1.

5 Such an orientation can be introduced during manufacturing of the implant (i.e. with electro spinning). Such a fiber structure mimics the natural fiber alignment in native tissues, e.g. the hammock-like collagen architecture in native heart valve (as depicted in Figure 1, Sauren et al. 1981) and the helical collagen fiber orientation in native arteries (as depicted in Figure 2, by Holzapfel(2000))

10 By mimicking the extra cellular matrix of the natural environment a tissue can be grown having good structural properties which eventually develop towards a native-like architecture.

In an embodiment of the present invention the linear elastic stiffness ratio between the stiffness in the preferred fiber direction and the stiffness perpendicular to the preferred fiber direction is at least 2:1, preferably at least 4:1 and more preferred at  
15 least 10:1 and even more preferred at least 50:1. Implants having such a ratio have good structural properties while still providing for a substrate for cells to grow on mimicking the natural environment.

In an embodiment of the present invention, the implant further comprises  
20 biologically active compounds and/or contrast agent. In order to monitor how fast the in vivo degradation of the implant proceeds and in order to judge the ultimate success of the tissue engineering procedure a contrast agent can be present in the implant. Said contrast agent can be visible in relevant clinical imaging techniques, such as computed tomography (CT), magnetic resonance imaging (MRI) and/or diagnostic sonography (or  
25 ultrasonography) using ultrasound for imaging purposes, for example. A preferred contrast agent is described in European patent application having application number 10193654, a fluorinated polymer having a glass transition temperature ( $T_g$ ) below 40 °C, preferably below 20 °C, more preferably below 0 °C, as an imaging label or contrast agent in  $^{19}\text{F}$  magnetic resonance imaging (MRI). The amount of fluorine ( $^{19}\text{F}$ ) in the fluorinated  
30 polymer is preferably at least 5 wt%, based on the total mass of the polymer. Said fluorinated polymer comprises at least one polymer selected from the group consisting of (per)fluorinated polyethers, (per)fluorinated polyesters, (per)fluorinated poly(meth)acrylates, and (per)fluorinated polysilicones, preferably (per)fluoroethers. Said polymers can be incorporated in the polymers making up the fibrous network Alternatively

the polymers are present separately in the fibrous network.

Biological active compounds can be added to for example promote cell infiltration, retainment, differentiation and proliferation, as well as tissue formation and remodeling.

5           The present invention further relates to a method for manufacturing an implant, preferably as described above, having a matrix material one or more supramolecular compounds, wherein the matrix material has 60% porosity and preferably between 70 and 90% porosity, comprising the steps of:

- Providing a mold;
- 10           - Applying the matrix material to the mold by means of electro spinning of one or more supramolecular compounds; and
- Separating the matrix material from said mold.

The obtained implant has the same advantages as described above.

In an embodiment of the present invention the method further comprises the step of  
15           providing at least one support structure to the implant or matrix material.

The invention further relates to a crimped implant, preferably the implant according to present invention as previously described, which can be crimped to a diameter size of up to 20% compared to the diameter of the implant before crimping (uncrimped). This allows for the implant to be easily provided by minimal invasive surgery.

20           A further advantage is that since the implant can be crimped to 20% of its initial diameter size it can be provided to subjects which currently are excluded from receiving an implant via minimal invasive surgery because for example their arteries are too narrow for a crimped implant according to the prior art to pass through. Preferably said crimped implant is a heart valve implant. Crimping an implant according to the present invention is  
25           achieved by methods known in the art. An example of crimping is given in the examples.

The present invention further relates to a method for growing a valve, comprising the step of providing an implant, preferably an implant according to the present invention to a subject (a patient). Said implant is preferably an implant according to the present invention. This step can be preceded by the step of making an incision in the skin  
30           of the subject.

After implanting said implant in the patient (human or animal) said implant is capable of functioning (as the tissue to be grown) after implantation and before cellular ingrowth occurs and wherein cellular ingrowth occurs after implantation and said matrix material is degraded over time.

The invention will be further illustrated by the following non limiting examples. The appended claims also form part of the description of the present application.

## 5 Examples

### Example 1

Implants were manufactured according to the following method. A required amount of PCL, PCL bisurea or PCL UPy is dissolved in an appropriate solvent/solvent mixture and stirred until dissolution. The resulting solution is delivered at a  
10 constant flow rate (flows varying with time are also possible and will result in scaffolds with different properties) to a nozzle that can be electrically charged. Typically, this is done using a syringe pump. A high voltage is applied to the nozzle. Voltage differences (combination of positive and negative voltages) used range from 10-20kV, although it is possible to produce fibres at other voltages. A rotating collector, usually in the form of a  
15 cylinder is placed. The collector is connected to the ground or a negative terminal. The speed of rotation is typically 100 rpm. The fibres are deposited on the collector. The length and thickness of the produced implant is affected by flow, voltage, collector rotation speed, sweep and the nozzle speed. After the desired thickness is achieved, the spinning is stopped and the collector is removed. The implant in the collector is vacuum dried and  
20 annealed (~37 °C) overnight. The implant is removed by the collector by soaking it in warm water (~37 °C) although other methods of removal are possible. A SEM image of an electrospun fibre mesh is shown in figure 14.

### Example 2

25 The implants obtained according to the method of example 1 were tested in accordance with ISO5840:2005. The hemodynamic performance of a valvular implant is assessed by loading with physiologically relevant flow and pressures by means of a mock loop system. Figure 7 shows an image of the mock loop used. The valves to be mounted in this mock loop are subjected either to pulmonary pressures and flow or to  
30 aortic pressures and flow. The fluid used in the experiments is a physiological saline solution. In the mock loop system shown above, the circulation fluid is displaced by means of a computer (PC) controlled piston pump (P). The piston is connected to a servomotor (SM) system that is controlled by a motion control board. The piston fills the left ventricular cavity (LV; VLV = 1L) from a reservoir through a model mitral valve (MV) and

subsequently ejects the fluid through the arterial valve (AV) into a WindKessel (WK) model that consists of two resistances (R1 and R2) and a compliance tank ( $C; VC = 2L$ ). From the Windkessel model, the fluid flows back into the reservoir through a section of silicone tubing. The pulsatile flow through the arterial valve is measured by a Flow Meter (FM1). Additionally, the mean Cardiac Output is registered by means of a Clamp-On flow sensor (FM2) on the outlet silicon tube of the WindKessel. Ventricular and arterial pressure is recorded using pressure transducers ( $P_v$  and  $P_a$ ) that are connected to a bridge amplifier (Picas, Peekel Instruments). The signals are recorded by a Data-Acquisition board and stored on a harddisk in a PC. An endoscope is introduced into the systemic artery to which a high-speed color camera is connected (M5) to capture valve dynamics throughout the heart cycle at a frame rate of 200 Hz. Valvular pressure and flows are monitored over time to assess valve functionality.

Valves made from PCLbu and PCL were subjected to systemic conditions at 120/80 mmHg for 20 hours. The obtained results clearly show better results for PCLbu (Figures 3 and 4.) implants than for PCL implants (Figures 5 and 6).

The pictures of figures 4 and 6 show an valve in the opened (left top picture) and closed (right top picture) configuration at the start of the test and in the opened (left bottom picture) and closed (right bottom picture) after 20 hours. The pictures of the tested valves clearly show that the PCL valves are damaged whereas the PCLbu valves remained largely undamaged.

### Example 3 Uniaxial tensile test

The Zwick tensile stage is connected to a measurement module, which is connected to a PC. After the necessary preparations this system can be used to retrieve the stress-strain characteristics of strips of for example biological tissue. First both sides of the sample are mounted in the tensile stage with the use of the two clamps. Software on the PC triggers the tensile stage, thereby elongating the sample. During this elongation displacement as well as force is recorded, and subsequently stored in an TRA file. From this file, complemented with the dimensions of the specimen, mechanical parameters (Young's Modulus, ultimate tensile strength/strain) can be determined using Matlab. RT (dry), grip-to-grip separation = 9mm, elongation rate = 9 mm/min, 20N loadcell.

Width and thickness are used to calculate the Young's Modulus [Pa], which is a measure for the stiffness of the strips.

$$E = \frac{F_2 l_2 - F_1 l_1}{(l_2 - l_1) A_0} \quad (\text{Eq. 1})$$

F [N] is the force and l [m] the length of the sample (length [mm] \* 10<sup>-3</sup>).

5        A0 [m<sup>2</sup>] denotes the cross-sectional area of the sample before testing  
(width [mm] \* thickness [mm] \* 10<sup>-6</sup>).

Figure 8 shows uniaxial tensile test results for PCL and PCL-bisurea electrospun scaffolds along (left) and perpendicular to (right) the main fiber direction, showing a clear difference in elastic regime (straight line) between the 2 materials. For  
10    PCL plastic deformation around 10% strain and breakage observed below 15% strain (perpendicular). For PCL-bisurea, no plastic deformation or breakage within physiological strain region (< 60%) was observed under the same conditions.

#### Example 4 Fatigue testing

##### 15    A) Uniaxial fatigue test

Using a set-up similar to the uniaxial tensile test, cyclic loading was performed to assess the fatigue behavior in a uniaxial fatigue tests (10% strain, 2Hz,) on PCL and PCLbisurea. Results confirm failure modes and timelines observed in the valve test (Example 2), showing fatigue within 1000 cycles (< ½ hour in-vivo) for valves made  
20    from PCL, and no fatigue for valves made from PCL-bisurea. Even after 1 million cycles (> 11 days in-vivo) no fatigue damage was observed for the PCLbisurea valves (Figure 9 A).

##### B) Conduit fatigue test

The implants obtained according to the method of example 1 were  
25    tested for fatigue resistance by applying cyclic pressure loads to tubular shaped scaffolds. This benchtop test is used to determine the durability of a vascular device by subjecting it to hydrodynamic pulsatile loading with a relevant pressure differential. Device specimens are submerged in an environmental chamber and fatigued for 3 million cycles. Test conditions are designed to meet the requirements of in vitro mechanical fatigue testing  
30    stated in ASTM F 2477 – 07 “Standard Test Methods for in vitro Pulsatile Durability Testing of Vascular Devices” and FDA Guidance 1545 (2010) “Non-Clinical Engineering Tests and Recommended Labeling for Intravascular Devices and Associated Delivery Systems”. The test is controlled and monitored via the pressure control method, which

dictates that the test will control the cycle pressure range within desired ranges. The frequency was set to 5Hz, temperature to 37C, and the pressure ranges were set at 35/15 mmHg. As output, the outer diameter of the tested scaffold is measured as a function of the amount of cycles.

Figure 9B clearly shows that PCLbu based materials have a higher increase in outer diameter as a function of amount of cycles when compared to UPy materials, indicating that UPy materials are even more resistant to fatigue failure. Comparing the results from shown in Figure 9 A with Figure 9 B it is clear to see that the PCL-bisurea withstands fatigue better PCL implants and furthermore PCL-UPy implants withstand fatigue even better than PCL-bisurea implants.

Figure 15 also shows results for 2 different PCLbu configurations and 2 different UPy configurations, which demonstrates that by tuning the scaffold material, the fatigue properties can be improved for PCLbu as well as UPy based scaffolds

#### Example 5

Youngs modulus for isotropic and anisotropic electrospun PCLbu strips were obtained from which the stiffness ratios were calculated. The results are listed in Table 1.

Table 1

| 1 – 6% strain<br>n = 3 | Initial Youngs modulus [MPa] |               | Ratio   |
|------------------------|------------------------------|---------------|---------|
|                        | Parallel                     | Perpendicular |         |
| <b>Isotropic</b>       | 5.1 ± 0.29                   | 4.2 ± 0.23    | 1.2 : 1 |
| <b>Anisotropic</b>     | 31 ± 4.0                     | 0.60 ± 0.10   | 52 : 1  |

Table 1 clearly shows that anisotropic spun PCLbu strips show a high Young modulus when measured parallel to the preferred orientation of the fibres and a low Young modulus when measured perpendicular to the preferred fibre orientation. Table 1 shows that for isotropic spun PCLbu strips the Young modulus measured in the parallel direction is comparable to the Young modulus in the perpendicular direction.

#### Example 6 Crimping test

Implants according to the present invention having a diameter of 28 mm were subjected to a crimping test. The implants were shrunk to a certain diameter using a commercially available device for crimping transcatheter heart valves. The different stages of the crimping process are depicted in Figure 11. After that they were allowed to return to their normal size. After unfolding the diameters were measured again. The results are

shown in figure 10 wherein the striped bars represent the diameter to which the implant is crimped, the white bar represents the diameter of the implant after it has been allowed to return to its uncrimped size and the black bar represents the same as the white bar but after soaking the implant in PBS at 37 °C for 1 hour.

5                      From the results it is clear that even after the implant has been crimped to a diameter of 6 mm return to its initial size (diameter of 29mm) was still observed after soaking in PBS at 37°C for 1 hour. Figure 12 shows pictures of the valves after being allowed to return to their uncrimped size. The numbers next to the picture correspond to the numbers of figure 10.

10

#### Example 7 In vivo testing

                    An implant according to the present invention was implanted at the pulmonary valve position in an adult sheep using open heart surgery. Cells were visualized with DAPI staining and cell infiltration was assessed under a microscope. Cell  
15                      infiltration was assessed 1 day, 7 days and 8 weeks after implantation. The results are depicted in Figure 13. The upper left picture shows cell infiltration after 1 day and the upper right picture after 7 days for the PCLbisurea implant and the lower pictures shows cell infiltration in the PCL-Upy implant after 8 weeks. The pictures clearly show that cells in vivo infiltrate the PCLbisurea implant and the PCL-UPy implant.

20

## Claims

1. Implant comprising a matrix material comprising one or more  
supramolecular compounds, wherein the matrix material comprises a fibrous network and  
5 which has at least 60% porosity, preferably a porosity of between 70% and 90%.
2. Implant according to claim 1, wherein the implant is a cardiovascular  
implant and preferably an implant chosen from the group consisting of a (blood) vessel, a  
heart valve, a cardiovascular patch or a valved conduit.
3. Implant according to claim 1 or 2 wherein the implant is reinforced by at  
10 least one support structure, preferably the at least one support structure is chosen from  
the group consisting of a reinforcement ring, a suture ring or a stent structure, and is  
preferably biodegradable, preferably the implant consists of the reinforced matrix material.
4. Implant according to one or more of the preceding claims wherein the  
matrix material is biodegradable.
- 15 5. Implant according to one or more of the preceding claims wherein the  
matrix material consists of a fibrous network, preferably the fibrous network consists of  
electrospun fibers.
6. Implant according to one or more of the preceding claims wherein the  
matrix material consists of one or more supramolecular compounds.
- 20 7. Implant according to any of the preceding claims wherein the one or more  
supramolecular compounds have a backbone comprising or consisting of  
polycaprolactone (PCL) or a combination of PCL, caprolactone, poly lactic acid and/or  
lactic acid.
8. Implant according to claim 7 wherein the supramolecular compounds  
25 further comprise one or more groups chosen from Upy (ureido-pyrimidinone) and/or  
bisurea.
9. Implant according to claim 8 wherein the one or more supramolecular  
compounds comprises at least PCL UPy, preferably the matrix material consist of PCL  
UPy.
- 30 10. Implant according to any one or more of the claims 5-8 wherein the fibrous  
network comprises nano fibers and/or micro fibers, preferably the diameter of the fibers  
ranges from 3 to 20 micrometer and preferably from 5 to 10 micrometer.
11. Implant according to one or more of the preceding claims wherein the  
matrix material comprises pores having a diameter ranging from 1-300 micrometer and

preferably ranging from 5-100 micrometer.

12. Implant according to one or more of the preceding claims wherein the matrix material has a linear elastic stiffness ranging from 0.1-50 MPa and preferably from 0.1-10.0 MPa.

5 13. Implant according to one or more of the preceding claims having a (linear) elastic regime of at least 30%, and preferably at least 45% and more preferred at least 60%.

10 14. Implant according to one or more of the preceding claims 5-13, wherein the fibers have a preferred orientation direction, preferably the preferred fiber alignment is circumferential.

15 15. Implant according to one or more of the preceding claims, where the linear elastic stiffness ratio between the preferred fiber direction and perpendicular to the preferred fiber direction is at least 2:1, preferably at least 4:1 and more preferred at least 10:1 and even more preferred at least 50:1.

16. Implant according to any one or more of the preceding claims wherein the implant further comprises biologically active compounds and/or contrast agent.

17. Method for manufacturing an implant having a matrix material one or more supramolecular compounds, wherein the matrix material has at least 60% porosity and more preferred 70% to 90% porosity, comprising the steps of:

- 20
- Providing a mold;
  - Applying the matrix material to the mold by means of electro spinning of the one or more supramolecular compounds to obtain an implant; and
  - Separating the implant and mold

25 18. Method according to claim 17 further comprising the step of providing at least one support structure to the implant.

19. Crimped implant obtainable by crimping an implant according to any one or more of claims 1-16.

20. Crimped implant according to claim 19 wherein the crimped implant has a diameter size which is 20% or less compared to the volume of the uncrimped implant.

30 21. Method for growing a tissue in a patient, comprising the step of implanting an implant according to one of claims 1-16 or according to claim 19 in the patient.

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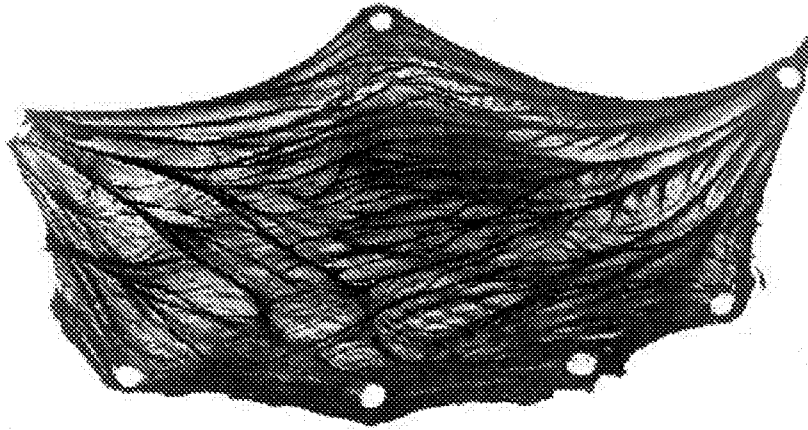


Fig. 1

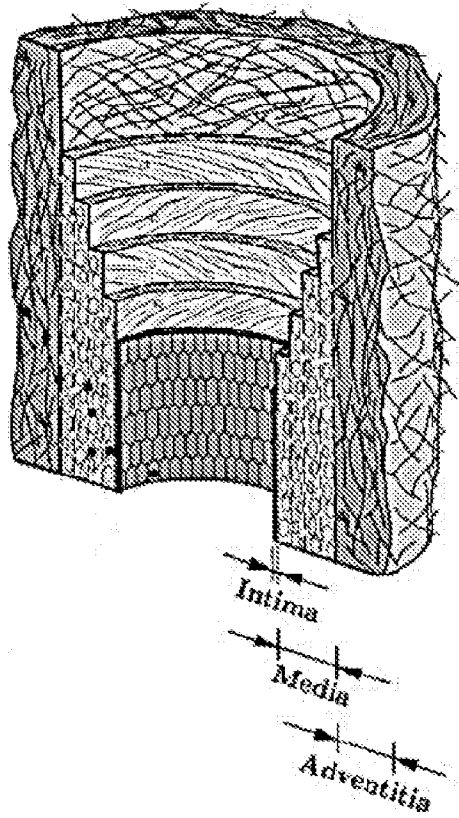


Fig. 2

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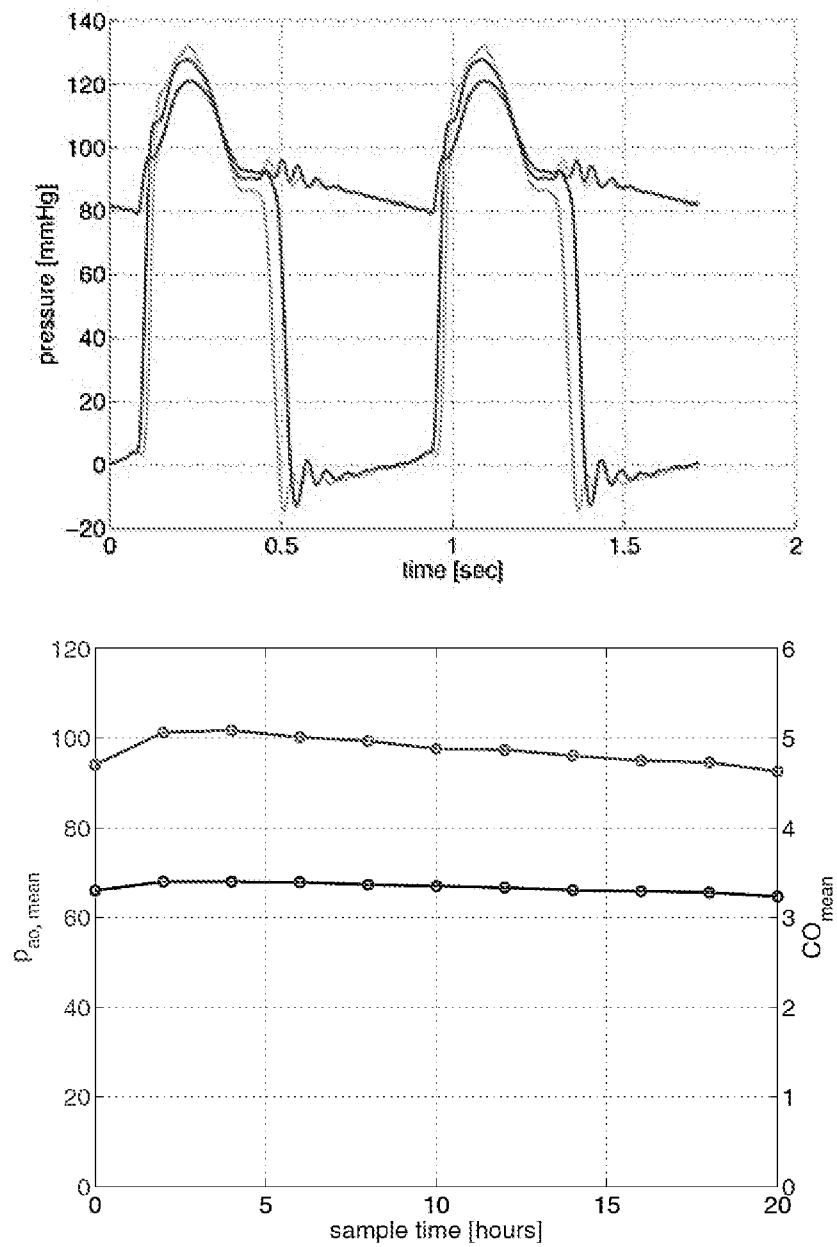


Fig. 3

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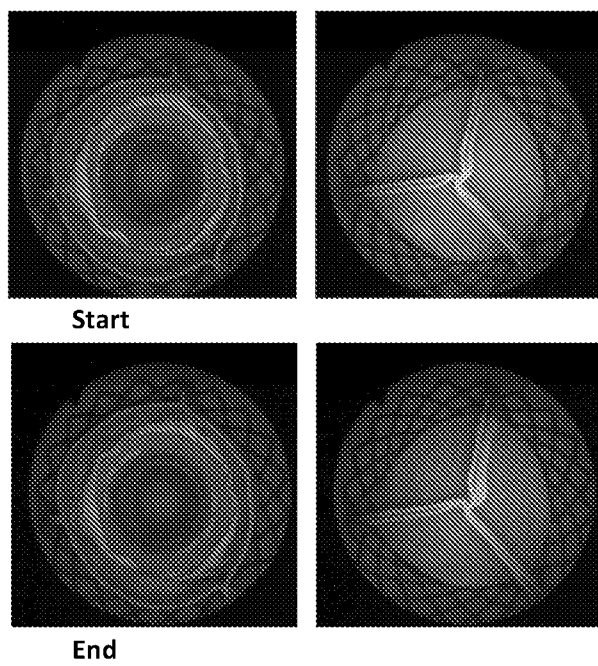


Fig. 4

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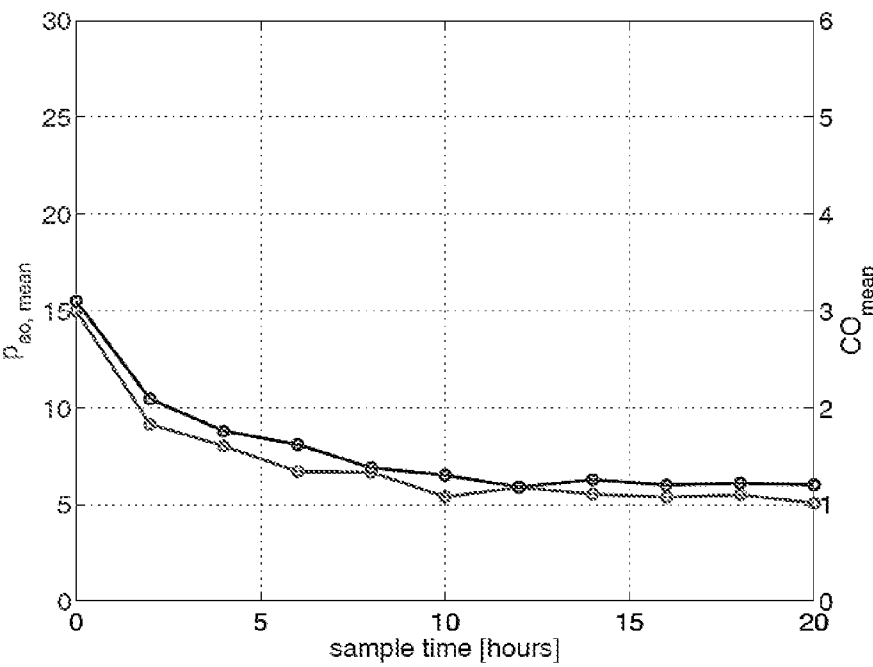


Fig. 5

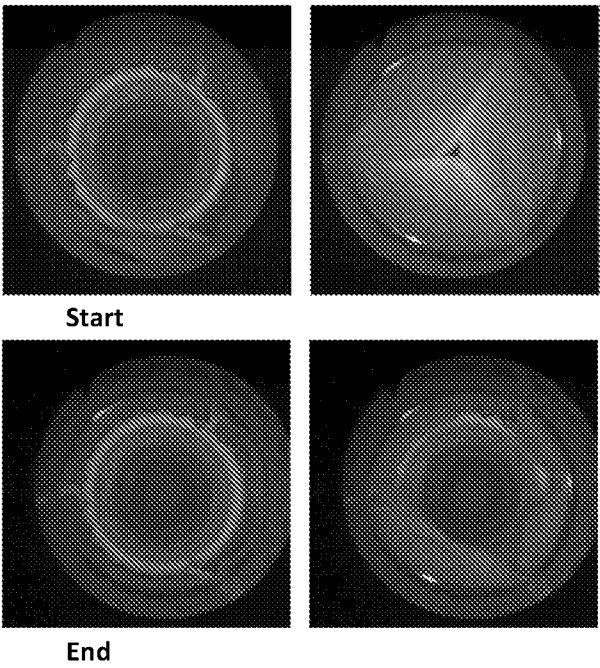


Fig. 6

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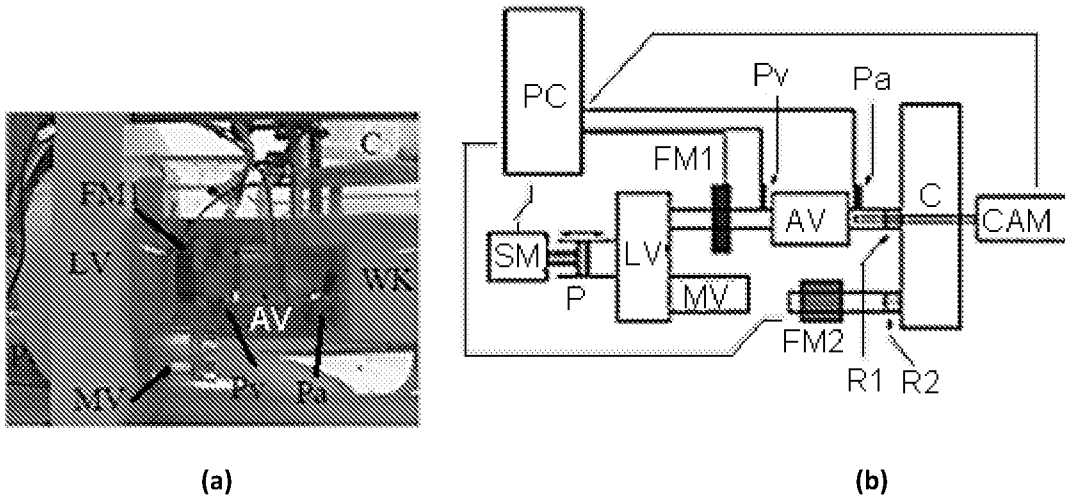


Fig. 7

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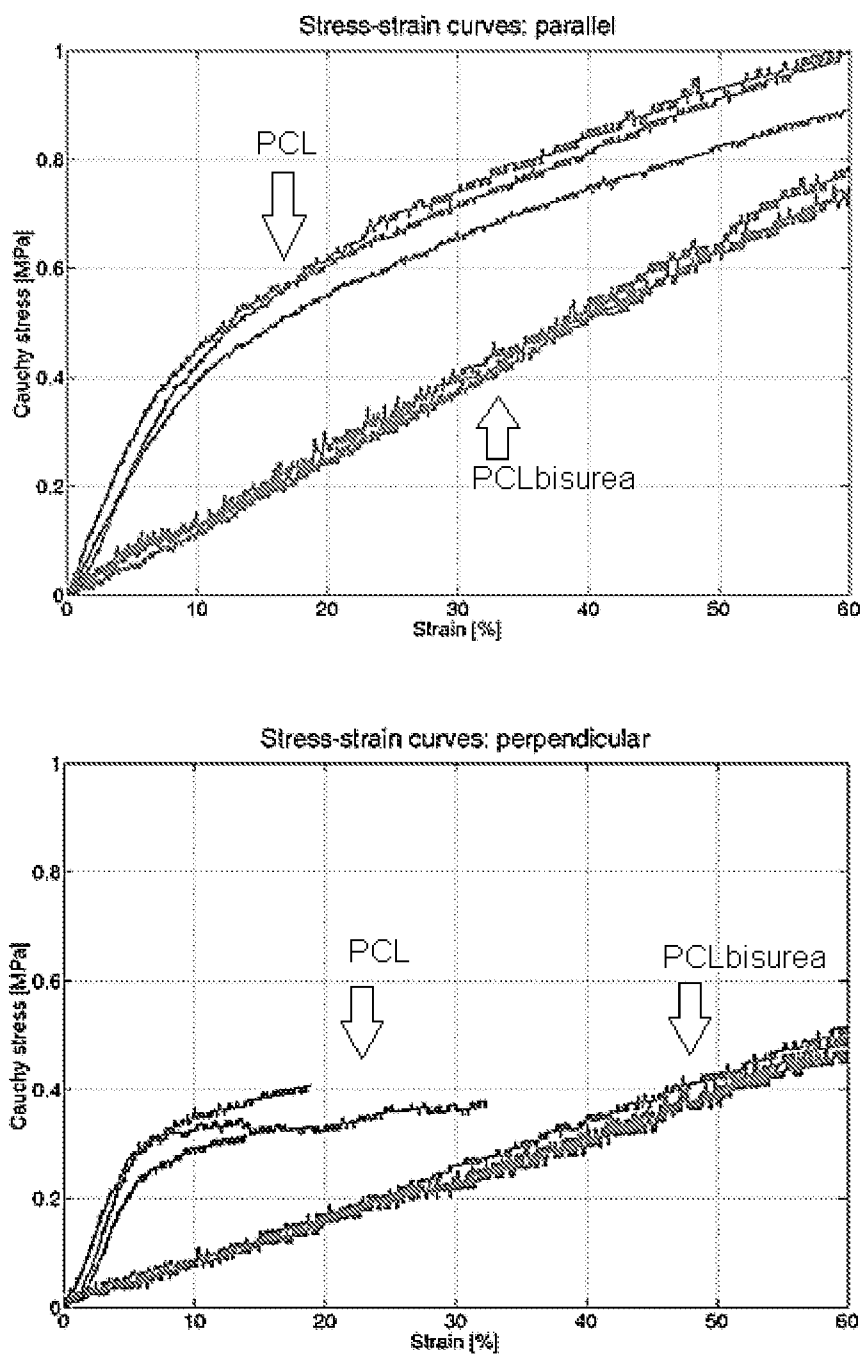


Fig. 8

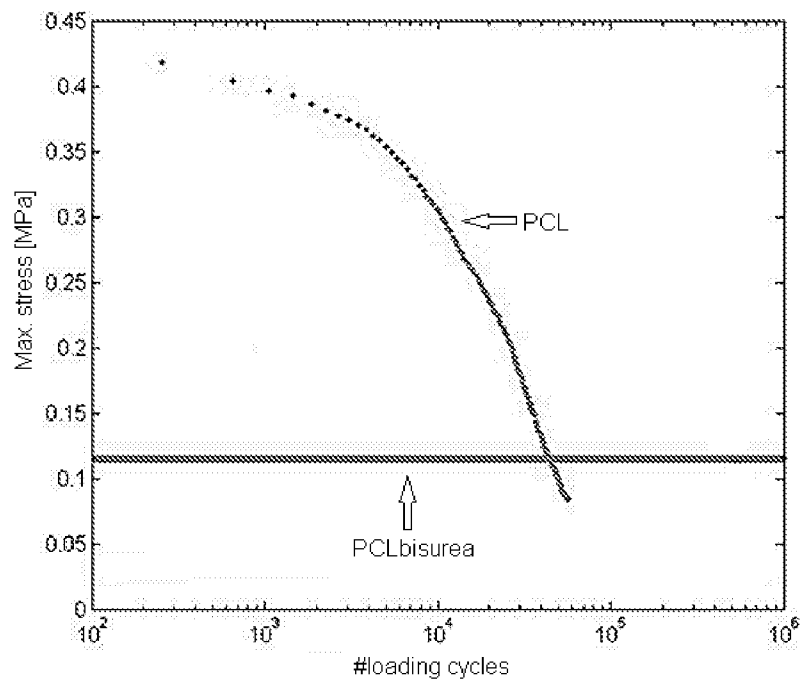


Fig. 9 A

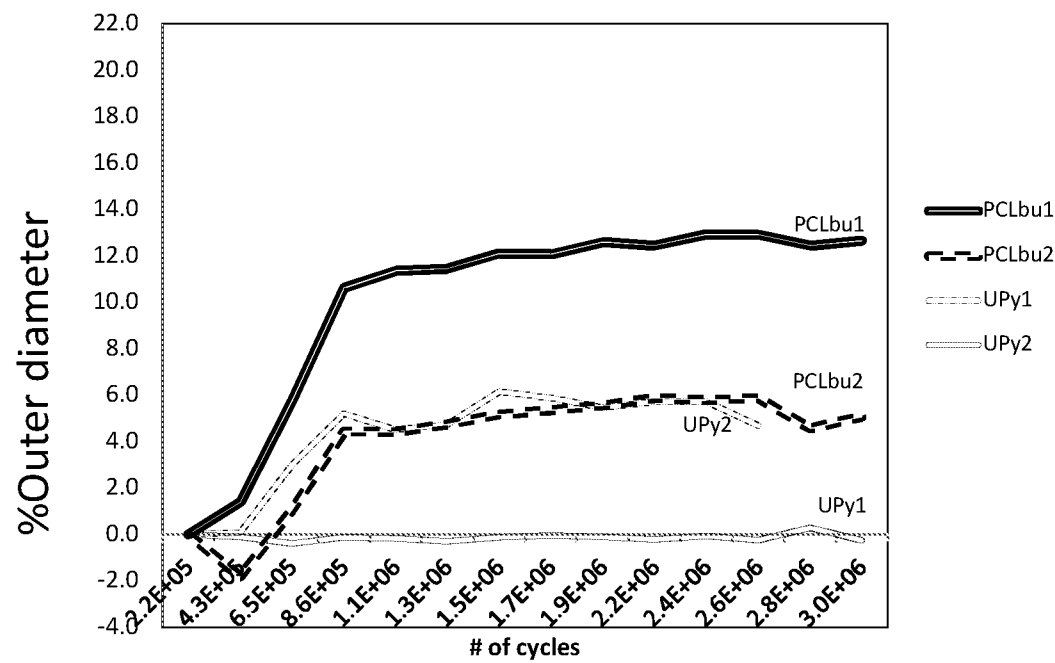


Fig. 9 B

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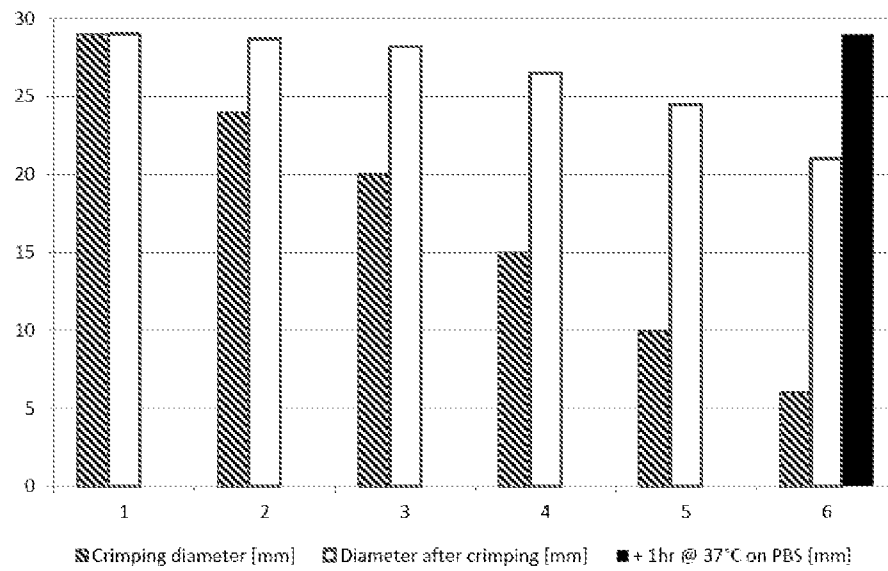


Fig. 10

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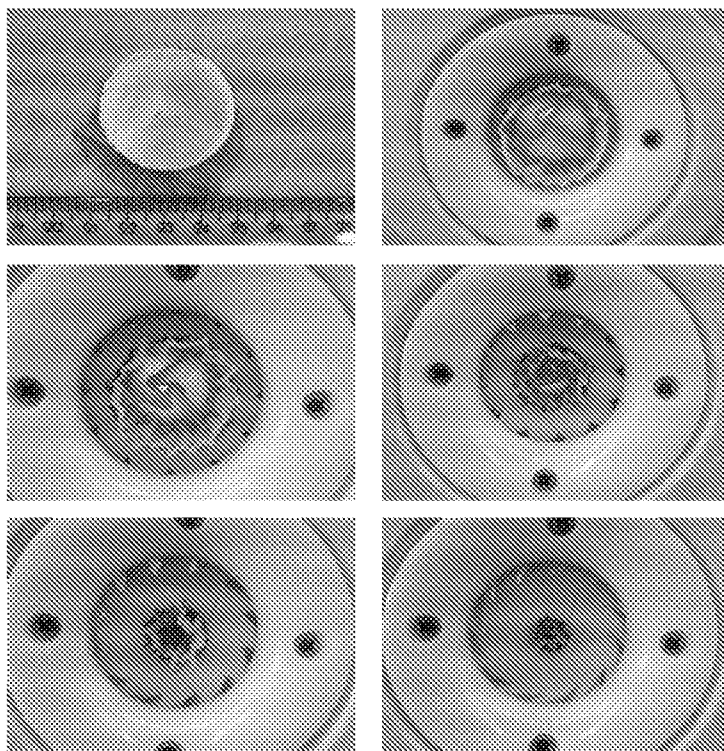


Fig. 11

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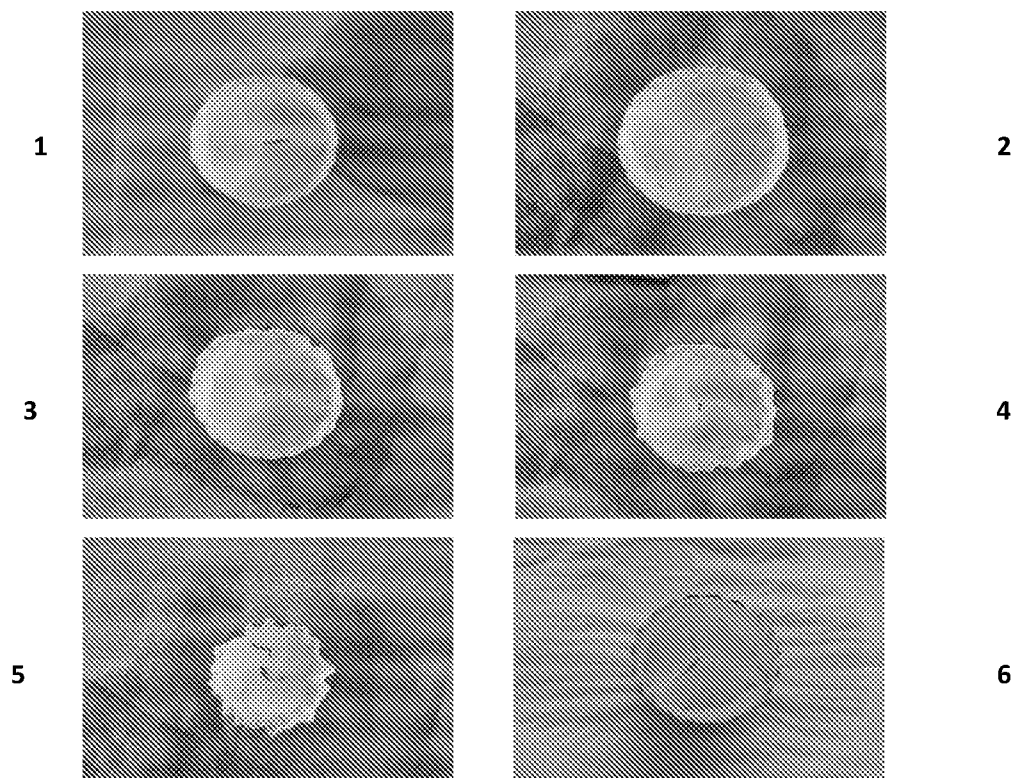


Fig. 12

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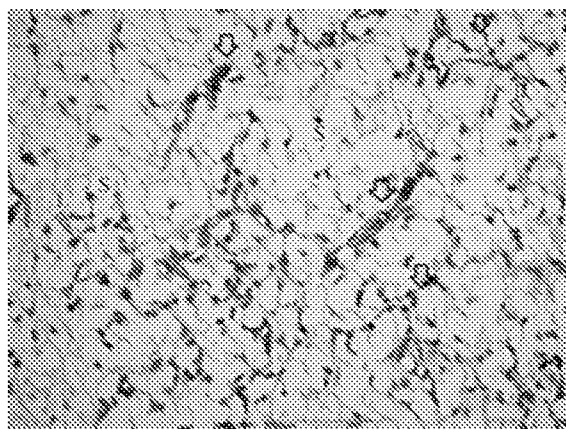
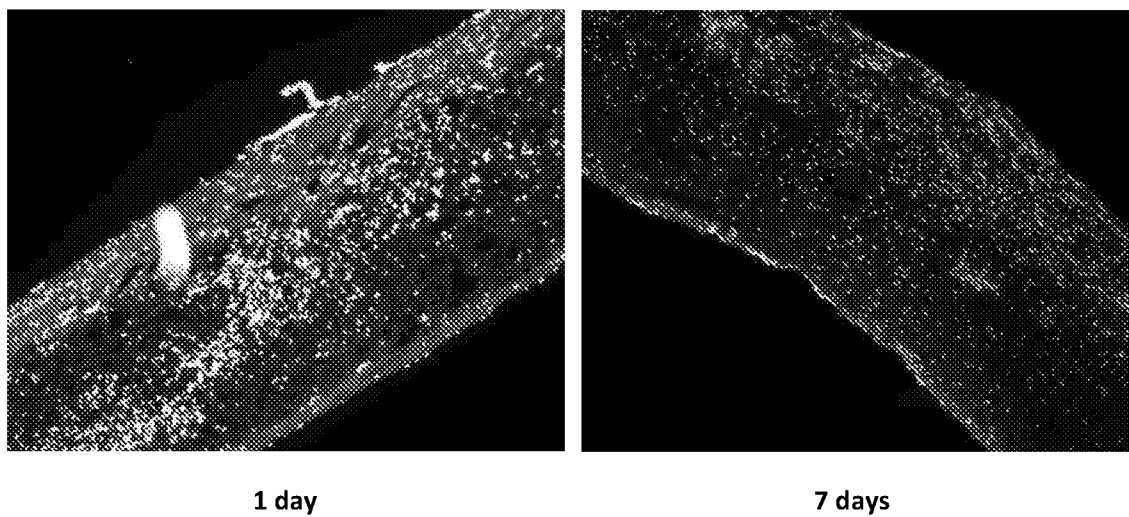


Fig. 13

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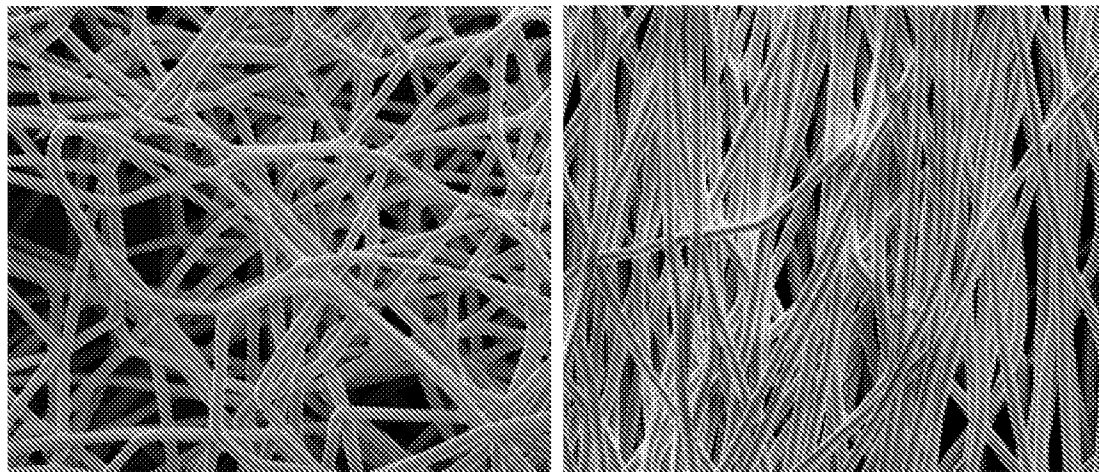


Fig. 14

# INTERNATIONAL SEARCH REPORT

International application No  
PCT/NL2013/050500

A. CLASSIFICATION OF SUBJECT MATTER  
INV. A61L27/18 A61L27/50 A61L27/56  
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)  
A61L C08L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EP0-Internal, WPI Data

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages                                                                                                                                                                                                                                                                                                                                                   | Relevant to claim No. |
|-----------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------|
| X         | <p>PATRICIA Y W DANKERS ET AL: "A modular and supramolecular approach to bioactive scaffolds for tissue engineering", NATURE MATERIALS, NATURE PUBLISHING GROUP, LONDON, GB, vol. 4, no. 7, 1 July 2005 (2005-07-01), pages 568-574, XP002606540, ISSN: 1476-4660, DOI: 10.1038/NMAT1418 [retrieved on 2005-06-19] Modular design and synthesis; page 569 - page 570; figure 2</p> <p style="text-align: center;">-----<br/>-/--</p> | 1-21                  |



Further documents are listed in the continuation of Box C.



See patent family annex.

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Date of the actual completion of the international search

2 September 2013

Date of mailing of the international search report

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Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2  
NL - 2280 HV Rijswijk  
Tel. (+31-70) 340-2040,  
Fax: (+31-70) 340-3016

Authorized officer

Siebum, Bastiaan

# INTERNATIONAL SEARCH REPORT

International application No  
PCT/NL2013/050500

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages                                                                                                                                                                                                                                                                                                   | Relevant to claim No. |
|-----------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------|
| A         | BOUTEN C V C ET AL: "Substrates for cardiovascular tissue engineering",<br>ADVANCED DRUG DELIVERY REVIEWS, ELSEVIER<br>BV, AMSTERDAM, NL,<br>vol. 63, no. 4,<br>14 January 2011 (2011-01-14), pages<br>221-241, XP028374182,<br>ISSN: 0169-409X, DOI:<br>10.1016/J.ADDR.2011.01.007<br>[retrieved on 2011-01-25]<br>5.2 supramolecular biomaterials;<br>page 231 - page 233<br>----- | 1-21                  |
| A         | D. HERMIDA-MERINO ET AL: "Electrospun<br>supramolecular polymer fibres",<br>EUROPEAN POLYMER JOURNAL,<br>vol. 48, no. 7, 1 July 2012 (2012-07-01),<br>pages 1249-1255, XP055030855,<br>ISSN: 0014-3057, DOI:<br>10.1016/j.eurpolymj.2012.04.015<br>the whole document<br>-----                                                                                                       | 1-21                  |
| A         | GB 1 530 990 A (ICI LTD)<br>1 November 1978 (1978-11-01)<br>page 4, lines 83-89<br>-----                                                                                                                                                                                                                                                                                             | 1-21                  |
| A         | WO 2010/041944 A1 (UNIV EINDHOVEN TECH<br>[NL]; BAAIJENS FRANCISCUS PETRUS THO [NL];<br>RUBBENS) 15 April 2010 (2010-04-15)<br>page 8, lines 7-11<br>-----                                                                                                                                                                                                                           | 1-21                  |
| A         | EP 2 468 305 A1 (QTIS E B V [NL];<br>SUPRAPOLIX B V [NL]; KONINKL PHILIPS<br>ELECTRONICS NV [NL])<br>27 June 2012 (2012-06-27)<br>column 11, paragraph 68<br>-----                                                                                                                                                                                                                   | 1-21                  |

# INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/NL2013/050500

| Patent document<br>cited in search report |    | Publication<br>date | Patent family<br>member(s) | Publication<br>date |
|-------------------------------------------|----|---------------------|----------------------------|---------------------|
| GB 1530990                                | A  | 01-11-1978          | NONE                       |                     |
| -----                                     |    |                     |                            |                     |
| WO 2010041944                             | A1 | 15-04-2010          | EP 2334857 A1              | 22-06-2011          |
|                                           |    |                     | JP 2012505320 A            | 01-03-2012          |
|                                           |    |                     | US 2011250689 A1           | 13-10-2011          |
|                                           |    |                     | WO 2010041944 A1           | 15-04-2010          |
| -----                                     |    |                     |                            |                     |
| EP 2468305                                | A1 | 27-06-2012          | EP 2468305 A1              | 27-06-2012          |
|                                           |    |                     | US 2012148500 A1           | 14-06-2012          |
| -----                                     |    |                     |                            |                     |