

An Apparatus and Method For Producing Nanofibres

Field

5 The present invention relates broadly to an apparatus and a method for producing aligned nanofibres.

Background

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Presently, millions of surgical procedures requiring arterial prostheses are performed each year, worldwide. However, there are currently no acceptable synthetic scaffolds for small-diameter blood vessels. Surgeons have to harvest a patient's own blood vessel for transplants. This procedure is time consuming and
15 may lead to unnecessary complications.

Electrospinning offers a method of developing blood vessel scaffolds that resemble that of naturally occurring blood vessels. A significant advantage of electrospinning is its ability to generate a non-woven, nanometer scale fibrous
20 structure using a wide variety of polymers.

A typical electrospinning process involves passing an external electric field to a polymer solution. This causes ions in the polymer solution to move towards an electrode of opposite polarity. When an electric charge is applied to a metal syringe
25 needle filled with the polymer solution, a droplet of the polymer solution forms at the tip of the syringe needle, and the ions in the polymer solution of like-polarity are forced to collect at the surface of the droplet. Once the electric potential of the surface charge on the droplet surpasses a critical value, the electrostatic force overcomes the surface tension of the droplet and a thin jet of polymer solution erupts
30 from the surface of the droplet to form a Taylor cone. The resulting jets of polymer can be collected as polymer fibres on a collector.

Most conventional processes for developing blood vessel scaffolds using electrospinning produce tubes with nanofibres that are deposited randomly or aligned either circumferentially or longitudinally with respect to the tube. Tubes that are produced in this manner have their limitations. For example, tubes with randomly deposited nanofibers may not exhibit consistent mechanical properties. Tubes with circumferentially aligned nanofibers are generally weak along their longitudinal axis, and tubes with longitudinally aligned nanofibers are generally weak circumferentially.

Summary

According to a first aspect of the present invention, there is provided an apparatus for producing aligned nanofibers comprising: a spinneret structure; an auxiliary electrode; and a collector for collecting nanofibers discharged from the spinneret structure; wherein an electric field is created between the spinneret structure and the auxiliary electrode that causes the discharged nanofibres to align substantially diagonally on the collector.

According to a second aspect of the present invention, there is provided a method for producing aligned nanofibers comprising creating an electric field between a spinneret structure and an auxiliary electrode that causes discharged nanofibers to align substantially diagonally on a collector.

The electric field may cross a deposition surface of the collector at an angle α . The spinneret structure may comprise an electrically conducting plate in electrical contact with a spinneret. The electric field may be created between the electrically conducting plate and a knife-edge of the auxiliary electrode.

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A tip of the spinneret may protrude or may be placed inline with the electrically conducting plate. The collector may be moveable in two directions substantially parallel to a plane of deposition of the nanofibres. A charge may be applied to the collector.

The spinneret and the auxiliary electrode may be oppositely charged. A relative distance between the spinneret structure and the auxiliary electrode may be adjustable to vary an angle of alignment of the nanofibers.

The tiltable component may comprise the electrically conducting plate. The collector may be movable to vary an angle of alignment of the nanofibers. The collector may be movable to vary an angle of alignment of the nanofibers. The collector may comprise a mandrel.

Brief Description of the Drawings

The invention will now be further described by way of non-limiting examples, with reference to the accompanying drawings, in which:-

Figure 1 is a schematic representation of an apparatus for producing aligned nanofibres, according to an embodiment of the present invention.

Figure 2 is a schematic diagram showing a travel path of a jet of fluid and an electric field generated by the apparatus of Figure 1.

Figure 3 is a scanning electron microscope (SEM) photograph of a nanofibre tube obtained using the apparatus of Figure 1.

Figure 4 is a schematic diagram showing a change in the angle of an electric field with respect to a collector, according to another embodiment of the present invention.

Figure 5 is a schematic representation of an apparatus for producing aligned nanofibres, according to yet another embodiment of the present invention.

5 Figure 6 is a schematic diagram showing the travel path of the jet of fluid and the electric field generated by the apparatus of Figure 5.

Figure 7 is a scanning electron microscope (SEM) photograph of a nanofibre tube obtained using the apparatus of Figure 4.

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Figure 8 is a schematic diagram showing a change in the angle of the electric field with respect to the collector, according to another embodiment of the present invention.

15 Figure 9 is a schematic diagram showing a change in the angle of a spinneret with respect to the collector, according to yet another embodiment of the present invention.

20 **Detailed Description**

Generally, the described embodiments provide a method and apparatus for producing nanofibres that are aligned diagonally. The apparatus generally
25 comprises a spinneret, a collector and an auxiliary electrode. The diagonally aligned nanofibers are produced by controlling the direction of a jet of fluid leaving the spinneret. This is achieved through controlling the electric field in combination with understanding how factors such as gravity, viscosity, humidity, etc, influence the path of the jet.

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Figure 1 shows a schematic representation of an apparatus for producing diagonally aligned nanofibres in accordance with an embodiment of the present invention. The apparatus 100 comprises a spinneret structure 120, a collector 140

and an auxiliary electrode 160. The collector 140 is generally disposed between the auxiliary electrode 160 and the spinneret structure 120. The spinneret structure 120 is positioned such that the plane of the blade 126 is substantially perpendicular to the longitudinal axis of the collector 140. The spinneret structure 120, in the example

5 embodiment, comprises a single spinneret in the form of a syringe needle 122 having an electrically grounded tip 124. The syringe needle 122 may be made of an electrically conducting material, such as metal. A blade 126 is attached to the syringe needle 122. The blade is made of an electrically conducting material, such as metal, and is electrically connected to the syringe needle 122. The blade 126 is

10 positioned on the syringe needle 122 such that the syringe needle 122 is substantially midway between the length of the blade 126, and the tip 124 of the syringe needle 122 protrudes or is placed inline with the blade 124. The auxiliary electrode 160 comprises a knife-edge 162 and is made of metal such as aluminium. However, it should be appreciated that the auxiliary electrode 160 may be in the

15 form of other shapes, for example, rods, strips, etc. and may be made of other electrically conducting materials.

A fluid used for forming nanofibres, such as a polymer solution, is fed to the spinneret structure 120. A syringe pump (not shown) is used to regulate the flow of

20 the polymer solution through the syringe needle 122. A variety of polymers such as homopolymers, copolymers, etc can be used. During electrospinning, jets of the polymer solution are ejected from the tip 124 of the syringe needle 122 and deposited onto the collector 140 as nanofibres.

25 In this example embodiment, a positive voltage, for example, of about +12kV is applied to the spinneret structure 120 by a high voltage power supply (not shown), and negative voltage of about -5kV is applied to the auxiliary electrode 160 to create an electric field 190 between the blade 126 of the spinneret structure 120 and the knife-edge 162 of the auxiliary electrode 160, as shown in Figure 2. The

30 polarity of the voltage supplied to the spinneret structure 120 and the auxiliary electrode 160 may be switched. The magnitude of the applied voltages may be varied to alter the angle of alignment of the nanofibers deposited on the collector 140 or to determine an optimum electric field to carry out the electrospinning

process. The voltage supplied to the spinneret structure 120 typically ranges from 6kV to 20kV while the voltage supplied to the auxiliary electrode 160 typically ranges from 2kV to 10kV.

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The auxiliary electrode 160 is disposed such that the resulting electric field 190 is at an angle α with respect to the longitudinal axis of the collector 140, and crosses the surface of the collector 140.

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In this embodiment, the collector 140 is not given any charge. It should be appreciated that the collector 140 may be grounded or a charge may be applied to the collector 140 to encourage the deposition of nanofibers onto the collector 140. Charge applied to the collector may affect the angle and extent of alignment of the nanofibers. The collector 140 is in the form of a mandrel in the example

15 embodiment and is rotated during deposition of the nanofibres to facilitate alignment of the nanofibres on the collector 140. The collector may be rotated at various speeds, typically in the range of 300rpm to 2000rpm.

The direction of a travel path of the jet 170 and the direction of the electric

20 field 190 are indicated by the solid and dashed arrows, respectively, as shown in Figure 2. The collector 140 disposed between the auxiliary electrode 160 and the spinneret structure 120 is positioned such that the collector 140 is at an angle α relative to the electric field 190. When the jet 170 leaves the spinneret structure 120, both the initial momentum of the jet 170 and the force of gravity cause the jet 170 to

25 initially accelerate vertically downwards. However, the electric field 190 between the blade 126 of the spinneret structure 120 and the auxiliary electrode 160 causes the jet 170 to travel in a generally arched path under the influence of the electric field 190. As the jet 170 travels towards the electric field 190, the nanofibres are deposited on the collector 140, which is positioned in the path of travel of the jet

30 170. The electric field 190 is used to control the direction of travel of the jet 170 ejected from the spinneret structure 120 such that the nanofibres are deposited aligned in a generally diagonal orientation on the collector 140.

Various structures, for example, nanofibre tubes, can be made using the process described. A scanning electron microscope (SEM) photograph of the surface of a nanofiber tube that is produced using the apparatus described above is shown in Figure 3. It is observed that the nanofibres e.g. 300 on the nanofiber tube are
5 generally aligned diagonally.

To obtain the nanofibers shown in Figure 3, the spinneret structure 120 was given a charge of +12kV while the auxiliary electrode 160 was given a charge of -8kV. The electric field was oriented at 45° from the spinneret structure 120 to the
10 auxiliary electrode 160.

Returning to Figure 2, it is possible to vary the angle of alignment of the nanofibres on the collector 140. This can be achieved by various ways, for example,
15 by varying the angle α of the electric field 190 between the auxiliary electrode 160 and the spinneret structure 120 with respect to the collector 140.

An example embodiment of the present invention showing a change in the angle of alignment of the nanofibres is shown Figure 4. The initial angle a_1 of the
20 electric field with respect to the collector 440 may be changed by varying the distance between the auxiliary electrode 460 and the spinneret 420 either horizontally or vertically. In this embodiment, the auxiliary electrode 460 is moved horizontally away from the spinneret 420 by a distance d_1 . The new position of the
auxiliary electrode 460 is represented by dashed lines. When the distance of the
25 auxiliary electrode 460 is changed by the distance d_1 , the angle of the electric field 490 from a_1 to a_2 (where a_1 is greater than a_2), as shown in Figure 4.

An alternative embodiment to the apparatus in Figure 1 is shown in Figure 5. The apparatus 500 in Figure 5 is generally similar to that in Figure 1, thus only the
30 differences are described. In this embodiment, the spinneret structure 520 is positioned such that the plane of the blade 526 is substantially parallel to the longitudinal axis of the collector 540. As a result of the relative positions of the

spinneret structure 520, the auxiliary electrode 560, and the collector 540, an electric field 590 is created across the surface of the collector 540, as shown in Figure 6.

When the jet 570 leaves the spinneret structure 520, the initial momentum of the jet 520 causes the jet 570 to move horizontally forward. The electric field 590 generated by the spinneret structure 520 and the auxiliary electrode 560 cause the jet 570 to accelerate towards the auxiliary electrode 560 under the further influence of gravitational forces. As the jet 570 moves towards the auxiliary electrode 560, nanofibers are deposited and aligned generally diagonally on the collector 540 placed in the path of the jet 570. A scanning electron microscope (SEM) photograph of a nanofibre tube that is produced using the apparatus in the above embodiment is shown in Figure 7. It is observed that the nanofibres e.g. 700 on the nanofiber tube are generally aligned diagonally.

Returning now to Figure 6, the angle of alignment of the nanofibres can be varied by varying the angle α of the electric field 590 with respect to the collector 540. For example, as shown in Figure 8, the auxiliary electrode 560 is moved horizontally away from the spinneret 520 by a distance d_2 . The new position of the auxiliary electrode 560 is represented by the dashed lines. As a result, the angle of the electric field 890 with respect to the longitudinal axis of the collector 540 is changed from θ_1 to θ_2 (where θ_1 is greater than θ_2).

Alternatively, the angle of the spinneret 520 can be changed in order to change the angle of alignment of the nanofibres. The change in the angle of the spinneret 520 is achieved by tilting the blade 526 and the spinneret 520, as shown in Figure 9. As a result, the initial path of the jet 570 changes to a new path 970 such that the angle of alignment of the nanofibres is altered.

Factors that affect the electrospinning process also affect the morphology of the collected nanofibers using the methods described. This will include, but is not limited to, polymer solution concentration, the solvent used, electric field, gravity, addition of ionic salt to the polymer solution, etc.

It will be appreciated that while only a few specific embodiments of the invention have been described herein for the purposes of illustration, various changes or modifications may be made without departing from the scope and spirit of the invention.

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In another example embodiment, the collector may be moved laterally along its longitudinal axis to enable a more even distribution of the nanofibers along its axis.

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In yet another embodiment, multiple layers of the diagonally aligned nanofibers can be deposited on the collector and arranged in cross-diagonal layers.

Apart from the methods described above, another method that can be used to change the angle of alignment of the nanofibers is to change the angle of the collector relative to the electric field.

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The diagonally aligned nanofiber tubes produced using the example apparatus and methods described can be used in biomedical applications such as small diameter blood vessel scaffolds or nerve-guided tubes. Other hollow shapes and structures with aligned nanofibers can also be made.

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Further, the apparatus described in the example embodiments may be used to deposit nanofibers on a braided tube or any substrate, instead of on the collector.

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Claims

1. An apparatus for producing aligned nanofibers comprising:
a spinneret structure;
5 an auxiliary electrode; and
a collector for collecting nanofibers discharged from the
spinneret structure;
wherein an electric field is created between the spinneret structure
and the auxiliary electrode that causes the discharged nanofibres to align
10 substantially diagonally on the collector.
2. The apparatus according to claim 1, wherein the electric field crosses a
deposition surface of the collector at an angle α .
- 15 3. The apparatus according to any one of the preceding claims, wherein the
spinneret structure comprises an electrically conducting plate in electrical contact
with a spinneret.
4. The apparatus according to claim 3, wherein the electric field is created
20 between the electrically conducting plate and a knife-edge of the auxiliary electrode.
5. The apparatus according to claim 4, wherein a tip of the spinneret protrudes
or is placed inline with the electrically conducting plate.
- 25 6. The apparatus according to any one of the preceding claims, wherein the
collector is moveable in two directions substantially parallel to a plane of deposition
of the nanofibres.
7. The apparatus according to any one of the preceding claims, wherein a
30 charge is applied to the collector.
8. The apparatus according to any one of the preceding claims, wherein the
spinneret and the auxiliary electrode are oppositely charged.

9. The apparatus according to any one of the preceding claims, wherein a relative distance between the spinneret structure and the auxiliary electrode is adjustable to vary an angle of alignment of the nanofibers.
- 5 10. The apparatus according to any one of the preceding claims, wherein at least a component of the spinneret structure is tiltable to vary an angle of alignment of the nanofibers.
- 10 11. The apparatus according to claims 10 and 3, wherein the tiltable component comprises the electrically conducting plate.
12. The apparatus according to any one of the preceding claims, wherein the collector is movable to vary an angle of alignment of the nanofibers.
- 15 13. The apparatus according to any one of the preceding claims, wherein the collector comprises a mandrel.
14. A method for producing aligned nanofibers comprising creating an electric field between a spinneret structure and an auxiliary electrode that causes discharged
20 nanofibers to align substantially diagonally on a collector.
15. The method according to claim 14, wherein the electric field crosses the deposition surface of the collector at an angle α .
- 25 16. The method according to any one of claims 14 or 15, wherein the spinneret structure comprises an electrically conducting plate in electrical contact with a spinneret.
17. The method according to claim 16, wherein the electric field is created
30 between the electrically conducting plate and a knife-edge of the auxiliary electrode.
18. The method according to claim 17, wherein a tip of the spinneret protrudes or is placed inline with the electrically conducting plate.

19. The method according to any one of claims 14 to 18, comprising moving the collector in two directions substantially parallel to a plane of deposition of the nanofibers.
- 5 20. The method according to any one of claims 14 to 19, wherein a charge is applied to the collector.
21. The method according to any one of claims 14 to 20, wherein the spinneret and the auxiliary electrode are oppositely charged.
- 10 22. The method according to any one of claims 14 to 21, wherein a relative distance between the spinneret structure and the auxiliary electrode adjusted to vary an angle of alignment of the nanofibers.
- 15 23. The method according to any one of claims 14 to 22, wherein at least a component of the spinneret structure is tilted to vary an angle of alignment of the nanofibers.
- 20 24. The method according to claims 23 and 16, wherein the tilted component comprises the electrically conducting plate.
25. The method according to any one of claims 14 to 24, wherein the collector is moved to vary an angle of alignment of the nanofibers.
- 25 26. The method according to any one of claims 14 to 25, wherein the collector comprises a mandrel.