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A novel electrospinning target to improve the yield of uniaxially aligned fibers

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Abstract

Electrospinning is a useful technique that can generate micro- and nano-meter sized fibers. Modification of the electrospinning parameters, such as deposition target geometry, can generate uniaxially aligned fibers for use in diverse applications ranging from tissue engineering to material fabrication. For example, meshes of fibers have been shown to mimic the extracellular matrix networks for use in smooth muscle cell proliferation. Further, aligned fibers can guide neurites to grow along the direction of the fibers. Here we present a novel electrospinning deposition target that combines the benefits of two previously reported electrodes: the standard parallel electrodes and the spinning wheel with a sharpened edge. This new target design significantly improves aligned fiber yield. Specifically, the target consists of two parallel aluminum plates with sharpened edges containing a bifurcating angle of 26°. Electric field computations show a larger probable area of aligned electric field vectors. This new deposition target allows fibers to deposit on a larger cross-sectional area relative to the existing parallel electrode and at least doubles the yield of uniaxially aligned fibers. Further, fiber alignment and morphology are preserved after collection from the deposition target.

Keywords

Electrospinning; Fiber Deposition; Uniaxial Alignment; Parallel Fibers; Microfibers; Electric Fields; Tissue Engineering Scaffold

1. Introduction

Electrospinning has become a ubiquitous and inexpensive technique to acquire polymeric fibers with micrometer to nanometer diameters. The fibers, with their large surface to volume ratios, have been utilized in many applications including material fabrication (1–3) and filtration (4). In recent years the technique has been expanded to such applications as tissue engineering scaffold design (5–8). Generally, electrospun fibers have been used in scaffold constructions for the regeneration of blood vessels (9,10), extracellular collagen networks (11), smooth muscle cells (12), nervous tissue (13,14) and construction of bone tissue scaffolds (15). Nano- and micro-fibers specifically are important in tissue engineering as they mimic the scales of natural cellular environments (16). Aligned microfibers are of particular interest to nerve tissue engineering because the diameters of axons and myelinated nerve fibers are on the order of a few to tens of microns (17–19). Therefore aligned micro-fibers can be used as sacrificial templates to fabricate tubular nerve tissue engineering scaffolds with aligned micro-channels. These micro-channels are expected to provide

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micron-scale contact guidance for regenerating axons and nerve fibers. Nerve tissue engineering scaffolds with channels have been reported before, however, the number of channels is relatively low and the diameters are about 200 microns (20). Our goal is to create scaffolds with approximately hundreds of channels with diameters of several microns to tens of microns. Here we report a new electrospinning target that can greatly increase the yield of aligned micro-fibers based on water-soluble polymers.

During electrospinning, a polymeric solution is ejected from a syringe at an appropriate flow rate. A large electrical potential (5–30 kV) is placed across a gap flanked by the charged syringe needle and an electrically grounded deposition target. As the solution flows from the syringe needle, Coulombic forces pull the stream into a fine, continuous polymer stream. The short transition from the needle to the stream occurs via a Taylor cone common to charged fluid motion in electric field gradients (21). The electric field accelerates the stream onto the grounded deposition target. The polymeric solution dries before depositing to yield dry fibers. Resultant fiber diameter, porosity, and other characteristics can be controlled by modifying the solution flow rate, composition, electric field potential, and distance between the needle and target (22,23). Additionally, fiber arrangement can be altered by modifying the deposition target geometry (23).

Much work has been performed when designing deposition targets that yield uniaxially aligned fibers. Uniaxially aligned fiber arrangements at the micro- and nano- scales allow for unprecedented control in nanotechnology and tissue engineering applications. There are many excellent reviews examining current fiber deposition geometries and applications of electrospinning in materials, drug delivery, and tissue engineering fields (23–28). We will therefore only briefly review electrospinning techniques that are most applicable to our research.

One approach to obtain aligned electrospinning fibers is to deposit fibers on a rotating, electrically-grounded wheel with a sharpened edge and a bifurcating angle of 26.6° (29). The sharpened wheel is grounded and rotated at a constant angular velocity. The fiber stream is ejected such that the fibers align parallel and on top of the sharpened edge. This technique consists of a relatively simple setup and can yield highly aligned fibers, but the yield and the maximum fiber diameter are limited to the small region surrounding the rotating edge (23). Another uniaxially aligned fiber deposition target consists of two parallel electrodes (30). The electrodes are grounded, and the electrospinning solution is deposited in the region spanning the two electrodes. This technique can generate highly aligned fibers at inter-electrode distances of up to 1 mm, but the fiber yield is limited because the fiber alignment region is restricted to the orthogonal edges of the electrodes. Further, alignment quality decreases with inter-electrode distances larger than 1 mm (30).

We hypothesized that introducing a sharp edge into the parallel electrode design would increase the uniaxially aligned fiber yield by focusing the electric field along the sharp edges and increasing the parallel electric field vectors. We validated this hypothesis theoretically (Figure 2) and demonstrated that the aligned fiber yield increased experimentally. We will refer to the original parallel electrode as the standard parallel electrode and the new parallel electrode with sharp edges as the sharpened parallel electrode.

2. Materials and Methods

2.1 Electric Field Calculations

Electric field computations were performed using Students' QuickField 5.5 (Terra Analysis Ltd., Svendborg, Denmark). For simplification, the software assumed a 2-dimensional, planar computation region; thus, a profile view of each deposition electrode was modeled

with relative dimensions. The models were then encased in a rectangular, uncharged container (not shown in images) to provide computational boundaries. The computational boundaries were neither charged nor given a 0 V potential (which would erroneously model the boundaries as ground). Although it was assumed that these boundaries would not affect the theoretical computations, several models were performed while varying the target-to-boundary distances with no appreciable change in distribution of electric field vectors.

The targets, along with the syringe needle, were assigned a relative permittivity (ϵ_{target}) of 10, and the surrounding air region was assigned a relative permittivity (ϵ_{air}) of 1. The needle was modeled as a long rectangle and assigned a potential of 10 kV. The target's surfaces and vertices were assigned a potential of 0 V (to model as electrical ground). The materials were therefore assumed to be electrically homogenous with constant permittivities and voltage values. Finally, all closed polygonal regions were given a mesh grid, and electric field computations were performed.

The software utilized a proprietary finite element analysis technique to independently solve for the electric fields at discrete positions between the needle and deposition target. The computed electric fields were represented as field lines within the air space spanning the gap between the needle and target. Poisson's equation for scalar electric potentials was solved by the software to obtain the electric field vectors (equation 1), where E = electric field vector, V = electric potential, ρ = total charge density, and ϵ = permittivity of location.

$$\begin{aligned}\frac{\rho}{\epsilon} &= \nabla \cdot \vec{E} = -\nabla^2 V(x, y) \\ &= \frac{\partial}{\partial x} E_x + \frac{\partial}{\partial y} E_y = -\frac{\partial}{\partial x} \left(\frac{\partial}{\partial x} V \right) - \frac{\partial}{\partial y} \left(\frac{\partial}{\partial y} V \right)\end{aligned}\quad (1)$$

2.2 Target Construction

An electrospinning deposition target was constructed, consisting of the standard and sharpened parallel electrodes on opposite sides. Such a target was used to directly compare uniaxially aligned fiber yield of the two targets.

One 6 mm × 97 mm × 50 mm aluminum plate was obtained from McMaster-Carr (alloy 6061, Atlanta, Georgia, USA). Sharpened points were machined on one of the 97 mm surfaces of each aluminum plate such that the bifurcating angle of each sharpened peak apex was 26°. The plates were aligned with the sharpened sides positioned parallel to one another along a 2 mm gap; the standard parallel electrodes were similarly aligned on the opposite side. Bare copper wire was wrapped along the long axis of the plates. To further insulate the device and isolate the alignment regions, the apparatus was completely enveloped in paraffin wax (Acros Organics, New Jersey, USA). The wax was then removed from the alignment areas on each end of the apparatus to expose the bare aluminum regions. The bare aluminum alignment surface areas were kept constant; the surface area of the standard parallel electrode end equaled the surface area of the region in between the sharpened edges.

2.3 Electrospinning

The electrospinning solution consisted of 50% polyethylene glycol (PEG, average MW = 10,000 g/mol, Alfa Aesar, Ward Hill, Massachusetts, USA) and 0.5% polyethylene oxide (PEO, average MW = 1,000,000 g/mol, Alfa Aesar, Ward Hill, Massachusetts, USA) in a 50% / 50% (v/v) water / ethanol solvent. This PEG / PEO solute ratio was chosen because it generated micrometer diameter fibers that dissolve in water, are easily analyzed with visible light microscopy, and generate minimal beading (22). Further, the water / ethanol solvent ratio was chosen because it enabled rapid fiber drying during deposition. Ethanol also

lowered the solutions' surface tension, which further reduced beading (31). All electrospinning experiments were conducted using the same solution.

For each electrospinning experiment, 120 μL of solution was loaded into a syringe and placed on a syringe pump (model NE-300, New Era Pump Systems Inc., Farmingdale, New York, USA). The electrospinning target was placed such that fibers deposited only on one end of the electrode (standard or sharpened parallel electrode) as shown in Figure 1. A DC voltage source (model ES309-5W, Gamma High Voltage Research Inc., Ormond Beach, Florida, USA) was used to generate a 10 kV potential across a 35 cm deposition gap between the positive syringe needle and the grounded deposition target. DC voltage was used because AC voltages have been shown to reduce dry fiber yield (32). A 22 G syringe needle was used, and the syringe pump was programmed to maintain a constant 25 $\mu\text{L}/\text{min}$ flow rate. All 120 μL of solution was electrospun into fibers. The entire electrospinning process was performed in a polycarbonate enclosure to assist with removing ambient electromagnetic radiation. The housing dimensions were 60 cm $\times$ 30 cm $\times$ 30 cm. To obtain fibers from either deposition target, the engineered electrode was placed such that the appropriate target was facing the syringe.

2.4 Fiber Harvesting

The aligned fibers were isolated and harvested by lifting a pre-weighed, nonconductive substrate through the gap between the electrodes. The mass of the fibers was recorded for five trials on the standard parallel electrode. The target was then flipped within the electrospinning setup to present the sharpened parallel electrode as the deposition target. Five samples of aligned fibers were harvested from the new sharpened parallel electrode and weighed.

2.5 Fiber Imaging

Images were taken with a Nikon D70 digital camera equipped with a 90 mm macro lens (Melville, NY, USA). Scanning Electron Microscopy (SEM) was also performed as previously mentioned (33). Briefly, harvested fibers were placed on an aluminum stub lined with carbon tape, and the fibers were gold-sputtered for 120 seconds (approximately 67.3 nm thick of gold). Fibers were imaged at 250x and 1000x (Leo 1530, Zeiss, Jena, Germany).

2.6 Statistical Analysis

To statistically analyze the aligned fiber yield data, a 1-tailed Student's *t*-test was performed. A conservative heteroscedastic condition between the two sample sets was assumed, and *p*-values < 0.05 were considered statistically significant.

3. Results

3.1 Electric Field Analysis of Deposition Target Electrodes

The equipotential lines shown in Figure 2 are within the space spanning the positive voltage source (above each electrode but not shown) and the grounded target. Electric field vectors, perpendicular to the equipotential lines, are superimposed. In Figure 2(a) and 2(b), the electric field is concentrated at the sharp edges (orthogonal corners or sharp peak, confirming previously reported data and validating our computational simulation (29,30)). In Figure 2(c) (the novel target), the electric field is not only concentrated at the peaks, but also contains a lateral component in the region between the electrode peaks; the electric fields from the two electrodes sum together to generate laterally-oriented electric field vectors. In essence, the fiber alignment region of laterally-oriented electric field vectors of Figure 2(a) is enlarged throughout the larger cross-sectional area spanning the two electrodes in the sharpened target of Figure 2(c).

3.2 Fiber Deposition Study: Alignment Morphology and Yield

Representative images of the aligned fibers on both targets are shown in Figure 3(a) & (c) side views; detail images of the aligned fibers are shown in Figure 3(b) & (d) top views. Further, the deposited, aligned fibers were removed, and their masses were recorded for 5 trials on each target. The relative mass yields are compared in Figure 4, and relative fiber morphologies and diameters are compared in Figure 5.

4. Discussion

The electrospinning target reported here has several important characteristics. First, both the control and the new sharpened parallel electrodes were constructed on the same apparatus. This was important to normalize ambient and target-specific electromagnetic noise for the purposes of comparison testing. Further, encasing the electrospinning deposition target in paraffin wax (which covers the non-sharpened edges where unaligned fibers deposit) appears to potentially aid in the deposition process by concentrating the electric field to the regions which will produce aligned fibers. The amount of waste fibers was likely reduced because areas which would have yielded nonaligned fibers were blocked by the paraffin.

Another characteristic of the new sharpened parallel electrode deposition target is the larger regions where fiber alignment can occur. Figure 2(c) shows that the proposed target not only contained a region of large voltage drop at the apex (high density of equipotential lines) that pulled on the fibers from either end and uniaxially aligned them, but also contained an electric field with lateral vector components in the gap spanning the two electrodes. These lateral vectors guided the fibers to deposit in parallel; as the charged fiber stream approached the grounded electrode, the lateral-pointing electric field vectors pulled the fibers in opposite directions toward both electrodes. This eventually pulled the fibers in a direction perpendicular to the electrode aligning the fibers.

Fiber alignment within the gap by laterally-pointing electric field vectors is similar to that reported at the orthogonal corner of the standard parallel electrode target (30). The geometric apex of the presented target, in addition to the laterally-pointing vectors, generates a large deposition region that can uniaxially align fibers. As shown in Figure 3(a) and (c), the reported deposition target allows for aligned fiber deposition throughout a larger cross-sectional area compared to that of the standard parallel electrode. Further, because more deposition target surface area is utilized in the fiber alignment process, fewer fibers were wasted in the surrounding area (where uniaxial alignment was not possible), relative to the standard parallel electrode (Figure 3(b) versus (d)). As shown in Figure 4 the presented target increased the yield of uniaxially aligned fibers by more than twofold.

One caveat to the reported target is its slightly more complicated arrangement. The use of copper wire to envelop the electrodes allowed for a strong bond between the aluminum plates (the copper wire also served as a conductive interface to the grounding source). Another caveat to the new sharpened parallel electrode target is the loosely parallel fiber alignment relative to the standard parallel electrode. Because electric fields in general decrease inversely proportional to the distance squared, fiber alignment on the novel parallel electrode can decrease because the sharpened edges produce varied inter-electrode distances; the inter-electrode distance on the new sharpened parallel electrode changes from an inter-electrode distance of 2 mm at the bottom of the sharpened edges to an inter-electrode distance of 8 mm at the top of the sharpened edges (measured from apex to apex). Although the original parallel electrode target demonstrated highly uniaxially aligned nanofibers, it is important to note that the inter-electrode distance in the previously reported data was less than 1 mm (30). Nonetheless, observed fiber morphologies were relatively unchanged on the new sharpened target. Uniaxial alignment in Figure 5 (a) and (c) are

similar. Moreover, the fiber diameter was maintained between the two targets (around 10 μm), and alignment was preserved after harvesting (Figure 5 is of fibers removed from the targets).

Accordingly, the new sharpened parallel electrode target may be best used in applications where a large amount of long, uniaxially aligned fibers are required. For example, one use for the presented deposition target and microfibers is in tissue engineering scaffolds (8,17–19,34–36). Particularly, we will use bundles of microfibers as a sacrificial matrix to generate microchannels in bioactive polymer scaffolds for peripheral nerve regeneration. Microfibers will be placed in a bioactive polymer solution in a mold. After solvent removal, the PEO/PEG microfibers will be dissolved completely in water creating aligned microchannels within the insoluble biopolymer. The micro-channeled scaffolds may provide a useful alternative to other forms of scaffolds used in nerve regeneration (17,19,36,37).

To further refine the reported parallel electrode, removing the back portion with the standard parallel electrode (implemented here only to directly compare the two targets) and encasing the area in paraffin might improve the deposition efficiency. It is possible that having both electrodes on one target might have decreased the deposition efficiency and fiber alignment; each electrode generated an electric field that may have affected fiber deposition. However, since the deposition target was turned so that only one side was facing the fiber stream, we do not anticipate the opposite side to have significantly altered the deposition process. Another possible improvement is to use larger aluminum plates. Larger plates increase the electrical capacitance of the deposition target, thereby aiding with the deposition efficiency and fiber alignment.

5. Conclusion

We have shown that using sharpened parallel electrodes as deposition targets increased the yield of uniaxially aligned fibers by more than twofold. This new target resulted in fibers with alignment that was comparable to that of the standard electrode, even after removal from the target. The new sharpened parallel electrode likely increased the local voltage drop and enlarged the aligned region of the electric field generating a larger cross-sectional area where fibers can align. The aligned fibers would be very useful for tissue engineering and similar biotechnology applications where a larger amount of long, uniaxially aligned microfibers are required.

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References

1. Pawlowski KJ, Belvin HL, Raney DL, Su J, Harrison JS, Siochi EJ. Electrospinning of a micro-air vehicle wing skin. *Polymer*. 2003; 44:1309–1314.
2. Gibson PA, Schreuder-Gibson HL, Rivin D. Electrospun Fiber Mats: Transport Properties. *Amer. Inst. of Chem. Engineers Journal*. 1999; 45:190–195.
3. Kim C, Kim JS, Kim SJ, Lee WJ, Yang KS. Supercapacitors Prepared from Carbon Nanofibers Electrospun from Polybenzimidazol. *J. of the Electrochemical Society*. 2004; 151:A769–A773.
4. Gopal R, Kaur S, Feng CY, Chan C, Ramakrishna S, Tabe S, Matsuura T. Electrospun nanofibrous polysulfone membranes as pre-filters: Particulate removal. *J.I of Membrane Science*. 2007; 289:210–219.

5. Li WJ, Laurencin CT, Caterson EJ, Tuan RS, Ko FK. Electrospun nanofibrous structure: a novel scaffold for tissue engineering. *J. of Biomaterials Research*. 2002; 60:613–621.
6. Li M, Mondrinos MJ, Gandhi MR, Ko FK, Weiss AS, Lelkes PI. Electrospun protein fibers as matrices for tissue engineering. *Biomaterials*. 2005; 26:5999–6008. [PubMed: 15894371]
7. Buttafuoco L, Kolkman NG, Engbers-Buijtenhuijs P, Poot AA, Dijkstra PJ, Vermes I, Feijen J. Electrospinning of collagen and elastin for tissue engineering applications. *Biomaterials*. 2006; 27:724–734. [PubMed: 16111744]
8. Kidoaki S, Kwon IK, Matura T. Mesoscopic spatial designs of nano- and microfiber meshes for tissue-engineering matrix and scaffold based on newly devised multilayering and mixing electrospinning techniques. *Biomaterials*. 2005; 26:37–46. [PubMed: 15193879]
9. Xu CY, Inai R, Kotaki M, Ramakrishna S. Aligned biodegradable nanofibrous structure: a potential scaffold for blood vessel engineering. *Biomaterials*. 2004; 25:877–886. [PubMed: 14609676]
10. Vaz CM, van Tuiji S, Bouten CVC, Baaijens FPT. Design of scaffolds for blood vessel tissue engineering using a multi-layering electrospinning technique. *Actabiomaterialia*. 2005; 1:575–582.
11. Matthews JA, Wnek GE, Simpson DG, Bowlin GL. Electrospinning of collagen nanofibers. *Biomacromolecules*. 2002; 3:232–238. [PubMed: 11888306]
12. Mo XM, Xu CY, Kotaki M, Ramakrishna S. Electrospun P(LLA-CL) nanofiber: a biomimetic extracellular matrix for smooth muscle cell and endothelial cell proliferation. *Biomaterials*. 2004; 25:1883–1890. [PubMed: 14738852]
13. Yang, Yang; Murugan, R.; Wang, S.; Ramakrishna, S. Electrospinning of nano/micro scale poly(l-lactic acid) aligned fibers and their potential in neural tissue engineering. *Biomaterials*. 2005; 26:2603–2610. [PubMed: 15585263]
14. Bini TB, Gao S, Tan TC, Wang S, Lim A, Hai LB, Ramakrishna S. Electrospun poly(L-lactide-co-glycolide) biodegradable polymer nanofibre tubes for peripheral nerve regeneration. *Nanotechnology*. 2004; 15:1459–1464.
15. Yoshimoto H, Shin YM, Terai H, Vacanti JP. A biodegradable nanofiber scaffold by electrospinning and its potential for bone tissue engineering. *Biomaterials*. 2003; 24:2077–2082. [PubMed: 12628828]
16. Li W, Jiang YJ, Tuan RS. Chondrocyte Phenotype in Engineered Fibrous Matrix Is Regulated by Fiber Size. *Tissue Engineering*. 2006; 12:1775–1785. [PubMed: 16889508]
17. Nain AS, Phillippi JA, Sitti M, MacKrell J, Campbell PG, Amon C. Control of Cell Behavior by Aligned Micro/ Nanofibrous Biomaterial Scaffolds Fabricated by Spinneret-Based Tunable Engineered Parameters (STEP) Technique. *Small*. 2008; 4:1153–1159. [PubMed: 18651720]
18. Sun T, Norton D, Vickers N, McArthur SL, Neil SM, Ryan AJ, Haycock JW. Development of a Bioreactor for Evaluating Novel Nerve Conduits. *Biotechnology and Bioengineering*. 2008; 99:1250–1260. [PubMed: 17929317]
19. Bini TB, Gao S, Wang S, Ramakrishna S. Poly(l-lactide-co-glycolide) biodegradable microfibers and electrospun nanofibers for nerve tissue engineering: an in vitro study. *Journal of Materials Science*. 2006; 41:6453–6459.
20. Yu TT, Shoicet MS. Guided cell adhesion and outgrowth in peptide-modified channels for neural tissue engineering. *Biomaterials*. 2005; 26:1507. [PubMed: 15522752]
21. Taylor G. Disintegration of water droplets in an electric field. *Proceedings of the Royal Society London*. 1964; 280:383–397.
22. Yu JH, Fridrikh SV, Rutledge GC. The role of elasticity in the formation of electrospun fibers. *Polymer*. 2006; 47:4789–4797.
23. Teo WE, Ramakrishna S. A review on electrospinning design and nanofiber assemblies. *Nanotechnology*. 2006; 17:R89–R106. [PubMed: 19661572]
24. Chronakis IS. Novel nanocomposites and nanoceramics based on polymer nanofibers using electrospinning process – A review. *J. of Materials Processing Tech*. 2005; 167:283–293.
25. Huang ZM, Zhang YZ, Kotaki M, Ramakrishna S. A review on polymer nanofibers by electrospinning and their applications in nanocomposites. *Composites and Science Technology*. 2003; 63:2223–2253.
26. Pham QP, Sharma U, Mikos AG. Electrospinning of Polymeric Nanofibers for Tissue Engineering Applications: A Review. *Tissue Engineering*. 2006; 12:1197–1211. [PubMed: 16771634]

27. Rutledge GC, Fridrikh SV. Formation of fibers by electrospinning. *Advanced Drug Delivery Reviews*. 2007; 59:1384–1391. [PubMed: 17889398]
28. Ma Z, Kotaki M, Inai R, Ramakrishna S. Potential of nanofiber matrix as tissue-engineering scaffolds. *Tissue Engineering*. 2005; 11:101–109. [PubMed: 15738665]
29. Theron A, Zussman E, Yarin AL. Electrostatic field-assisted alignment of electrospun nanofibers. *Nanotechnology*. 2001; 12:384–390.
30. Li D, Wang Y, Xia Y. Electrospinning of polymeric and ceramic nanofibers as uniaxially aligned arrays. *Nano Letters*. 2003; 3:1167–1171.
31. Fong H, Chun I, Reneker DH. Beaded nanofibers formed during electrospinning. *Polymer*. 1999; 40:4585–4592.
32. Kessick R, Frnn J, Tepper G. The use of AC potentials in electrospraying and electrospinning processes. *Polymer*. 2004; 45:2981–2984.
33. Gao J, Crapo PM, Wang Y. Macroporous Elastomeric Scaffolds with Extensive Micropores for Soft Tissue Engineering. *Tissue Engineering*. 2006; 12:917. [PubMed: 16674303]
34. Zhu X, Cui W, Li X, Jin Y. Electrospun Fibrous Mats with High Porosity as Potential Scaffolds for Skin Tissue Engineering. *Biomacromolecules*. 2008; 9:1795–1801. [PubMed: 18578495]
35. Tuzlakoglu K, Bolgen N, Salgado AJ, Gomes ME, Piskin E, Reis RL. Nano- and micro-fiber combined scaffolds: A new architecture for bone tissue engineering. *J. of Materials Science: Materials in Medicine*. 2005; 16:1099–1104.
36. Kubicek JD, Brelsford S, Ahluwalia P, LeDuc PR. Integrated Lithographic Membranes and Surface Adhesion Chemistry for Three-Dimensional Cellular Stimulation. *Langmuir*. 2004; 20:11552–11556. [PubMed: 15595783]
37. Baker BM, Gee AO, Metter RB, Nathan AS, Marklein RA, Burdick JA, Mauck RL. The potential to improve cell infiltration in composite fiber-aligned electrospun scaffolds by the selective removal of sacrificial fibers. *Biomaterials*. 2008; 29:2348–2358. [PubMed: 18313138]

Figure 1.

A high voltage power supply generated an electrical potential to control the fiber deposition process across a 35 cm gap. Fibers were extruded from a syringe, and they dried before depositing on the deposition target. The positive electrode was connected to the syringe needle and electrical ground was connected to the deposition target. A clear, rectangular-cubic polycarbonate housing (not shown in Figure) was used to encase the components to further shield the process from ambient interference.

Figure 2.

Electric fields computed for (a) standard parallel electrode, (b) single sharpened electrode (original wheel deposition electrode), and (c) sharpened parallel electrode. The lines represent a region of equal voltage within the space spanning the needle and deposition target, whereas the vectors (arrows perpendicular to the lines) represent the direction and relative magnitude of the electric field. Images (a) & (b) are consistent with previously published data (29,30), validate our simulation (alignment areas are only at the sharp corners or peak), and help to explain the uniqueness of the novel target. Image (c) shows that the inclined internal surfaces generate electric field vectors with additional laterally-pointing vectors (relative to (a)) which can aid in uniaxially aligning fibers.

Figure 3.

(a) side view image and (b) top view image of aligned fibers on the standard parallel electrode; (c) side view image and (d) top view image of the aligned fibers on the new sharpened parallel electrode. All scale bars are 1 mm. The sharpened parallel electrode allowed the fibers to deposit through a larger cross-sectional area (a vs c), increasing the yield of parallel fibers. For a clear view of fiber alignment, only a small amount of fibers were collected. Images were captured with a Nikon D70 digital camera equipped with a 90 mm macro lens.

Figure 4.

The average mass of aligned fibers collected by the standard parallel electrodes and the sharpened parallel electrodes is shown with $n = 5$ for each data set. Data represents mean $\pm$ 1 standard deviation. The p-value was obtained using a one-tailed, heteroscedastic t-test.

Figure 5.

SEM micrographs for (a) & (b) fibers from sharpened target; (c) & (d) fibers from standard target. (a) & (c) scale bar is 100 μm ; (b) & (d) scale bar is 10 μm . The arrows depict alignment direction. The alignment of the fibers was well preserved after removal from the target; the fibers shown were removed from the deposition targets via lifting a thin, non-conductive film substrate through the deposition gap. Fiber uniaxial alignment on the new target is similar to that of the standard target, and the fiber diameter was consistent between the two targets at about 10 μm . Only a thin layer of fibers was collected to present a clear view of the fiber alignment.