Production of Conducting Polymer Nanowires for Use as Intravascular Neural Recording Electrodes

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ABSTRACT

A crucial factor limiting the adoption of brain-machine interfaces is the invasiveness of conventionally implanted cortical microelectrode arrays. Recently, Llinás *et al.* proposed a new, less invasive type of multielectrode neural recording, using sub-micrometer insulated nanowires placed in the capillary bed of the central nervous system [1]. Initial experiments using platinum wires were plagued by wire stiffness and metal fatigue.

We report the production of conductive, insulated polymer nanowires with a doped polyaniline core and a poly(ethylene oxide) shell by coaxial electrospinning. These fibers have continuous insulated conducting polymer lengths over 10 mm, and a core polymer conductivity of 3 S/m.

Keywords: conducting polymers, nanowires, neural stimulation, electrical recording, nanobiotechnology

1 INTRODUCTION

The development of brain-machine interfaces (BMIs) is likely to be one of the defining technologies of the next several decades [2]. Devices utilizing BMIs stand to restore normal lifestyles to those who have lost motor control or sensory input due to injury or illness, while potentially extending the capabilities of the healthy human brain. One of the primary obstacles currently preventing the wider development of BMIs is the invasiveness of current techniques. In order to obtain rich enough signals to implement BMI-based motion control systems or near-real-time BMIs, arrays of microelectrodes must be surgically implanted in the cerebral cortex [3, 4]. These microelectrode arrays tend to degrade over time due to the formation of scar tissue, making them unsuitable for long-term implantation [1].

Recently, the authors have proposed an alternative scheme by which neuroelectrical signals could be recorded from the central nervous system (CNS) without violating its physical integrity [1]. Rather than implantation of microelectrode arrays in nervous tissue, this scheme uses arrays of insulated nanowires placed in the capillary bed of the CNS. These nanowires can be implanted using a catheter, without opening the skull. The authors have demonstrated recording of high-fidelity action potentials using this approach in the frog spinal cord with glass-insulated platinum wires 600 nm in diameter [1].

Metallic nanowires pose durability and biocompatibility problems, so we have been pursuing the use of conducting polymer wires in their place. Conducting polymers have conductivities as high as 10^7 S/m when appropriately doped, comparable to those of metals, with the mechanical properties of conventional polymers [5]. Preliminary recordings were successfully demonstrated using 17 μm polyimide-insulated polypyrrole wires, but these wires are not small enough to be placed in the capillary bed [1].

Fabrication of insulated conducting polymer wires under one micrometer in diameter and over one millimeter in length presents a challenge for conventional fabrication techniques. Recently, production of sub-micrometer conducting polymer fibers has been reported by a technique known as coaxial electrospinning [6-8]. Conventional electrospinning produces kilometers of continuous polymer fibers with diameters as fine as 10 nm by applying a large electrical potential between a nozzle and a collection plate, and pumping a concentrated polymer solution through the nozzle. The electric field pulls the polymer solution into a fine jet, which is stretched several orders of magnitude by an electrohydrodynamic bending instability [9]. Conventional electrospinning is limited to viscoelastic solutions of very high molecular weight polymers [10].

By using a coaxial nozzle geometry, with one nozzle inside another, pumping an electrospinnable solution through the outer nozzle, and pumping almost any fluid though the inner nozzle, many meters of sub-micrometer fiber can be produced with a core-shell morphology. This technique can be used to produce insulated conducting polymer fibers, by spinning a suitably viscoelastic polymer solution in the outer nozzle and a conducting polymer solution in the inner nozzle [6-8]. To date, conducting polymer core/shell fibers comprised of poly(alkylthiophene)/poly(ethylene oxide) [6], poly(phenylene vinylene)/poly(vinyl pyrrolidone) [7], and polyaniline/poly(vinyl alcohol) [8] have been reported in the literature.

Motivated by these reports the authors have chosen coaxial electrospinning as the technique by which to produce conducting polymer nanowires for neural

recording. The fibers described in the literature do not yet meet the requirements of neural recording, however, as the conducting polymers were not doped and thus were not conductive. This paper reports on early progress towards the production of electrospun core/shell nanofibers containing doped conducting polymers. Polyaniline was chosen as the conducting polymer for this study, due to its excellent solubility in common solvents and good environmental stability. This paper presents a description of the chemical processing and electrospinning protocol used to produce highly conductive core/shell doped polyaniline/poly(ethylene oxide) nanofibers, followed by microscopic verification of the fiber morphology and discussion of the next steps required to produce fibers useful for intravascular neural recording.

2 SYNTHESIS

Emeraldine base polyaniline ($M_W = 3\times10^5$, Aldrich) was doped with (±)-10-camphorsulfonic acid (Aldrich) to form the emeraldine salt form of polyaniline (PANI-CSA). 0.962 g of polyaniline was dissolved along with 1.283 g of camphrosulfonic acid in 500 mL of chloroform, and stirred for 24 hours. The resulting PANI-CSA was then recovered by evaporating the chloroform at room temperature (100% yield).

A 2% (w/w) solution of poly(ethylene oxide) (PEO) ($M_W = 2\times10^6$, Aldrich) in formic acid (98%, Fluka) was used as the shell electrospinning solution. A 9% (w/w) solution of PANI-CSA in formic acid was used as the core electrospinning solution. Both solutions were prepared by mixing the appropriate polymer with formic acid on an orbital shaker for 72 hours; the PANI-CSA solution was further processed by syringe filtration through a 1 μm glass filter (Gelman Glass Acrodisc).

3 FABRICATION

Production of core-shell electrospun fibers required the design and fabrication of an electrospinning apparatus, as well as determination of appropriate spinning parameters.

3.1 Apparatus Design

Design of a coaxial electrospinning apparatus requires special care to maintain concentric alignment between the inner and outer nozzles. Leakage between the fluids must be eliminated, so as to maintain the conductivity of the core and the insulating capacity of the shell. Furthermore, the corrosive nature of the electrospinning fluids demands the use of solvent- and acid- resistant construction materials.

The electrospinner was designed for maximum versatility subject to the above constraints. All components, unless otherwise mentioned, were made from 316 stainless steel. The heart of the apparatus (shown in figure 1) is a pair of modules containing fluid passages and nozzle mounting points, aligned on two hardened carbon steel rods. The nozzles are held with standard compression fittings (Parker Automation) with polyimide ferrules (Small Parts). The nozzles are standard hypodermic tubes: 23 ga. (635 μm OD, 508 μm ID) for the inner nozzle, and 13 ga. (2413 μm OD, 1956 μm ID) for the outer nozzle.

The nozzle assembly was mounted to the top electrode with an adjustable protrusion (9 mm protrusion was used in the experimental configuration. The entire top electrode-nozzle assembly was contained in an acrylic enclosure with an adjustable height above the ground electrode, as shown in figure 2. Acrylic rods were used to support and electrically isolate the top electrode and nozzle assembly.

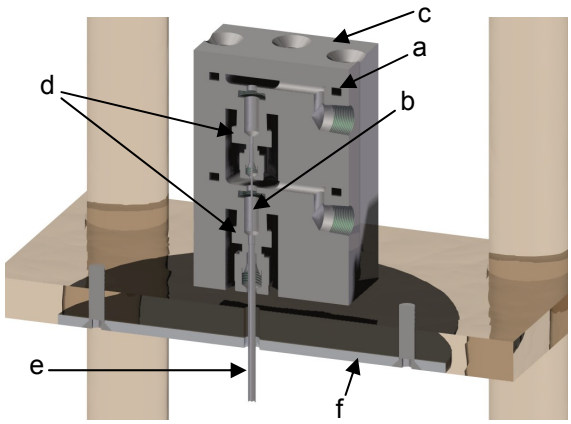

Figure 1: Cross-section of electrospinning apparatus. a: O-ring; b: inner nozzle; c: lid; d: compression fitting; e: outer nozzle; f: top electrode

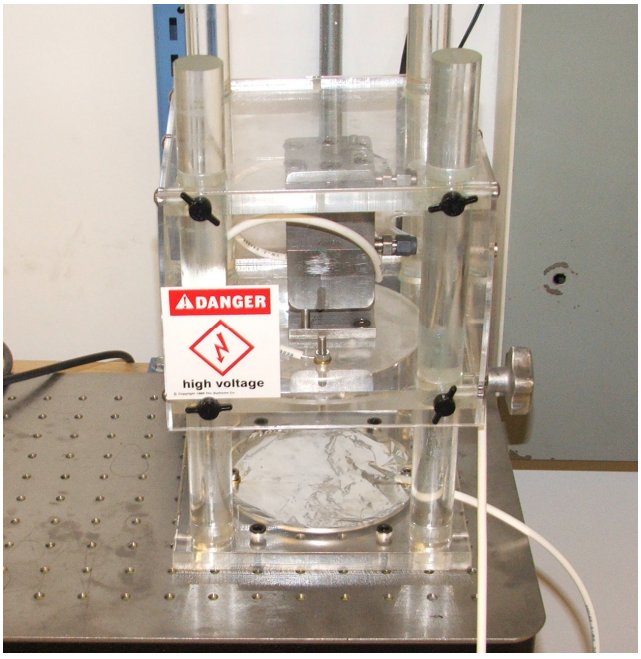

Figure 2: Photograph of complete electrospinning apparatus. The nozzle assembly is located at the center of the image.

Fluid was delivered to the electrospinner using a Harvard Apparatus model 33 dual syringe pump. The electrical potential between the top electrode and ground was maintained using a Spellman CZE1000R 30 kV power supply.

3.2 Fabrication Procedure

Fibers were successfully spun at several flow rates and potentials. All experiments were performed with 260 mm of plate separation. Approximately five minutes were allowed after each flow rate change to allow the system to stabilize before collecting samples. At a core flow rate of 1 mL/hr and shell flow rate of 3 mL/hr, spinning commenced at a potential of 16 kV (61.5 V/mm), and continued at all potentials up to 30 kV (115 V/mm). Samples were collected at 16 kV and 30 kV. Fibers were also produced at a core flow rate of 5 mL/hr and shell flow rate of 15 mL/hr, at a potential of 30 kV.

The fibers appeared as green mats deposited on and around the ground electrode. As spinning continued, the mats became wispier, and climbed the support rods towards the top electrode. When the electrospun fibers connected the top and bottom electrodes, the high voltage power supply suddenly delivered its maximum current.

4 CHARACTERIZATION

Electrospun fibers were collected on glass slides and copper grids. The fibers were examined using a light microscope and a transmission electron microscope. The solution used to produce the core of the fibers was also used to produce a drop-cast polyaniline film; the conductivity of the film was used as an indication of the conductivity of the fiber core.

4.1 Light Microscopy

A high-magnification light microscope image of two core/shell fibers (1 mL/hr core, 3 mL/hr shell, 115 V/mm) is shown in figure 3. While the fiber size approaches the diffraction limit of this microscope, the fiber diameter is clearly under 5 µm, and shows a continuous dark blue/green PANI-CSA fiber. A survey of the collected fibers showed several continuous PANI-CSA fibers over 10 mm in length. The shell is not discernible in these images, as it is similar in scale to the diffraction fringes.

4.2 Transmission Electron Microscopy

A transmission electron micrograph of a core/shell fiber (1 mL/hr core, 3 mL/hr shell, 115 V/mm) is shown in figure 4. The PEO shell has been ablated by the electron beam in the center region, exposing the stable PANI-CSA core. The core diameter of this fiber is 650 nm, with a PEO layer thickness of 650 nm.

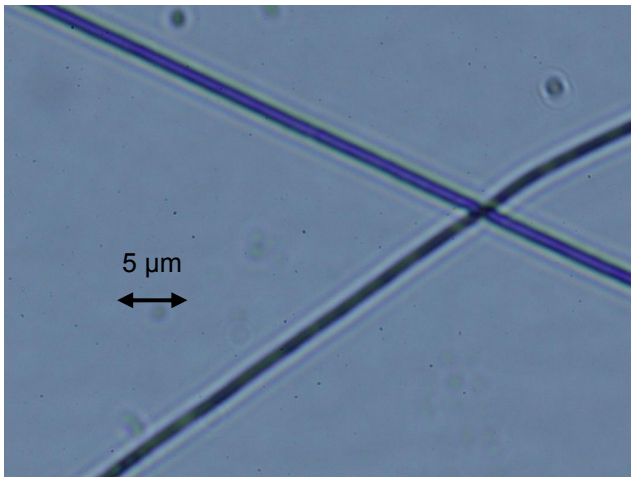

Figure 3: Light micrograph of electrospun fibers. These fibers were produced at a core flow rate of 1 mL/hr, shell flow rate of 3 mL/hr, and potential of 30 kV.

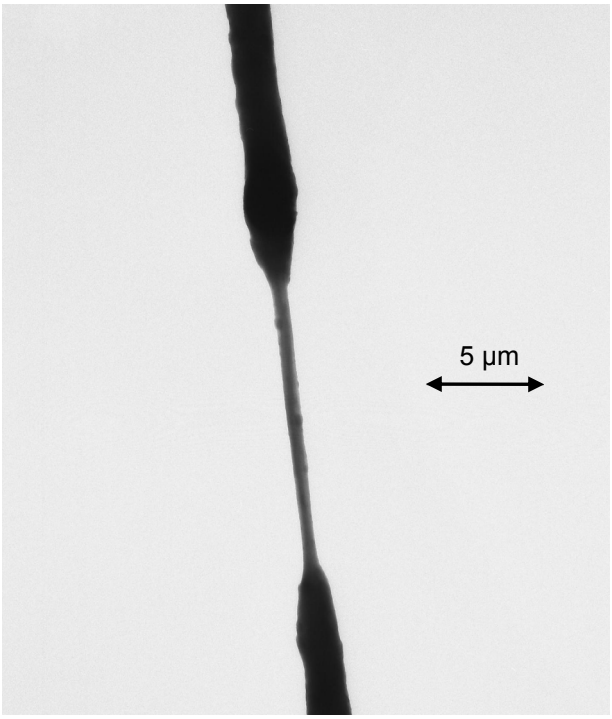

Figure 4: Transmission electron micrograph of an electrospun fiber (1 mL/hr core, 3 mL/hr shell, 115 V/mm). The PEO shell has been ablated by the electron beam in the center of the image.

4.3 Electrical Conductivity

A film of PANI-CSA was drop cast from the core solution onto a glass slide on a hot plate set to 100° C. The resulting somewhat brittle film was cut into a strip 2.5 mm wide and 20 mm long. A 4-point linear probe resistance measurement yielded a film conductivity of 3 S/m. There is a well-known improvement in conductivity for PANI-CSA

upon exposure to *m*-cresol; after placing a drop of *m*-cresol on the film and allowing it to evaporate at 100° C, the film conductivity increased to 1360 S/m [11].

5 DISCUSSION

This work represents merely a preliminary step towards the production of clinically useful nanowire electrodes. The PEO shell dissolves in water within 15 minutes of immersion, making the current generation of wires unsuitable for intravascular recording. However, other electrospinnable polymers, such as medical-grade polyurethane and polycarbonate, can be used to replace the PEO in the shell. Nonetheless, this represents the first published production of electrospun PANI-CSA nanofibers. The conductivity of the PANI-CSA as cast from formic acid solution is poor, but the increase of conductivity upon *m*-cresol exposure implies that better results may be obtained by spinning nanowires from *m*-cresol solution.

The light and electron micrographs clearly illustrate that the electrospun fibers are indeed continuous and exhibit the desired core-shell morphology. The relative core and shell thicknesses differ somewhat from the expected values; assuming PANI-CSA is 50% denser than PEO, the shell should be only 200 nm thick, rather than 650 nm. One possible explanation for this discrepancy is that the electrostatic force on the polyaniline core jet is much higher than that of the much less conductive PEO shell jet, causing the core fluid to have a higher velocity than the shell fluid. More detailed modeling and experimentation is required to explain the shell thickness discrepancy and to better predict the fiber geometry.

6 CONCLUSION

We report the production of micrometer-scale electrospun PANI-CSA core/PEO shell wires. The fibers exhibited continuous core-shell morphology over tens of millimeters.

More work will be required to develop electrospun PANI-CSA fibers sufficiently for use as intravascular neural recording electrodes. Changing the electrospinning solvent to *m*-cresol will greatly increase the core conductivity, reducing the nanowire impedance to manageable levels. Changing the shell polymer to a polymer stable in aqueous biological environments will allow the fibers survive long-term exposure to the bloodstream.

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