Nanofiber Electrodes for intercortical recordings

Objective

To design and develop a nanosized conductive-polymer based electrode

Introduction

Neurons form the fundamental information processing units of human brain. They communicate amongst themselves through an action potential resulting from electro-chemical activities. Essentially, axons of transmitting neurons move closer to the dendrites of receiving neurons for a shot of ion release. This action creates an electric potential of around +40mV that last for around 1 ms. For any information process, large numbers of neurons work and communicate in parallel, and any neuron can be excitatory or inhibitory depending upon the characteristics of synapses it generates [1]. Brain Machine Interfacing (BMI) primarily need to read these signals that are generated from different neurons for any specific activity of the living being. Properties of a suitable electrode for the interface include optimized bio-compatibility, conductivity, diameter, surface-morphology, tensile and bending characteristics. Studies have shown that polymers exhibit more compatibility than their metallic counterparts in several biomedical applications; sutures and substrates are common examples. Hence, the objective of the current phase of research is to develop a nanoscale fiber-based electrode that can be used to record neuron signals.

Background

Electrospinning

Fibers that are of order 10^{-9}m are called nanofibers. Several methods have been demonstrated to develop a one dimensional structure in the form of fibers, ribbons, rods, etc. Electrospinning is one of the widely popular techniques to form nanofibers using various polymers. Two variants are solution and melt electrospinning. Electrospinning operates on the principle of applying uniaxial stretch to a viscous solution (a polymer solution or melt) through electrostatic force so that a continuous reduction of diameter happens, resulting in a nanoscale fiber [2].

In the process of electrospinning, a high electric field is generated between the polymer solution pumped (at the rate of as low as 1 mlh^{-1} through a syringe capillary and a collector plate. The polymer drop gets charged up and as the voltage increases (to the order of around 20 to 30 kV), the surface tension of the polymer drop is overcome by the electrostatic forces resulting in an attenuation process of the solution. Since the polymer throughput is continuous and the continuous existence of electrostatic forces result in a continuous spinning of fibers [3]. Figure-1 shows a schematic representation of an electrospinning setup.

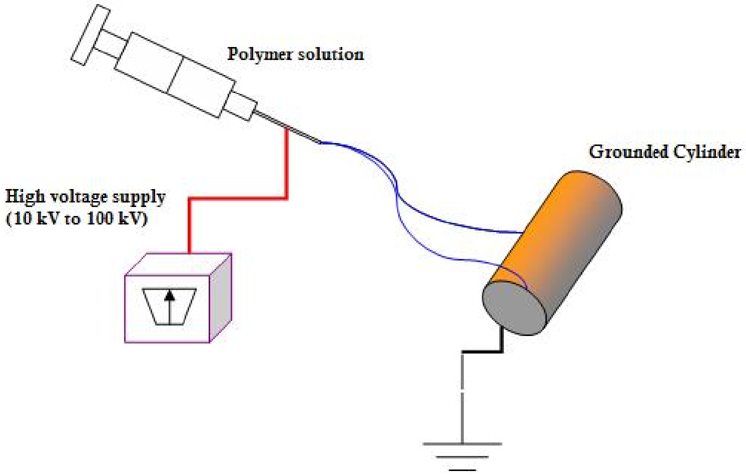

Figure – 1 Schematic of Electrospinning

Prime objective in electrospinning is to generate fibers whose diameters are consistent and reproducible. Several researchers have studied the parameters that influence fiber diameter and many parameters were identified; strength of the electric field, polymer viscosity, distance between the Taylor cone (conical shaped polymer drop under the influence of electrostatic force in the needle tip) and collector plate, polymer concentration and charge carrying capacity of the polymer solution are those principle influencing parameters [5]. Fiber diameter can be controlled by controlling the throughput rate, conductivity of the solution and needle diameter.

Melt electrospinning operates on the same principle except few changes in the control parameters. Dalton et al. demonstrated the method of extrusing melt electrospun fibers out of poly-(ethylene glycol-block-ε-caprolactone) [6]. Melt electrospinning is advantageous in fiber realization but the technology is yet to be established for a consistent production.

Modifications in Electrospinning

Though the set up of an electrospinning unit is relatively simple, controlling the process needs considerable effort. Mechanics of electrospinning shows that the fiber exhibits a rigorous whipping and high bending instability under the influence of electric field. This is, in fact, a cause of additional thinning down of the fiber [7]. Schematic representation of fiber whipping is shown in Figure-2. This instability in conjunction with a flat collector causes the fiber to settle down as a random oriented web as seen in Figure-3. Several modifications on the electrospinning process were attempted to control the orientation of the fiber at the collector and to spin a continuous strand of nanofiber yarn.

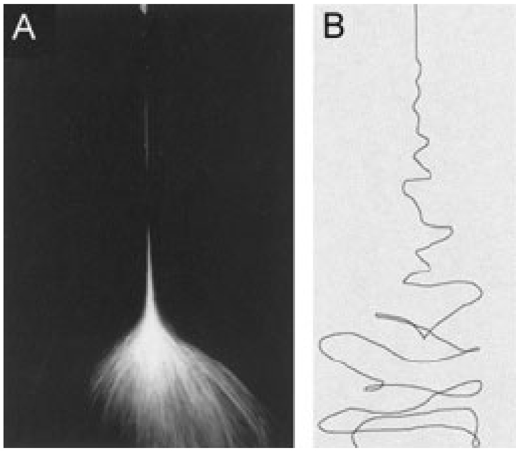

Figure – 2 Whipping phenomenon (a) at 1/250 s and (b) 1/18 ns [2]

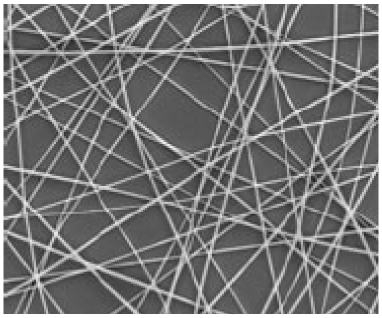

Figure – 3 Nanofibers settled as a web

Two major modifications include the use of a rotating drum collector and to use a split collector. Figures 4(a) and 4(b) depict both the methods. In the method involving a split electrode, Xia and Li demonstrated that when two conductive strips are placed apart with an insulating gap of few centimeters between them and grounded can produce well aligned nanofibers [7, 14]. Introduction of an insulating gap between the grounded collector plates alter the way the electrostatic field affecting the polymer solution. Also, at the time of settlement, the residual charges on the fiber increase the alignment to further considerable degree. The other method involves a high speed rotary drum to act as the collector, resulting in the collection of a continuous strand of fiber.

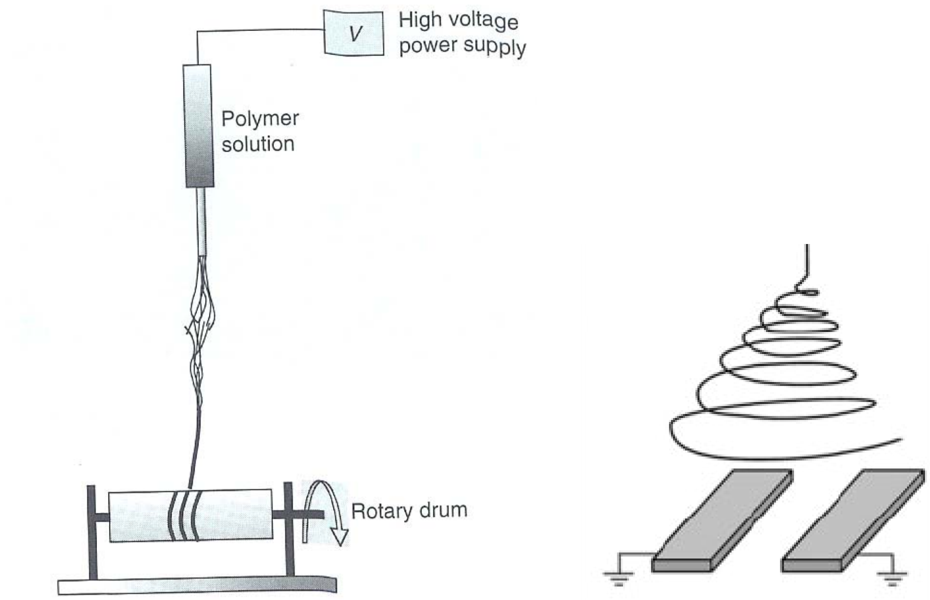

Figure – 4 (a) Rotary drum collector (b) Split collector

The above processes explain about methods to obtain a continuous strand of fiber and studies took place to obtain a continuous strand of yarn made of nanofibers. Teo et al. reported a technique that uses a water vortex to collect the electrospun fibers and assemble them to form a continuous yarn. This is explained in Figure-5 [8].

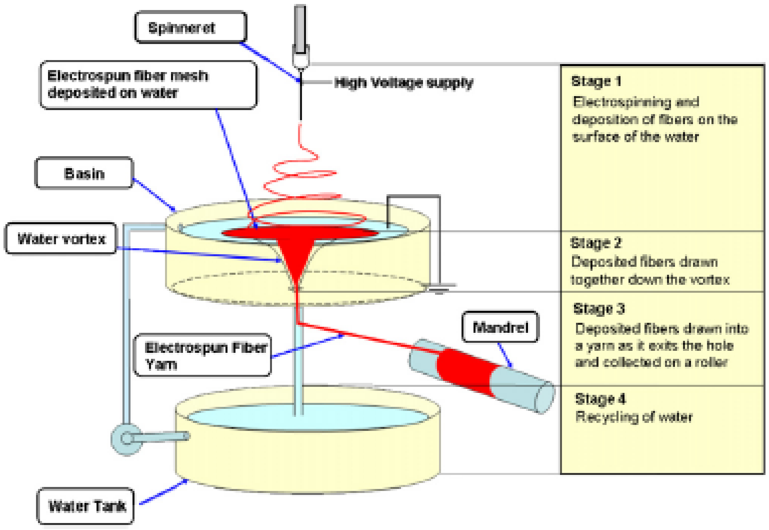

Figure – 5 A collection mechanism for continuous Nanofiber yarn using water vortex

Conductive Polymers

Nanoscale fiber based electrode includes two key components, viz., the fiber being at nanoscale and having the properties of an electrode. To be an electrode, the fiber should possess the property of adequate conductivity. Conductivity can be incorporated into a fiber by choosing a polymer that is conductive or by doping conductive additives. Polymers of the Polyacetylene, Poly (p-Phenylene), Polypyrrole and Polyaniline families possess conductive characteristics ranging from 10^7 to 10^1 S cm^{-1} [9, 16]. For experimental purposes, these polymers can be dissolved in a suitable solvent so that the solution could be fed to the electrospinning unit. Such a fiber will possess the property of conductivity along being a nanofiber. Ruddy et al. studied the possibility of developing and using Polypyrrole based electrode for neural recordings. Figure – 6 shows the recordings of such an electrode [10].

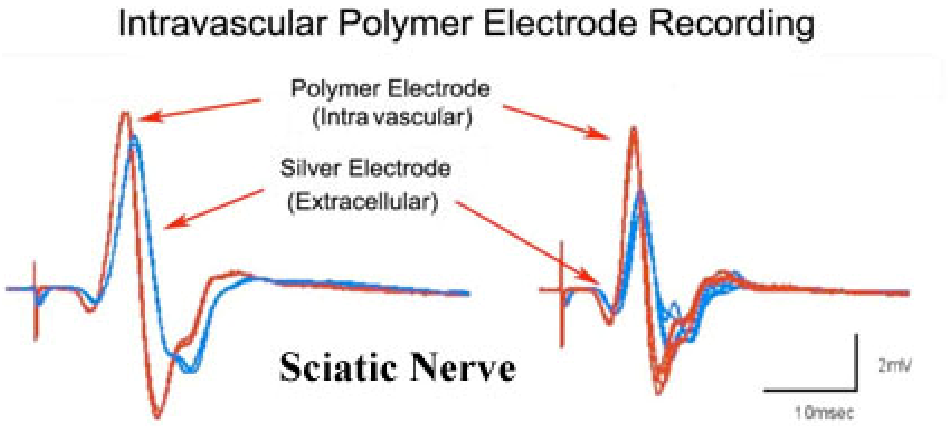

Figure – 6 Illustration for polymer electrode recordings

In the method of doping, carbon nanotubes can be added to make the polymer conductive [11, 15]. Carbon nanotubes (Single walled and Multiwalled) are chemical structures that are purely (up to 99%) carbon and that makes them conductive. Though they are conductive, production mechanism for a long length nanotubes is still under research. But, a suitable quantity of these nanotubes can be doped under controlled distribution in the polymer at the time of extrusion to make it conductive. Xue et al. studied the conductivity properties of fibers coated with PVA-CNT (PolyVinyl Alcohol – Carbon Nano Tube) coagulant [12]. Laxminarayana and Jalili showed that adding a 0.05% of CNT dramatically increased the sensing capability of piezoelectric polymer by thirty five times [13].

Carbon Fibers

Several methods were reported to develop carbon fibers. Pyrolysis and Vapor Phase Growth are widely adopted procedures for carbon fiber generation. Pyrolysis technique involves the oxidation followed by pyrolitic exposure of the precursor in inert atmosphere. The most general precursor is PAN (PolyAcryloNitrile). The process essentially eliminates all the other groups present in the polymer leaving the carbon chain alone; this makes it conductive.

Approach

Option – A

Develop infrastructure for electrospinning

Purchase Carbon Nano Tubes (CNTs)

Purchase conductive polymer chips and solvents

Cost analysis

Component	Vendor	Cost
High voltage supply	Glassman	$5082.80
	Gamma	$2310.50
Syringe pumps	Harvard Apparatus	$4640.00
	KD Scientific	
	New Era	$1075.00
CNTs	www.mknano.com	
	www.nanomaterialstore.com	$100/5gm
	www.nano-lab.com	$650/5gm

Advantages

Indigenous set up for fiber production

Experiments can be conducted for optimization of fiber properties, nanotube doping, etc.

Option – B

Carbon fiber production

Since the Department of Chemistry replied that they are neither having the expertise or infrastructure for carbon fiber production, we are left only with Option-A

Time line

Options A: 5 to 6 months

Outcome

Conductive fibers that can be used for neural recordings

References

[1] Coolen A.C.C., R Kohn and P Sollich, Theory of Neural Information Processing Systems, Oxford University Press, Oxford, 2005

[2] Li, Dan and Y.Xia, Electrospinning of NanoFibers: Reinventing the Wheel, Advanced Materials, Vol 16, No.14, 2004, 1151 – 1170

[3] Mitchell, S.B. and J.E. Sanders, A unique device for controlled Electrospinning, Wiley Periodicals, 4, 2006

[4] Rutledge, C. Gregory and Sergey V. Fridrikh, Formation of fibers by Electrospinning, Advanced Drug Delivery Review, In print, 2007

[5] Ko, K. Frank, Nanomaterials Handbook (Ed. Yuri Gogotsi), CRC Press, FL, 2006

[6] Dalton, D Paul, J L Calvet, Ahmed Mourran, Doris Klee and Martin Moller, Melt Electrospinning of Poly-(ethylene glycol-block-ε-caprolactone), Biotechnology Journal, Vol 1, 2006, 998-1006

[7] Li, Dan and Y.Xia, Nano Letters, Vol 3, 2003, 1167

[8] Teo, Wee-Eong, Renuga Gopal, Ramakrishnan Ramaseshan, Kazutoshi Fujihara, Seeram Ramakrishna, A dynamic liquid support system for continuous electrospun yarn fabrication, Polymer Vol 48, 2007, 3400-3405.

[9] Li, Mengyan, Yi Guo, Yen Wei, Alan Macdiarmid, Peter Lelkes, Electrospinning Polyaniline-contained gelatin nanofibers for tissue engineering applications, Biomaterials, Vol 27, 2006, 2705 – 2715

[10] Ruddy, P Bryan, Conductive Polymer wires for Intravascular neural recordings, Masters Thesis

[11] Fischer, E. John, Nanomaterials Handbook (Ed. Yuri Gogotsi), CRC Press, FL, 2006

[12] Xue, P, K.H. Park, X.M. Tao, W. Chen, X.Y. Cheng, Electrically conductive yarns based on PVA/carbon nanotubes, Composite structures, vol 78, 2007, 271-277

[13] Laxminarayana, Karthik and Nader Jalili, Functional Nanotube-based Textiles: Pathway to Next Generation Fabrics with Enhanced Sensing Capabilities, Textile Research Journal, Vol 75 (9), 2005, 670-680.

[14] Xin, Yi, Zonghao Huang, Jinfeng Chen, Cheng Wang, Yanbin Tong, Sidong Liu, Fabrication of well aligned PPV/PVP nanofibers by electrospinning, Materials Letter, 2007

[15] Macossay, Javier, Juan H. Leal1, Anxiu Kuang and Robert E. Jones, Electrospun fibers from Poly (methyl methacrylate) / Vapor grown carbon nanofibers, Polym. Adv. Technology, Vol 17, 2006, 391-394

[16] Miaudet, P, C Bartholome, A Derre, M Maugey, G Sigaud, C Zakri, P Poulin, Thermo-electrical properties of PVA-nanotube composite fiber, Polymer, Vol 48, 2007, 4068-4074