Review of Polymer Solutions for Near-Field Electrospinning with Spatial Control

Antonio Osamu Katagiri Tanaka, Héctor Alán Aguirre Soto

Abstract

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1. Introduction

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2. NFES

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Table 1: Electrospun Polymer Solutions - Solution and Process Parameters

Polymer(s)	Solvent(s)	NFES Variant	Process Parameters and Fiber Characterization	Ref.
Poly(ethylene oxide) (PEO)	Deionized water	Low-Voltage NFES	**Solution Concentration:** 1, 2, and 3 $wt\%$ PEO **Nozzle:** 27 gauge type 304; stainless steel needle **Solution deposition rate:** lower than $1\mu L/h$ **Nozzle-to-substrate distance:** $1mm$ **Substrate composition:** Pyrolyzed SU-8 carbon and Si **Applied voltage:** polymer jet initiated at 400-600 V and dispensed at 200-400 V **x-y stage velocity:** 10-40mm/s **Fiber Diameter:** 50-425nm **Distance between adjacent fibers:** *Not determined*	[1]
Poly[2-methoxy-5-(2-ethylhexyloxy)-1,4-phenylenevinylene] (MEH-PPV) with Poly(ethylene oxide) (PEO)	acetonitrile toluene mixture (65/35); acetic acid toluene (17/83); pure toluene	Typical NFES process	**Solution Concentration:** $10mg$ of MEH-PPV in $2mL$ of toluene; $500mL$ of MEH-PPV solution with $250mg$ of PEO in $3.5mL$ of acetonitrile; $500mL$ of MEH-PPV solution with $250mg$ of PEO in $3mL$ of acetic acid / toluene (17 / 83). The resulting MEH-PPV/PEO concentration is 1:100 **Nozzle:** mm-diameter tip Tungsten spinneret in a 26 gauge needle **Solution deposition rate:** $50\mu L/h$ **Nozzle-to-substrate distance:** $500\mu m$ **Substrate composition:** SiO2/Si (oxide thickness = 800 nm) **Applied voltage:** around $1.3kV$ **x-y stage velocity:** $50cm/s$ **Fiber Diameter:** $100nm$ **Distance between adjacent fibers:** around $100\mu m$	[2]

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Table 1 continued

Poly(ethylene oxide) (PEO)	Water	Scanning Tip Electrospinning and NFES	**Solution Concentration:** $7wt\%$ PEO **Nozzle:** Needle outer diameter of $200\mu m$ and inner diameter of $100\mu m$ **Solution deposition rate:** $0.1\mu L/h$ **Nozzle-to-substrate distance:** $500\mu m$ **Substrate composition:***Not determined* **Applied voltage:** polymer jet initiated at 1.5 kV and dispensed at $600V$ **x-y stage velocity:** $120mm/s$ **Fiber Diameter:** $709\pm131nm$; 49-$74nm$ when applied voltage is $800V$ **Distance between adjacent fibers:** *Not determined* **Notes:** $108m$ yield in $15min$ with a fiber diameter of $709\pm131nm$	[3]
Poly(vinylidine fluorid) (PVDF)	N,N Dimethylformamide (DMF)	Helix Electrohydrodynamic Printing (HE-printing)	**Solution Concentration:** $1.8g$ PVDF in $4.1g$ of DMF and $4.1g$ of acetone. The resulting concentration is 18% PVDF. **Nozzle:** Needle outer diameter of $510\mu m$ and inner diameter of $260\mu m$ **Solution deposition rate:** $400nL/min$ **Nozzle-to-substrate distance:** 10-$50mm$ **Substrate composition:** Poly(dimethylsiloxane) (PDMS) on Ecoflex **Applied voltage:** 1.5–$3kV$ **x-y stage velocity:** 0-$400mm/min$ **Fiber Diameter:** about 1.5-$3\mu m$ **Distance between adjacent fibers:** *Not determined*	[4]

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Table 1 continued

Polyhedral Oligomeric Silsesquioxane-Poly(Carbonate-Urea)Urethane (POSS-PCU) and Polyhedral Oligomeric Silsesquioxane Poly(Caprolactone-Poly(Carbonate-Urea)Urethane) (POSS-PCL-PCU)	Dimethyl acetamide (DMAC) and 1-Butanol	Electrohydrodynamic 3D Print-patterning or Electrohydrodynamic Jetting	**Solution Concentration:** POSS-PCU and POSS-PCL-PCU used in 20%w/w concentration in DMAC **Nozzle:** needle of 750 μm in diameter **Solution deposition rate:** less than 1$\mu L/min$ **Nozzle-to-substrate distance:** about between 500μm to 2mm **Substrate composition:** *Not determined* **Applied voltage:** 8.0-10.0kV **x-y stage velocity:** 10mm/s **Fiber Diameter:** 5-50μm **Distance between adjacent fibers:** 250μm	[5]
Poly(ethylene oxide) (PEO)	Distilled water	Electrohydrodynamic Writing or Mechano-electrospinning (MES)	**Solution Concentration:** 6wt% PEO **Nozzle:***Not determined* **Solution deposition rate:** 1200nL/min **Nozzle-to-substrate distance:** 7.5mm **Substrate composition:** *Not determined* **Applied voltage:** polymer jet initiated at 2 kV and dispensed at 0.8-1kV **x-y stage velocity:** around 400mm/s **Fiber Diameter:** 200-350nm **Distance between adjacent fibers:** 5μm	[6]

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Table 1 continued

Poly(ethylene oxide) (PEO)	Deionized water and the ethanol with a volume ratio of 3:1	Airflow-assisted Electrohydrodynamic Direct-writing (EDW)	**Solution Concentration:** $8wt\%$ PEO **Nozzle:** Outer airflow passage diameter: $1mm$ Airflow gas pump pressure: $25kPa$ Inner liquid passage diameter: $0.21mm$ **Solution deposition rate:** $30\mu L/h$ **Nozzle-to-substrate distance:** $2mm$ **Substrate composition:** Silicon **Applied voltage:** about $2kV$ **x-y stage velocity:** 1-$20mm/s$ **Fiber Diameter:** $3.73 \pm 1.37\mu m$ **Distance between adjacent fibers:** $5.13 \pm 6.67\mu m$	[7]
Poly(Vinylidene Fluoride) (PVDF)	Acetone and Dimethyl Sulfoxide (DMSO)	3D Electrospinning	**Solution Concentration:** $17wt\%$ PVDF; $1.7g$ of PVDF, $5g$ of acetone, $0.5g$ of Capstone FS-66, $5g$ of DMSO **Nozzle:** Needle inner diameter of $100\mu m$ **Solution deposition rate:** $14\ nL/min$ **Nozzle-to-substrate distance:** $750\mu m$ **Substrate composition:** A4 size commercial printing paper (Double A) **Applied voltage:** $1.9kV$ **x-y stage velocity:** $10mm/s$ **Fiber Diameter:***Not determined* **Distance between adjacent fibers:** *Not determined*	[8]

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Table 1 continued

Poly(9-Vinyl Carbazole) (PVK)	Styrene	Typical NFES process	**Solution Concentration:** 3.96wt% PVK in styrene **Nozzle:** Needle inner diameter of 100μm **Solution deposition rate:** 500nL/min **Nozzle-to-substrate distance:** around 2.5mm **Substrate composition:** Si/SiO2 **Applied voltage:** 3-4kV x-y stage velocity: 13.3cm/s **Fiber Diameter:** 289.26 $\pm$ 35.37nm **Distance between adjacent fibers:** 50μm **Notes:** 15m yield in 2min	[9]
Polystyrene (PS)	1,2,4-Trichloro benzene	Electrohydrodynamic (EHD) jet printing	**Solution Concentration:** 1 to 5wt% PS **Nozzle:** Glass nozzle inner diameter of 2μm and outer diameter of 2.66μm **Solution deposition rate:** Si **Nozzle-to-substrate distance: 20, 30, 40**μm **Substrate composition:** **Applied voltage:** 500 to 400V in 25V increments **x-y stage velocity:** 0.01-10mm/s **Fiber Diameter:** about 60-170μm **Distance between adjacent fibers:** *Not determined*	[10]
Poly(ethylene oxide) (PEO)	*Not determined*	Typical NFES process	**Solution Concentration:** 3wt% PEO **Nozzle:***Not determined* **Solution deposition rate:** *Not determined* **Nozzle-to-substrate distance:** 500μm **Substrate composition:** Si **Applied voltage:** 1000V **x-y stage velocity:** 20cm/s **Fiber Diameter:** 300nm **Distance between adjacent fibers:** 25μm	[11]

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Table 1 continued

Poly(ethylene oxide) (PEO)	Distilled water	Multinozzle NFES	**Solution Concentration:** $5wt\%$ **Nozzle:** four-nozzle and six-nozzle array with needle spacing changes from $1.5mm$ to $3.5mm$ **Solution deposition rate:** 1-3$\mu L/min$ **Nozzle-to-substrate distance:** $2mm$ **Substrate composition:***Not determined* **Applied voltage:** 1.7-2.7kV **x-y stage velocity:** *Not determined* **Fiber Diameter:** $5.47\mu m$ **Distance between adjacent fibers:** 3-5 mm	[12]
Poly(ethylene oxide) (PEO)	Distilled water	Multinozzle NFES	**Solution Concentration:**$5wt\%$ **Nozzle:** Dual-28G-needle array with needle inner diameter of $0.18mm$ and outer diameter of $0.36mm$; with needle spacing changes from $2.0mm$ to $3.0mm$ **Solution deposition rate:** $0.2\mu L/min$ **Nozzle-to-substrate distance:** 3.0-4.0mm **Substrate composition:** *Not determined* **Applied voltage:** 2.0-3.0kV **x-y stage velocity:** $20mm/s$ **Fiber Diameter:** *Not determined* **Distance between adjacent fibers:** 218-326μm	[13]

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Table 1 continued

Poly(ethylene oxide) (PEO)	Distilled water	Multinozzle NFES	**Solution Concentration:**5 $wt\%$ **Nozzle:** Dual-28G-needle array with needle inner diameter of 180μm and outer diameter of 360μm; with needle spacing changes of 2.0mm **Solution deposition rate:** 0.2$\mu L/min$ **Nozzle-to-substrate distance:** 4.0mm **Substrate composition:** chromium-plated glass **Applied voltage:** 2.5kV **x-y stage velocity:** 20mm/s **Fiber Diameter:** *Not determined* **Distance between adjacent fibers:** 2.3002-2.7224mm	[14]
Poly(ethylene oxide) (PEO)	*Not determined*	Typical NFES process	**Solution Concentration:** 2$wt\%$ **Nozzle:** G30 needle with inner diameter of 0.15mm **Solution deposition rate:***Not determined* **Nozzle-to-substrate distance:** 1-3mm **Substrate composition:** Silicon **Applied voltage:** 1250V **x-y stage velocity:** *Not determined* **Fiber Diameter:** *Not determined* **Distance between adjacent fibers:** 20μm	[15]

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Table 1 continued

Gelatin (porcine skin)	Acetic Acid and Ethyl Acetate	Typical process	NFES	**Solution Concentration:** $11wt\%$ gelatin, $30wt\%$ water, $35.4wt\%$ acetic acid, $23.6wt\%$ ethyl acetate **Nozzle:** 19G needle tip with outer diameter of $1.08mm$ **Solution deposition rate:***Not determined* **Nozzle-to-substrate distance:** $1.25mm$ **Substrate composition:** Poly(Dimethylsiloxane) (PDMS) films **Applied voltage:** $1000V$ **x-y stage velocity:** *Not determined* **Fiber Diameter:** around 2-3μm **Distance between adjacent fibers:** $40\mu m$	[16]
Poly(ethylene oxide) (PEO)	Water/Ethanol (v/v = 60/40)	Typical process	NFES	**Solution Concentration:** PEO concentrations of 16% adn 18% **Nozzle:** $40\mu m$ **Solution deposition rate:** **Nozzle-to-substrate distance:** $1mm$ **Substrate composition:** Planar silicon **Applied voltage:** $1.7kV$ **x-y stage velocity:** $0.36m/s$ **Fiber Diameter:** $5.15\mu m$ **Distance between adjacent fibers:** *Not determined*	[17]

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Table 1 continued

Poly(ethylene oxide) (PEO)	Water/Ethanol (v/v = 3/1)	Electrohydrodynamic Direct-Write (EDW)	**Solution Concentration:** $14wt\%$ PEO **Nozzle:** Stainless needle with inner diameter of $210\mu m$ and outer diameter of $400\mu m$ **Solution deposition rate:** $50\mu L/h$ **Nozzle-to-substrate distance:** $2mm$ **Substrate composition:** Poly(ethylene terephthalate) (PET) **Applied voltage:** $3kV$ **x-y stage velocity:** $700mm/s$ **Fiber Diameter:** 15-$35\mu m$ **Distance between adjacent fibers:** $70\mu m$	[18]

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Solution Concentration:
Nozzle:
Solution deposition rate:
Nozzle-to-substrate distance:
Substrate composition:
Applied voltage:
x-y stage velocity:
Fiber Diameter:
Distance between adjacent fibers:

3. Polymer Solution and Process Parameters

4. Applications

5. Fiber Characterization

6. Conclusion

References

[1] G. S. Bisht, G. Canton, A. Mirsepassi, L. Kulinsky, S. Oh, D. Dunn-Rankin, M. J. Madou, Controlled Continuous Patterning of Polymeric Nanofibers on Three-Dimensional Substrates Using Low-Voltage Near-Field Electrospinning, Nano Letters 11 (4) (2011) 1831–1837. doi:10.1021/nl2006164.

[2] D. D. Camillo, V. Fasano, F. Ruggieri, S. Santucci, L. Lozzi, A. Camposeo, D. Pisignano, Near-field electrospinning of conjugated polymer light-emitting nanofibers, Nanoscale 5 (2013) 11637–11642. doi:10.1039/C3NR03094F.

[3] C. Chang, K. Limkrailassiri, L. Lin, Continuous near-field electrospinning for large area deposition of orderly nanofiber patterns, Appl Phys Lett (2008) 3doi:10.1063/1.2975834.

[4] Y. Duan, Y. Ding, Z. Xu, Y. Huang, Z. Yin, Helix Electrohydrodynamic Printing of Highly Aligned Serpentine Micro/Nanofibers., Polymers 9 (9) (sep 2017). doi:10.3390/polym9090434.

[5] A. Gupta, A. M. Seifalian, Z. Ahmad, M. J. Edirisinghe, M. C. Winslet, Novel Electrohydrodynamic Printing of Nanocomposite Biopolymer Scaffolds, Journal of BIOACTIVE AND COMPATIBLE POLYMERS 22 (2007). doi:10.1177/0883911507078268.

[6] Y. Huang, Y. Duan, Y. Ding, N. Bu, Y. Pan, N. Lu, Z. Yin, Versatile, kinetically controlled, high precision electrohydrodynamic writing of micro/nanofibers, Scientific Reports 4 (1) (2015) 5949. doi:10.1038/srep05949.

[7] J. Jiang, X. Wang, W. Li, J. Liu, Y. Liu, G. Zheng, J. Jiang, X. Wang, W. Li, J. Liu, Y. Liu, G. Zheng, Electrohydrodynamic Direct-Writing Micropatterns with Assisted Airflow, Micromachines 9 (9) (2018) 456. doi:10.3390/mi9090456.

[8] J. Kim, B. Maeng, J. Park, Characterization of 3D electrospinning on inkjet printed conductive pattern on paper, Micro and Nano Systems Letters 6 (1) (2018) 12. doi:10.1186/s40486-018-0074-1.

[9] S.-Y. Min, T.-S. Kim, B. J. Kim, H. Cho, Y.-Y. Noh, H. Yang, J. H. Cho, T.-W. Lee, Large-scale organic nanowire lithography and electronics, Nature Communications 4 (1) (2013) 1773. doi:10.1038/ncomms2785.

[10] C. Song, J. A. Rogers, J.-M. Kim, H. Ahn, Patterned polydiacetylene-embedded polystyrene nanofibers based on electrohydrodynamic jet printing, Macromolecular Research 23 (1) (2015) 118–123. doi:10.1007/s13233-015-3024-2.

[11] D. Sun, C. Chang, S. Li, L. Lin, Near-Field Electrospinning (2006). doi:10.1021/nl0602701.

[12] H. Wang, S. Huang, F. Liang, P. Wu, M. Li, S. Lin, X. Chen, Research on Multinozzle Near-Field Electrospinning Patterned Deposition, Journal of Nanomaterials 2015 (2015) 1–8. doi:10.1155/2015/529138.

[13] Z. Wang, X. Chen, J. Zeng, F. Liang, P. Wu, H. Wang, Controllable deposition distance of aligned pattern via dual-nozzle near-field electrospinning, AIP Advances 7 (3) (2017) 035310. doi:10.1063/1.4974936.

[14] Z. Wang, X. Chen, J. Zhang, Y.-J. Lin, K. Li, J. Zeng, P. Wu, Y. He, Y. Li, H. Wang, Fabrication and evaluation of controllable deposition distance for aligned pattern by multi-nozzle near-field electrospinning, AIP Advances 8 (7) (2018) 075111. doi:10.1063/1.5032082.

[15] J. Xu, M. Abecassis, Z. Zhang, P. Guo, J. Huang, K. Ehmann, J. Cao, Accuracy Improvement of Nano-fiber Deposition by Near-Field Electrospinning, International Workshop on Microfactories IWMF2014 (9th) (2014).

[16] N. Xue, X. Li, C. Bertulli, Z. Li, A. Patharagulpong, A. Sadok, Y. Y. S. Huang, Rapid Patterning of 1-D Collagenous Topography as an ECM Protein Fibril Platform for Image Cytometry, PLoS ONE 9 (4) (2014) e93590. doi:10.1371/journal.pone.0093590.

[17] G. Zheng, W. Li, X. Wang, D. Wu, D. Sun, L. Lin, Precision deposition of a nanofibre by near-field electrospinning, Journal of Physics D: Applied Physics 43 (41) (2010) 415501. doi:10.1088/0022-3727/43/41/415501.

[18] J.-Y. Zheng, H.-Y. Liu, X. Wang, Y. Zhao, W.-W. Huang, G.-F. Zheng, D.-H. Sun, Electrohydrodynamic Direct-Write Orderly Micro/Nanofibrous Structure on Flexible Insulating Substrate, Journal of Nanomaterials 2014 (2014) 1–7. doi:10.1155/2014/708186.