Electrospinning alginate-based nanofibers: From blends to crosslinked low molecular weight alginate-only systems

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ARTICLE INFO

Article history:
Received 20 October 2010
Received in revised form 12 January 2011
Accepted 1 February 2011
Available online 26 February 2011

Abstract

We report here preparation of nanofibers containing alginate using two different molecular weights (MWs): 37 kDa and 196 kDa. Low MW alginates are attractive for in vivo tissue scaffolds where degradation and clearance from the body are desirable, whereas higher MW alginates are amenable for topical use as wound coverage because of their better mechanical properties. We use polyethylene oxide (PEO) as a carrier material to aid in electrospinning, and relate the solution properties, including entanglement concentration, relaxation time, conductivity, and surface tension, to their ability to be electrospun. In addition, we examine an FDA-approved, nonionic surfactant as a route to enhancing the alginate–PEO ratio (>80:20), and less toxic alternative to Triton X-100 surfactant. Finally, alginate-only nanofibers that are also water-insoluble are obtained by crosslinking the electrospun fibers with calcium and subsequently removing the PEO and surfactants by soaking the nanofibers in water.

1. Introduction

Electrospun nanofibers are promising materials for biomedical applications, such as drug delivery, wound dressings, and tissue scaffolds. Nanofibrous mats have high surface areas and tunable morphologies, which can influence cell proliferation and behavior (Chew, Wen, Dzenis, & Leong, 2006). Additionally, the abundance of polymers and polymer blends that can be electrospun provide researchers many options for tailoring the mechanical and biological properties for their desired application. Several synthetic polymers, such as poly(ε-caprolactone), polylactide, and polyglycolide, have been electrospun for use as tissue scaffolds (Liang, Hsiao, & Chu, 2007). However, one drawback of fibers made from these polymers is the use of cytotoxic organic solvents during fabrication, which would require thorough washing and/or solvent evaporation treatments on the mats prior to use with cells. Natural, water-soluble polymers are an attractive alternative, as they are readily soluble in aqueous media because of their hydrophilic nature, and have low immunogenicity (Lee, Jeong, Kang, Lee, & Park, 2009).

Sodium alginate is a water-soluble, biocompatible polysaccharide that is used in drug delivery (Augst, Kong, & Mooney, 2006), wound dressings (Hashimoto, Suzuki, Tanihara, Kakimaru, & Suzuki, 2004), and tissue engineering (Alsberg, Anderson, Albeiruti, Rowley, & Mooney, 2002). Ionically crosslinked alginate gels are biodegradable, a property which can be tuned by changing the composition and MW of the polymer chains. Alginate is composed of blocks of β-d-mannuronic acid (M) and α-L-guluronic acid (G). Only the G blocks in alginate can be crosslinked with divalent cations (e.g., Ca2+) (Smidsrod & Skjakbraek, 1990). When used in vivo, ionically crosslinked alginate degrades when the calcium ions are exchanged with other ions in the body, such as Na+ (Shoichet, Li, White, & Winn, 1996). As such, the variation in the M to G ratio, based on the alginate source, can provide one avenue to control the degradation. However, compared to the composition of alginate, modification of the polymer MW is a more exploitable route to controlling in vivo degradation. Alginate chains can be shortened to lower MWs by exposure to gamma-irradiation. Low radiation doses (<8 Mrad) create chain scissions of the glycosidic bonds between the M and the G blocks, with minimal effects on the block content and length (Alsberg et al., 2003). When used as tissue scaffolds, ionically crosslinked low MW alginate (<50 kDa) degrades more quickly than higher MW. Shorter degradation times may be more optimal for some tissue regeneration applications that want to match tissue formation with polymer degradation rate (Alsberg et al., 2003). One
significant advantage of low MW polymer chains is that polymers with MW less than 50 kDa can be passed by the kidneys when used in vivo (Al-Shamkhani & Duncan, 1995). Thus, nanofibers composed of low MW alginate are attractive for in vivo biomedical applications where degradation and clearance from the body are desirable.

The use of low MW polymers has important implications when developing material fabrication methods. In particular, electrospinning is influenced by polymer chain length, among many other variables (Shenoy, Bates, Frisch, & Wnek, 2005). Polymer chain entanglements in solution are essential to the formation of a continuous jet, leading to uniform, nonwoven fibers. Therefore, polymer solutions with inadequate entanglements, such as those in dilute concentrations or with low viscoelasticity or MW, may form only beaded fibers or droplets (McKee, Wilkes, Colby, & Long, 2004; Yu, Fridrich, & Rutledge, 2006). These added challenges have likely prevented the widespread usage of low MW polymers in electrospinning. In addition, ionic conductivity and surface tension have significant effects on the electrospinning process (Fong, Chun, & Reneker, 1999; McKee et al., 2004; Yu et al., 2006). The ability of a polymer solution to form uniform nanofibers can be linked directly to its solution properties.

Nanofibrous mats of alginate can be fabricated by electrospinning. Even though attempts to electrospin pure alginate in water have been unsuccessful, alginate solutions have been blended with a second material (i.e. glycerol, polyvinyl alcohol (PVA), polyethylene oxide (PEO)) to successfully form nanofibers (Bhattarai, Li, Edmondson, & Zhang, 2006; Jeong et al., 2010; Lu, Zhu, Guo, Hu, & Yu, 2006; Nie et al., 2008, 2009; Safi, Morshed, Ravandi, & Ghiaci, 2007). The second co-solvent/polymer is believed to mitigate the charge repulsions between the alginate chains, improve chain flexibility, and create hydrogen bonds (Caykara, Demirci, Eroglu, & Gucen, 2005; Nie et al., 2008). Blends of alginate with PEO have shown promise among the alginate-based solutions electrospinning. The ratio of alginate to PEO in the electrospun fiber has been maximized to 80:20 with the addition of Triton X-100, a non-ionic surfactant. The ratio of alginate to PEO in the electrospun fiber has shown promise among the alginate-based solutions electrospinning. In addition, ionic conductivity and surface tension have significant effects on the electrospinning process (Fong, Chun, & Reneker, 1999; McKee et al., 2004; Yu et al., 2006). The ability of a polymer solution to form uniform nanofibers can be linked directly to its solution properties.

2. Materials and methods

2.1. Materials

Sodium alginate was obtained from FMC Biopolymers (Princeton, NJ) (MW = 196 kDa, Mw/Mn = 1.6, 66-34 C:M blocks) and used as received. Low MW alginate (MW = 37 kDa, Mw/Mn = 1.5) was prepared from the high MW by gamma irradiation. Dry alginate was irradiated with a 5 Mrad dose at 25 °C (Phoenix Laboratory, University of Michigan, Ann Arbor, MI), following a previously reported procedure (Alsberg et al., 2003). Additionally, polyethylene oxide (Polysciences, Warrington, PA, PEO, Mw = 600 kDa), polyethylene glycol (Polysciences, Warrington, PA, PEG, Mw = 35 kDa), Triton X-100 (Sigma Aldrich, St. Louis, MO, and Pluronic F127 (Sigma Aldrich, St. Louis, MO) were also used. Solutions were prepared by making separate solutions of PEO (4 wt%) and PEG (40 wt%) and 196 kDa (4 wt%) or 37 kDa (13.5 wt%) alginate in deionized water, and then combining with the surfactant. Solution ratios of up to 2.8:1:2:2.0 (196 kDa alginate:PEO:surfactant) and 8.0:1:6:2.0 (37 kDa alginate:PEO:surfactant) were investigated. Solutions were mixed overnight at room temperature with a magnetic stir bar. Crosslinking treatment of electrospun fibers used ethanol (reagent grade, Sigma Aldrich, St. Louis, MO) and calcium chloride (Sigma Aldrich, St. Louis, MO).

2.2. Solution characterization

Rheological experiments were performed with a TA Instruments (New Castle, DE) AR2000 stress-controlled rheometer with a 40 cm, 2° cone and plate geometry. All samples were measured at 25 °C. Dynamic and steady state shear experiments were conducted on each sample. The stresses applied in the frequency sweeps were selected from the linear viscoelastic (LVE) regime in the stress sweeps. All rheological measurements were repeated on at least two different samples to ensure repeatability within ±5%. Ionic conductivity measurements were made using a potentiostat from Gamry Instruments (Warminster, PA). Surface tensions were determined using a pendant drop analyzer from SEO Co. Ltd (model Phoenix 300, Lathes, South Korea).

2.3. Preparation of alginate nanofibers

The electrospinning setup consisted of a syringe pump (model NE-1010, New Era Pump Systems, Inc., Wantagh, NY); high voltage power supply (model AU-60P0.5, Matusada Precision, Inc.
Fig. 1. Scanning electron micrographs of electrospun droplets of alginate (a) and alginate/Triton X-100 (b), both without PEO. Fibers were not seen with all aqueous alginate solutions investigated, regardless of the addition of a surfactant.

Kusatsu-City Japan), and collector plate covered in Reynolds Wrap non-stick aluminum foil for easy removal of mats. The polymer solution was pumped through a syringe with a 22 gauge needle at rates of 0.50–0.75 mL/h. The distance from the end of the needle to the collector plate was fixed at 15 cm. The voltage was varied from 10 to 15 kV until a stable Taylor cone was achieved, and then maintained at a constant level (Taylor, 1964). All nanofibers were made at room temperature (21–24 °C) and relative humidity 40–55%.

2.4. Crosslinking of alginate nanofibers

After electrospinning, nanofiber mats were removed from the collector plate and ionically crosslinked. Mats were soaked in ethanol (1 min), followed by a calcium chloride solution (2 wt%) in 1:5 ethanol:water (10 s). Finally, the mats were rinsed in water (1 min). The crosslinked fibers were submerged in water for up to four days, without agitation, at room temperature to confirm their stability. After soaking, mats were dried in a lyophilizer (VirTis 10-324 lyophilizer, Gardiner, NY) overnight.

2.5. Characterization of nanofibers

Nanofiber mats were analyzed with a scanning electron microscope (SEM). A FEI XL30 field emission SEM was used at the following settings: 6 mm working distance, 5 kV accelerating voltage, spot size 3, and ultrahigh resolution mode. Fiber diameters and standard deviations on 50 fibers per sample were measured using Adobe Photoshop C3. Spectra of stand alone fiber mats without salt windows were collected from 4000 to 400 cm⁻¹ with 4 cm⁻¹ resolution and 512 scans using a Fourier Transform Infrared (FTIR) Spectrometer (model Nicolet 6700, Thermo Electron Corp.) in the transmission mode.

3. Results and discussion

3.1. Solution rheology and electrospinning alginate

Our initial attempt at electrospinning pure alginate nanofibers focused on solutions containing alginate concentrations spanning two decades (0.04–5.0 wt% for 196 kDa alginate, and 0.15–15 wt% for 37 kDa alginate). Attempts to electrospin either MW resulted in beads or droplets but no nanofibers as shown in Fig. 1 for two representative samples. Other groups have also reported similar results when attempting to electrospin aqueous alginate solutions (Bhattarai et al., 2006; Nie et al., 2008, 2009; Safi et al., 2007). An explanation proposed by these groups has been the inability of alginate to form chain entanglements.

Solution rheology has been suggested to be a good indicator of the range of polymer concentration appropriate for electrospinning as well as determining the entanglement concentration. McKee et al. reported that neutral and charged polymer solutions could be electrospun into uniform fibers at concentrations 2–8 times...
above the entanglement concentration (McKee et al., 2004; McKee, Hunley, Layman, & Long, 2006). To estimate the entanglement concentrations of our sample, the viscosity-shear stress behavior was measured for polymer concentrations that spanned two decades. Fig. 2 shows the specific viscosity ($\eta_{sp} = (\eta_0 - \eta_s)/\eta_0$, where $\eta_0$ is the solution zero shear viscosity and $\eta_s$ the solvent viscosity) of these samples as a function of concentration ($C$). Several pieces of information can be obtained from these plots. First, there are two distinct changes in slope, corresponding to the overlap ($C^*$) and entanglement ($C_e$) concentrations. Alginites with MW 37 (Fig. 2a) and 196 (Fig. 2b) kDa were found to have entanglement concentrations ($C_e$) of approximately 4.0 and 0.6 weight percent in water solutions, respectively. Entanglement concentrations decrease with increasing polymer MW, as a result of the longer polymer chain lengths (Rubinstein & Colby, 2003). We also find that the entanglement concentrations of alginate solutions occur at zero shear viscosities $\sim 0.05$ Pa s, or $\sim 50 \times \eta_s$, which is consistent with theoretical predictions (Dobrynin, Colby, & Rubinstein, 1995). In addition, the slopes of the curves match well with scaling predictions of neutral polymers in good solvent: $\eta_{sp} \sim C^{1.0}$ for the dilute regime ($C < C^*$), $\eta_{sp} \sim C^{1.25}$ for the semidilute unentangled regime ($C^* < C < C_e$), and, $\eta_{sp} \sim C^{3.75}$ for the semidilute entanglement regime ($C_e < C < C^{**}$) (Dobrynin et al., 1995). ($C^{**}$ is the concentrated regime.) We speculate that the alginate solutions act as neutral polymers, instead of charged polyelectrolytes, due to counterions (e.g., Na$^+$) that effectively screen the carboxylic acid groups on alginate (Krause, Bellomo, & Colby, 2001). Purification of the alginate may be necessary to reduce counterions and cause alginate solutions to follow the scaling predictions of polyelectrolytes (Rubinstein, Colby, & Dobrynin, 1994). However, Nie et al. recently reported that concentration plots of unpurified alginate solutions matched charged polymer models (Nie et al., 2009). We hypothesize that the concentration of counterions varies with the source and distributor of alginate. Variation in the solution behavior of alginate based on its source is an important finding to consider for future materials research with the biopolymer.
In addition to solution behavior predictions from the concentration curves, we also found that alginate does in fact have an entanglement concentration well below the solution concentration attempted for electrospinning. Our efforts to electrospin aqueous alginate solutions in concentrations up to 5.5% or \( \sim 9 \times C_{\text{ent}} \) were unsuccessful, suggesting that chain entanglement is not the dictating factor for alginate solutions to electrospin (Fig. 1). It should be noted that strain rates at the transition between the Taylor cone and the jet during the electrospinning process are high (Han, Yarin, & Reneker, 2008); however, the zero shear viscosity provides information on chain entanglement of a system.

The inability of a polymer solution to be electrospun can often be overcome by blending it with another polymer. PEO has been blended with charged biopolymers, such as chitosan, or low MW polymers, such as polyethylene glycol (PEG), that are incapable of being electrospun alone to generate nanofibers (Klossner, Queen, Coughlin, & Krause, 2008; Yu et al., 2006). Recently, blends of sodium alginate and PEO have been electrospun (Bhattarai et al., 2006; Jeong et al., 2010; Lu et al., 2006; Saifi et al., 2007). PEO and alginate chains can interact by hydrogen bonding, which contributes to their compatibility in solution (Caykara et al., 2005; He, Zhu, & Inoue, 2004). However, hydrogen bonding between alginate and its carrier polymer alone does not allow for a blend to be electrospun. To demonstrate this, attempts were made to electrospin blends of alginate and 35 kDa PEG (2.0:20.0). The solutions electrospayed, but did not form continuous fibers (Fig. 3). We hypothesize that the chain length of the carrier polymer also plays a role in the electrospinning of alginate.

### 3.2. Effect of Triton X-100 surfactant on alginate/PEO blends

While blended nanofibers can be formed from electrospinning alginate and PEO, the amount of alginate in the blend can be increased with the addition of small amounts of surfactants (Bhattarai & Zhang, 2007). Initially, the effects of the nonionic surfactant Triton X-100 on the solution properties of alginate–PEO blends and on the morphology of the resultant nanofibers were investigated. Alginate–PEO solutions were maintained at a total concentration of 4 wt%, because PEO (600 kDa) can be electrospun at this concentration (data not shown). We find that alginate–PEO blends at a ratio of 70:30 by weight produce beaded nanofibers (Figs. 3c and d). However, the addition of small amounts (1 wt%) of Triton X-100 to the sample, generates bead-free fibers (Fig. 3). Surfactants lower the surface tension of the polymer solution, which suppresses bead defects (Fong et al., 1999). Table 1a shows the various properties of polymer solutions containing alginate and PEO. Alginate and PEO have limited surface activities and reduce the surface tension of water to 55 mN/m. The addition of Triton X-100 causes the surface tension of the polymer blend to decrease to 29 mN/m, which possibly contributes to the morphological transition from beaded to uniform fibers. However, it is important to note that reducing the surface tension of alginate solutions with surfactants did not lead to uniform fibers (Fig. 1b). Alginate solutions, regardless of added surfactants, that were not blended with PEO formed droplets (Saquing et al., 2008). Thus, reducing surface tension enhances the electrospinnability of alginate solutions for systems that have reached the onset of fiber formation.

The roles of other solution properties that could impact the electrospinnability of the alginate/PEO solutions were also examined. Rheological properties, such as zero shear viscosity and relaxation time have been known to affect fiber morphology (Talwar, Hinestroza, Pourdeyhimi, & Khan, 2008; Yu et al., 2006). However, we found that the addition of PEO did not have a significant effect on the solution relaxation time, as determined by dynamic oscillatory measurements. Solutions of alginate and alginate/PEO/Triton blends with similar zero shear viscosities also have similar moduli and relaxation times (Fig. 4). Additionally, the ionic conductivity of the alginate-only solutions was reduced after blending with PEO, thereby diluting its total solution concentration, showing that alginate is the greatest contributor of the solution conductivity due to its anionic nature in water. As expected, the addition of a nonionic surfactant did not affect the conductivity. These results (Figs. 3 and 4 and Table 1a) taken together indicate that the surface tension is the most important factor in electrospinning these polymers and that the additions of both PEO and Triton X-100 are necessary to generate nanofibers with up to 70% (relative to PEO) or 2.8 wt% alginate.

### 3.3. Role of biocompatible F127 nonionic surfactant

With the potential uses for alginate-based nanofibers in biomedical applications, there is strong interest in using only non-cytotoxic materials. Therefore, Triton X-100 was replaced with an
FDA-approved surfactant, Pluronic F127. Using the same procedure as discussed in the previous section, alginate–PEO blended solutions were characterized and electrospun. As shown before with Triton X-100, the addition of Pluronic F127 effectively suppressed bead defects (Fig. 5). Blends of alginate and PEO were electrospun with minimal beads at weight ratios up to 60:40 (2.4:1.6 wt%). The formation of fibers with minimal bead defects were primarily due to the decrease in surface tension, since the rheology and ionic conductivity of blends with and without surfactant were similar. As shown in Table 1b, the addition of F127 could not match the same maximum amount of alginate for bead-free fibers as with Triton X-100 (70% by weight). This is because the surface tension of F127 solutions is 35–36 mN/m compared to 29 for Triton solutions. Pluronic is a triblock copolymer (PEO–PPO–PEO) and is expected to have lower packing density at the water–air interface compared to Triton X-100 (Hiemenz & Rajagopalan, 1997). However, the use of an FDA-approved surfactant in electrospun solutions as a method to enhance the alginate loading fiber morphology is an attractive option.

### 3.4. Electrospinning low MW alginate

From a materials perspective, low MW polymer chains are less desirable to use in electrospinning due to limited entanglements. However, from a tissue engineering perspective, small polymer chain lengths have a faster rate of in vivo degradation than high MW chains and can be cleared by the kidneys (Al-Shamkhan & Duncan, 1995; Alsberg et al., 2003). In this study, we attempted to electrospin irradiated alginate ($M_W = 37$ kDa). As observed previously with the high MW alginate, solutions containing only low MW alginate in concentrations $>3 \times C_e$ did not electrospin. The inability to electrospin low MW alginate was overcome by blending it with PEO and Pluronic F127 surfactant, using the same approach as with the high MW alginate. However, compared to the high MW alginate case, the alginate content was raised from 2.8:1.2 to 8.0:1.6 (by polymer wt% relative to PEO) using the low MW polymer. A shorter chain length polymer requires a greater concentration to achieve comparable solution viscosities to a high MW polymer. Despite a greater concentration of alginate (8 wt%)

### Table 1b

<table>
<thead>
<tr>
<th>Samplea</th>
<th>Alginate</th>
<th>Alginate/F127b</th>
<th>Alginate/PEOb</th>
<th>Alginate/PEO/F127b,c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero shear visc (Pa s)</td>
<td>22.0</td>
<td>21.5</td>
<td>14.0</td>
<td>15.5</td>
</tr>
<tr>
<td>Relaxation time (s)</td>
<td>0.06</td>
<td>0.06</td>
<td>0.05</td>
<td>0.06</td>
</tr>
<tr>
<td>Conductivity (mS/cm)</td>
<td>7.15 ± 0.07</td>
<td>7.04 ± 0.07</td>
<td>4.10 ± 0.04</td>
<td>3.53 ± 0.05</td>
</tr>
<tr>
<td>Surface tension (mN/m)</td>
<td>63 ± 2</td>
<td>35 ± 1</td>
<td>57 ± 1</td>
<td>36 ± 1</td>
</tr>
<tr>
<td>Electrospun fibers</td>
<td>Droplets</td>
<td>Droplets</td>
<td>Beaded fibers</td>
<td>Uniform fibers</td>
</tr>
</tbody>
</table>

a Total polymer concentration was maintained at 4 wt%.
b Concentration of Pluronic F127 was 2 wt%.
c Concentrations of alginate and PEO were 2.4 and 1.6 wt% (60:40 by wt), respectively (means ± standard deviations are reported).
for the low MW solution, the zero shear viscosity was less than the high MW alginate solution (2.8 wt%) (2.3 vs. 14.5 Pa s, Supplemental Fig. 1). In addition, the longest relaxation time of the low MW solution was an order of magnitude less than the high MW solution. Polymers with short chain lengths have fewer entanglements than high MW chains, and relax sooner (Rubinstein & Colby, 2003).

Uniform nanofibers containing low MW alginate, PEO, and F127 surfactant were obtained (Fig. 6a and b). To our knowledge, we are the first to prepare alginate-based nanofibers from a low MW alginate. The average fiber diameters were ~150 nm, the same size as fibers with high MW alginate. Thus, the final fiber diameter was not dependent on solution composition of the concentrations investigated, despite using a solution with a low MW polymer as the majority species in the blend. We speculate the consistency in the solution and processing conditions (solution viscosity, temperature, humidity) contributed to similarities in the fiber sizes between the two different MW solutions (Tripatanasuwan, Zhong, & Reneker, 2007; Yu et al., 2006). Electrospraying blends containing low MW alginate reduced the amount of PEO as the inert, carrier polymer, thereby allowing for a greater polysaccharide component, which is of greater interest when these nanofibers are used as tissue scaffolds. In our case, we achieved nanofibers with alginate/PEO ratio of 8.0/16, i.e., with over 83% alginate in the blend. In addition, the complete removal of PEO (Mw 600 kDa) from the nanofibers would leave only the low MW material, which would be capable of renal clearance if used in vivo.

3.5. Crosslinked alginate-only nanofibers

Prior to use as tissue engineering scaffolds, alginate-based materials need to be crosslinked to preserve their structure in an aqueous environment. Ionic crosslinking with divalent ions (e.g. Ca²⁺) avoids
PEO (1.2–1.6 wt%) shrunk by fibers containing blends of high MW alginate (2.4–2.8 wt%) and alginates were shown to remain intact after exposure to water and durability. The nanofibers composed of both high and low MW the nanofiber mats were soaked in water to test their structural

tained using ethanol in a pre-crosslinking treatment and as part
We determined that the fiber morphology could be best main-
a high G–M block ratio (66–34) to increase ionic crosslinking sites.

Skjakbraek, 1990). The alginate used throughout these studies has
potentially toxic materials used in chemical crosslinking reac-
tions (Birnbaum et al., 1981; Huanglee et al., 1990; Smidsrod &

Fig. 7. Fiber diameters (a) of alginate (196 kDa)/PEO/Triton X-100 (2.8:1.2:1.0), alginate (196 kDa)/PEO/F127 (2.4:1.6:2:0), and alginate (37 kDa)/PEO/F127 (8.0:1.6:2.0) before and after crosslinking and soaking in water. (Error bars = 1 standard devia-
tion.) FTIR spectrographs (b) of nanofibers containing 37 or 196 kDa MW alginate
and PEO before (37 kDa (1)) and after (37 kDa (2), 196 kDa (3)) soaking. PEO peaks
at 844, 1102, and 1342 cm$^{-1}$ disappear after soaking.

4. Conclusions

The addition of small amounts of surfactants can enhance the concentration of alginate and morphology of electrospun fibers from alginate/PEO blends. We found this concept to hold true for low molecular alginates and an FDA approved Pluronic surfactant, both of which holds great promise for in vivo applications. In partic-
lar, nanofibers of alginate blends with compositions greater than 80/20 for alginate-to-PEO ratio were obtained in such systems. Alginate-only fibers, evidenced from FTIR, were also achieved by crosslinking the nanofibers and removing the PEO and surfactant.

Finally, compared to the rheological properties and ionic conduc-
tivity, we found surface tension of the solutions had the greatest effect on whether the solution blends could be electrospun. Reduc-
ing the surface tension could thus be an effective method to tune the fiber morphology while maximizing the amount of alginate.

Acknowledgments

This work was supported by U.S. Department of Education Grad-
uate Assistance in Areas of National Need (GAANN) Fellowship Program at North Carolina State University (CAB), and a National Science Foundation Graduate Research Fellowship (MDK). We also thank Professor Ralph Colby (Penn. State) for helpful discussions related to the specific viscosity plots.

Appendix A. Supplementary data
