Needle and Wire Electrospinning of a Shear-Thinning Polysaccharide for Biomedical Applications

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Statement of Purpose: Carrageenan (Cg) is a linear sulfated polysaccharide polymer with applications in tissue engineering and as an antimicrobial[1,2,3]. Electrospinning Cg into fibrous meshes presents a versatile approach for using Cg in these and other applications. However, Cg has proven challenging to electrospin because of the rigidity and shear-thinning properties of Cg polymers. To date, electrospinning Cg alone has failed to produce fibers due to its inability to entangle [4]. Here we show the electrospinnability of Cg in blends with poly(ethylene oxide) (PEO) and poly(vinyl alcohol) (PVA), two biocompatible polymers that are generally regarded as safe by the FDA. We identified solution properties and processing parameters that enable electrospinning of Cg from both a lab-based needle electrode and a production-scale wire electrode. While Cg alone cannot be electrospun, we successfully electrospun Cg/PEO and Cg/PVA fiber blends with high productivity to produce meshes with up to 16wt% Cg loading. Our work shows, for the first time, methods to electrospin Cg into biocompatible polymer fibers with uniform morphology, high material productivity and high Cg content.

Methods: Carrageenan (Cg) was combined with PVA (MW: 85-124kDa, 87-89% degree of hydrolysis), and PEO (MW: 400kDa, 900kDa and 1MDa) at different ratios and aqueous solution concentrations. Solution conductivity and viscosity were measured prior to electrospinning on either a custom-built needle electrospinning rig or a commercial free-surface electrospinning instrument (NS1WS500U, Elmarco, Inc.). The resulting Cg meshes were characterized for fiber morphology, Cg loading and encapsulation efficiency, and material productivity and yield. SEM micrographs were used to visualize and measure fiber diameter. Cg content in the resulting fibers was quantified using an established methylene blue assay. Productivity on the wire (P_{ws}) was calculated using the relation: $P_{ws}=mA_s^{-1}A_t t^{-1}$, where m is the mass averaged from different areas on the collected mesh; A_s, the area of mesh sampled; A_t, the total area of mesh; and t, the batch run time. Productivity for the needle (P_{ns}) was calculated using the relation: $P_{ns}=mQ^{-1}V^{-1}$, where m is the mass of the electrospun composite, Q is the volumetric flow rate, and V is the batch volume.

Results: Cg formulations blended with PEO-1MDa could not be electrospun on either the needle- or wire-electrode format. Instead, the collected meshes showed predominately a "beads-on-a-string" morphology (Fig.1a). The beaded fiber architecture and the low viscosity (~1.0Pa•s) suggests the solution was too aqueous and the Rayleigh instability during fiber formation was not overcome by electric field forces[5]. In contrast, PEO-400kDa and PEO-900kDa blends with Cg were successfully electrospun on both wire and needle electrospinning formats, and resulted in meshes with uniform fiber morphology and high Cg content. Cg blends with PEO-400 kDa were electrospun with up to 20wt% Cg content, but formulations blended with PEO-900 kDa were limited to Cg content below 15wt% due to the high viscosity of these solutions. Cg encapsulation efficiency for all PEO blend formulations was >80%. However, Cg blends with PEO-400 kDa resulted in the highest productivity (~0.6 g•h^{-1}) and Cg loading (16wt%). In general, we observed that the wire electrode is up to 50x more productive than the needle electrode for electrospinning Cg with PEO.

Formulation ID (FID)	ES Format	Polymer Solution Concentration (% w/w)	Expected	Actual	Productivity (x10^{-3} g•h^{-1})
PEO/Cg Blends			CG Loading (% w/w)		
PEO-400kDa					
7	Wire	5.00	10	10.07±0.23	558.3±99.4
8	Wire	5.00	15	11.30±1.40	580.5±250.4
9	Needle	5.00	15	13.84±0.38	14.2
10	Wire	5.00	20	16.55±1.64	452.9±237.1
PVA/Cg Blends					
11	Needle	15.00	10	n.d.	2.66
12	Needle	15.00	15	-	-
13	Wire	11.00	10	7.05±2.11	376.65±52.7
14	Needle	11.00	10	15.75±0.90	15.02
15	Wire	11.00	15	13.03±1.25	113.51±30.5

Table 1. Cg loading and productivity results for formulations tested.
Figure 1. SEM of a) FID-10 b) FID-13 c) FID-13 d) FID-15

Compared to Cg/PEO blends, electrospinning Cg/PVA blends showed lower mass productivity and resulted in meshes with lower Cg content. For the Cg/PVA formulations, we observed that blends resulting in the highest electrospinning productivity (~0.4 g•h^{-1}) had the lowest Cg content (7wt%). In contrast, Cg/PVA meshes with the highest Cg content (16wt%) had the lowest electrospinning productivity (~0.1 g•h^{-1}). Cg loading in PVA blends was less than loading values measure for Cg/PEO blends. This result suggests PVA may not entangle Cg as efficiently and may be due to the lower molecular weight of PVA.

Conclusions: We established optimized solution properties and processing parameters for successful electrospinning of Cg in blends with PEO and PVA. This is the first report of electrospinning Cg with high material productivity and loading. Our research provides a rational basis for further development of Cg fibers that may extend to other biological polymers with similar rheological properties. Our approach could allow for more polymer choices in the development of scaffolds for tissue engineering and could provide more options for antimicrobial drug delivery systems that require the use of polysaccharides.

References:
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