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Investigation of the correlation between electrospinnability and rheology

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ABSTRACT

Electrospinning is a fascinating technique to fabricate micro-/nano-scale fibers using a wide variety of materials. Molecular entanglement of the polymer solution was found to be an essential prerequisite for electrospinning.[1, 2] In this study, poly lactic-co-glycolic acid (PLGA), one of the most widely used polymers in pharmaceutical manufacturing, has been used to investigate the correlation between electrospinnability and rheological properties of PLGA. Electrospinnability was evaluated visually in terms of stability of the cone-jet and by scanning electron microscopy (SEM) observation of the fibers formed. The relevant viscoelastic properties of the polymer solutions were evaluated by a rheometer.

INTRODUCTION

Electrospinning has been recently attempted in pharmaceutics field to design novel drug delivery systems.[2] 3D scaffold matrices produced by electrospinning can bio-mimic micro-/nano-scale, porous artificial matrices, which is promising for tissue engineering.[3] For electrospinning, high voltage is used to generate charged polymer solution with sufficient molecular entanglements. As the voltage is increasing above the balance between Coulombic repulsion and surface tension, a stable jet is discharged from the tip of the Taylor cone. Due to sufficient chain overlap and entanglements of the polymer solution, a whip-like motion between the capillary tip and the grounded collector formed, and this motion results in thinning of the jet and formation of micro-/nano- scale fibers.[4]

PLGA is a biocompatible and biodegradable polymer, which is an attractive polymeric candidate used for drug delivery and tissue engineering application[5]. The rheological properties of the solution ultimately determine whether fiber formation is possible through electrospinning. Systemic rheological investigations of polymer solution correlate with electrospinnability are still limited at present.[6-9]

In this study, a specific molecular weight PLGA dissolved in proper solvent at different concentrations was studied to investigate the correlation between electrospinnability and rheological properties of PLGA solutions, and the electrospinning performance of PLGA under different processing conditions.

MATERIALS AND METHODS

PLGA (LA: GA, 50:50, molar ratio) with inherent viscosity (25°C, 0.1%, $CHCl_3$) in the range 0.61-0.74 dl/g was purchased from Evonik (Darmstadt, Germany). Molecular biology grade N,N-dimethylformamide (DMF) and anhydrous grade tetrahydrofuran (THF) were obtained

from Sigma-Aldrich (Denmark). All materials were used as obtained.

PLGA was dissolved in DMF-THF (50:50, v:v) at concentrations of 15% and 30% (w/v), respectively, at room temperature. Assemble of the electrospinning setup was as shown in Fig. 1. The distance between the nozzle tip to the grounded collector was 10 cm, and flow rate was 10 µL/min. The voltage was adjusted to get a stable cone-jet.

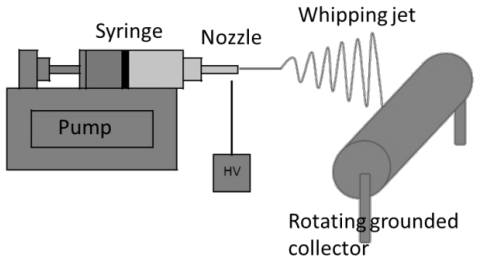

Figure 1. Schematic illustration of a typical electrospinning setup.

The viscoelastic properties of different concentrations of PLGA solutions were investigated using the DHR-3 Rheometer (TA instruments, USA). All samples were analysed on DHR-3 using the cone plate geometry (diameter = 40 mm, 1 degree) at 10°C, using solvent trap to create a thermally stable vapour barrier, eliminating solvent loss during rheological experiments. Oscillatory amplitude sweep tests were conducted with strain between 0.01 and 1000% to determine the linear viscoelastic region of each solution. Subsequently, oscillatory frequency sweeps were performed at torque of 1.0 µN·m and angular frequencies between 0.1 to 100 rad/s. The viscosities of solutions under shear rate were investigated through a logarithmic steady shear rate increase from 0.1 to 1000 s^{-1}.

RESULTS AND DISCUSSION

Rheological characterization of PLGA in DMF:THF=50:50

Oscillatory strain sweep tests provide useful information on the storage and loss moduli of PLGA solutions in response to the applied shear strain. From the collected data the linear viscoelastic region can be identified and used to conduct dynamic oscillatory frequency sweep tests in the solutions. The results demonstrated a concentration dependent loss modulus (Fig. 2), which is independent of strain, with the loss modulus increasing approximately 1 order of magnitude for PLGA concentration increasing from 15% to 30%. The linear viscoelastic region of the polymer solutions was between 0.1 to 50% strain.

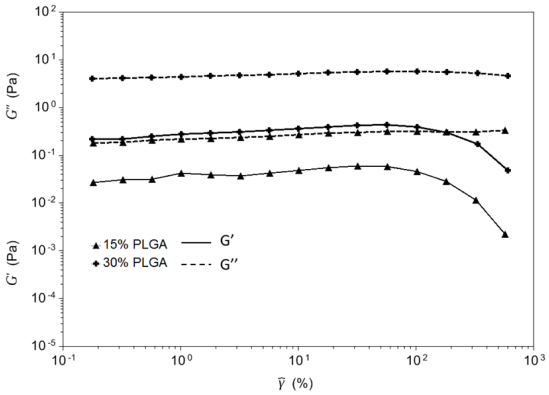

Figure 2. Oscillatory strain sweep of PLGA solutions at different concentrations.

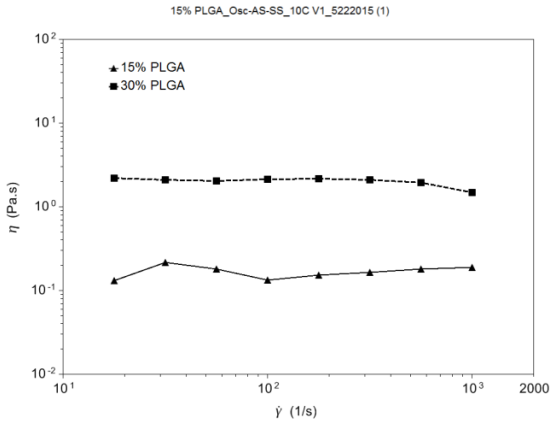

Figure 3. Shear viscosity of PLGA solutions at different concentrations.

Flow sweep was used to evaluate the shear induced changes in molecular entanglements, interaction, deformation and orientation. As expected, increasing PLGA concentration yielded solution with higher shear viscosity, due to increased molecular interaction within the solution (Fig. 3).

In the detected range, about 30 to 1000 s^{-1}, the solutions showed independent shear viscosity, indicating Newtonian behaviour.

Oscillatory frequency viscoelasticity measurements were performed within the linear viscoelastic region at 10 °C. Within the frequency range measured PLGA solutions were dominated by the loss modulus (G″ > G′; Fig. 4). Both the viscous and elastic moduli showed significant increases in response to increasing angular frequency with typical concentration dependence for a polymer solution. At a higher concentration (30 wt%) of PLGA, G′ and G″ are close to parallel, indicating that the solution is approaching gelation point, though no G′/G″ crossover was observed. Low concentration PLGA solutions (15 wt%) showed similar responses with significantly lower storage and loss moduli.

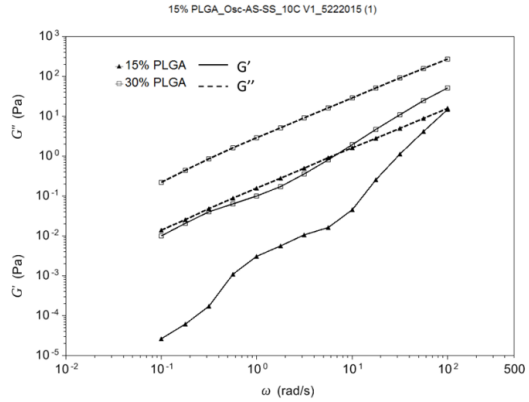

Figure 4. Storage and loss moduli as a function of angular frequency of PLGA solutions at different concentrations.

Electrospinning PLGA solutions

In order to investigate the effects of the PLGA solution rheological characteristics on the electrospinning process, the electrospun fibers were compared between PLGA solutions with different concentrations, keeping the processing parameters constant during the electrospinning process, except for the voltage, which need to be adjusted to get a stable cone-jet. The conditions and outcomes of electrospinning of PLGA solutions are shown in Table 1. For the lower concentration (15 wt%) solution, mixture of micro particles and nanofibers were produced by electrospinning. For the higher concentration (30 wt%) solution, uniform, smooth micro-/nano-scale fibers were produced. The morphology of the products is shown in Fig.5. Under both concentrations, stable cone-jet can be generated by adjusting the voltage to 9.5kv and 7.5kv for 15 wt% and 30 wt% PLGA solutions, respectively.

Table 1. Electrospinning conditions and outcomes for PLGA solution

PLGA conc.(wt%)	Distance (cm)	Voltage (kv)	Flow rate (μL/min)	Morphology
15	10	9.5	10	Microparticles /nanofibers
30	10	7.5	10	Micro-/nano-scale fibers

For electrospinning, the electrostatic force need to be sufficient enough to overcome the surface tension of the solution, then a cone-jet can be formed. Surface tension coefficient depends on the polymer and solvent. As reported earlier, it was assumed the surface tensions of the solutions at various concentrations did not significantly change.[10, 11] High surface tension drives towards the formation of beads. Changing the polymer concentration can vary the solution viscosity. At lower concentration, no sufficient entanglements and intermolecular interactions exist, the jet could not withstand the surface tension of the solution and the charged stream could be broken up into droplets. Therefore, at 15 wt% concentration, droplets and nanofibers were produced. When the concentration was

increased to 30 wt%, the number of entanglements and intermolecular interactions increased, the polymer solution viscosity increased, thereby facilitating the formation of defect-free fibers.

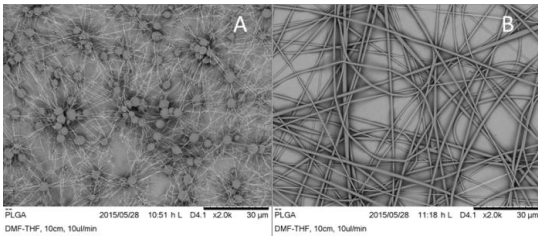

Figure 5. SEM results of electrospun fibers at different concentrations. A: 15 wt%; B: 30 wt%

For the same PLGA polymer, under all the same conditions, the morphology of the produced samples was dependent on the viscoelastic properties of the solution. The morphology was changed from mixture of droplets and nanofibers to uniform, defect free fibers when viscosity of polymer solution increased.

CONCLUSION

Electrospinnability of a polymer solution is dependent on viscoelastic properties, and sufficient viscosity, which means enough molecular entanglements and interactions within the solution, is prerequisite for electrospinning.

ACKNOWLEDGEMENTS

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