PCL-PLCG Composite Nanofibers Produced by Electrospinning
การผลิตเส้นใยนาโน PCL-PLCG ด้วยการอิเลคโตรสปิน

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Abstract

New electrospun fibers were successfully produced using single- and co-polymers of poly-(ε-caprolactone) (PCL) and poly-(L-lactide-co-caprolactone-co-glycolide) (PLCG). The composite nanofibers were also fabricated by injecting each polymer alternately and simultaneously. The electrospun PCL was found to form complete fibers with average diameter of 652.28 ± 297.40 nm, while the electrospun PLCG, layered PCL-PLCG composite, and mixed PCL-PLCG composite had a combination of fibers, nano-sized beads, and PLCG drops. The average sizes of PLCG, layered PCL-PLCG composite, and mixed PCL-PLCG composite electrospun fibers were 127.93 ± 84.50, 399.21 ± 361.09, and 586.42 ± 418.95 nm, respectively. Although the size of the mixed PCL-PLCG composite fibers was greater than the layered PCL-PLCG composite fibers, fewer nano-sized beads and PLCG drops were formed by electrospinning co-polymers, suggesting mixing of the two polymers in the produced fibers. The biological properties of these biodegradable fibers as suitable scaffolds for cell attachment and proliferation are currently under investigation.

บทคัดย่อ

เส้นใยนาโนชนิดใหม่ผลิตได้จากการอิเลคโตรสปินโพลิเมอร์เดี่ยวหรือผสมของโพลีคาโพรแลคโตน (poly-(ε-caprolactone), PCL) และโพลีแลคไตด์โคคาโพรแลคโตนโคไกลโคไลด์ (poly-(L-lactide-co-caprolactone-co-glycolide), PLCG) การผลิตเส้นใยนาโนด้วยเทคนิคอิเลคโตรสปินจากโพลิเมอร์ทั้งสองชนิดทำได้โดยการฉีดสารละลายโพลิเมอร์แต่ละชนิดสลับกันเป็นชั้น (แบบฉีดสลับ) และการฉีดสารละลายโพลิเมอร์ทั้งสองชนิดพร้อมกัน (แบบฉีดผสม) ผลที่ได้จากการฉีดสาร PCL ด้วยเทคนิคอิเลคโตรสปินพบว่าได้เส้นใยที่สมบูรณ์ซึ่งมีขนาดเส้นผ่านศูนย์กลางเฉลี่ย 652.28 ± 297.40 นาโนเมตร ส่วนผลจากการอิเลคโตรสปินสาร PLCG และสาร PCL กับ PLCG ทั้งแบบฉีดสลับและแบบฉีดผสม พบว่าได้เส้นใยร่วมกับเม็ดบีดขนาดนาโนเมตรและหยดของสาร PLCG โดยขนาดเส้นใยเฉลี่ยจากการฉีดสาร PCLG และสาร PCL กับ PLCG แบบฉีดสลับและแบบฉีดผสม มีค่าเท่ากับ 127.93 ± 84.50, 399.21 ± 361.09 และ 586.42 ± 418.95 นาโนเมตร ตามลำดับ แม้ว่าการอิเลคโตรสปินสาร PCL-PLCG แบบฉีดผสมจะได้เส้นใยที่มีขนาดใหญ่กว่าการอิเลคโตรสปินสาร PCL-PLCG แบบฉีดสลับ แต่ผลที่ได้จากการอิเลคโตรสปิน สารแบบฉีดผสมมีปริมาณของเม็ดบีดและหยดของสาร PLCG ในปริมาณที่ต่ำกว่าแบบฉีดสลับ ทำให้คาดว่าเส้นใยที่มีขนาดที่ใหญ่ขึ้นเกิดจากการผสมกันของโพลิเมอร์ทั้งสองชนิดหลังการฉีด สำหรับสมบัติทางชีวภาพของเส้นใยอิเลคโตรสปินที่ได้ต่อการยึดเกาะและการเจริญของเซลล์อยู่ในระหว่างการดำเนินการศึกษา

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Introduction

Nanotechnology is an applied science technology focusing on the design, synthesis, characterization, and application of materials and devices on the nanoscale. Nanofibers are fibers with nanometer size diameters. Their nanoscale size gives them unique properties, including extraordinarily high surface area per unit mass, small pores inside fibers, high permeability, and low basis weight (Ramakrishna et al., 2005). These outstanding properties give nanofibers a wide variety of applications, including medicinal gowns and drapes, cosmetics, bullet protective clothing, and non-wrinkle silk products (Nasongkla et al., 2004; Shuai et al., 2004; Krishnan et al., 2005).

Among many techniques to produce nanofibers, the electrospining technique has attracted tremendous interest simply because it is easy and effective in producing ultra fine fibers. This process involves using an electric field to draw a polymer solution from the tip of a capillary to a collector. After a high voltage is applied between the tip of capillary and a grounded collector, the electric field strength overcomes the surface tension of the droplet of polymer solution. Then a polymer solution jet is initiated and accelerated toward the collector. While the jet travels through the air, the solvent evaporates and a non woven polymer is formed (Kim et al., 2005). The electrospining technique has great potential to be used at laboratory scale as well as for manufacturing purposes.

In medicinal applications of nanofiber products, one of the fiber properties required is that the polymers must not be toxic to cells and can be naturally degradable. Thus, many polymers have been fabricated and their properties characterized. Poly-(ε-caprolactone) or PCL and poly-(L-lactide-co-caprolactone-co-glycolide) or PLCG are two polymers that are biodegradable, making them the choice of interest to us in fabricating their nanofibers using the electrospining technique. In this work, we are also interested in making nanofibers by electrospinning each single polymer and both polymers as composite nanofiber sheets, while the production of composite PCL-PLCG has never been reported.

Material and Methods

Material

Poly-(ε-caprolactone) or PCL, Poly-(L-lactide-co-caprolactone-co-glycolide) [70:20:10] or PLCG, and solvents including, 1,1,1,3,3,3-hexafluoro-2-propanol (HFIP), methylene chloride (MC), and N,N-dimethylformamide (DMF), were analytical grade.

Synthesis of Nanofiber Sheets

All electrospun fibers were fabricated using the KKUElectroSys electrospinning unit (Department of Physics, KKU). PCL solution was prepared as 10 wt% in MC:DMF (3:1, v/v). Electrospinning parameters of PCL nanofiber production were set at a distance of 20 cm, a voltage of 9.6 kV, and the spin rate of 0.6 ml/h. Electrospun fibers were collected on an aluminum foil sheet, and were kept at room temperature prior to use. PLCG solution was prepared as 10 wt% in HFIP and fabricated using the parameters of distance of 20 cm, a voltage of 9.5 kV, and the spin rate of 0.5 ml/h. The composite nanofibers were produced by using 10 wt% PCL and 10 wt% PLCG solution. The layered composite nanofibers were produced by electro injecting PCL solution as the first layer with the parameters of a

distance of 20 cm, a voltage of 9.5 kV, and the spin rate of 0.5 ml/h and injecting PLCG as the second layer with the parameters of a distance of 20 cm, a voltage of 10 kV, and the spin rate of 0.6 ml/h. The mixed composite nanofibers were produced by mixing both polymers prior to injecting the polymers at the parameters of a distance of 17 cm, a voltage of 10 kV, and the spin rate of 0.6 ml/h.

Fiber Morphology

The morphology and diameter of the electrospun fibers were observed and determined with the use of a scanning electron microscope (SEM) (LEO SEM1450VP, UK). The fabricated nanofibers of PCL, PLCG, layered PCL-PLCG, and mixed PCL-PLCG were cut to pieces of 1x1 cm^2. All nanofiber pieces were trapped with stubs and were coated with gold by sputter coater for 3 min. SEM was then used to observe the samples.

Results and Discussion

Nanofiber sheets of PCL, PLCG, layered PCL-PLCG composite, and mixed PCL-PLCG composite were fabricated by the electrospinning technique with different electrospinning conditions, and their morphology was studied under the scanning electron microscope (SEM). The electrospun PCL completely formed nanofibers (Figure 1). On the other hand, the electrospun PLCG gave a combination of nanofibers, nano-sized beads on fiber strings, and PLCG drops (Figure 1). The beads were probably generated due to the relatively low rate of solvent evaporation and short deposition distance. Droplet formation might have occurred because of the low molecular weight of the polymer and the low concentration of polymer in the solution (Koski et al., 2004). Since beads and drops were formed by PLCG solution, unsurprisingly, the combination of beads and drops of PLCG was observed along with the fibers in the sheets of layered PCL-PLCG and mixed PCL-PLCG. In addition, the flat fibrous structure was observed in electrospun samples of layered and mixed PCL-PLCG. These might be explained because wet fibers which were not evaporated completely before reaching the collector might flatten upon impact on the collector and undergo re-dissolution and coalescence as observed by the large size of the fibers (Hsu and Shivkumar, 2004). The diameters of fabricated PCL, PLCG, layered PCL-PLCG, and mixed PCL-PLCG fibers ranged from 200-1400 nm, 20-400 nm, 70-2200 nm, and 100-2000 nm, respectively (Figure 2). In addition, the average sizes of the above fibers were 652.28 ± 297.40, 127.94 ± 84.50, 399.21 ± 361.09, and 586.42 ± 418.95 nm, respectively. The sheets of electrospun PLCG, layered PCL-PLCG, and mixed PCL-PLCG fibers contained beads at a density of $19.94x10^3$, $3.56x10^3$, and $2.02x10^3$ beads/mm^2, respectively (Table 1). The areas containing drops of polymer were 33.82%, 41.08%, and 18.53% in electrospun sheets of PLCG, layered PCL-PLCG, and mixed PCL-PLCG fibers, respectively. All above data correlated well with the fiber morphology observed under the SEM. The electrospun PCL fibers were observed to have a larger size than PLCG fibers. Layered PCL-PLCG samples contained a distribution of fiber sizes covering 70-2200 nm, indicating that some were PCL fibers (smaller size distribution) and some were PLCG fiber (larger size distribution). The observed networks of fibers were probably formed when wet fibers of PCL and PLCG were re-dissolved on the collector. The observed fibers of mixed PCL-PLCG samples were larger than

those of layered PCL-PLCG. The enlarged sizes of fibers were probably caused by the mixing of wet fibers of PCL and PLCG in air, instead of the mixing on the collector that would give a network morphology to the fibers. The unique morphology of each electrospun nanofiber has been hypothesized as possibly providing different properties to allow cell attachment and proliferation, which would be important for tissue-engineering applications.

Conclusion

The present study demonstrated the production of electrospun nanofibers of single PCL and PLCG polymers, and PCL-PLCG composites, for which the latter have never been reported elsewhere. The electrospun PLC completely formed nanofibers, while PLCG, layered PLC-PLCG, and mixed PLC-PLCG had a combinations of fibers, nano-size beads, and PLCG drops. Each electrospun fibers showed unique morphology, which might provide different biological properties for cell adherence and proliferation.

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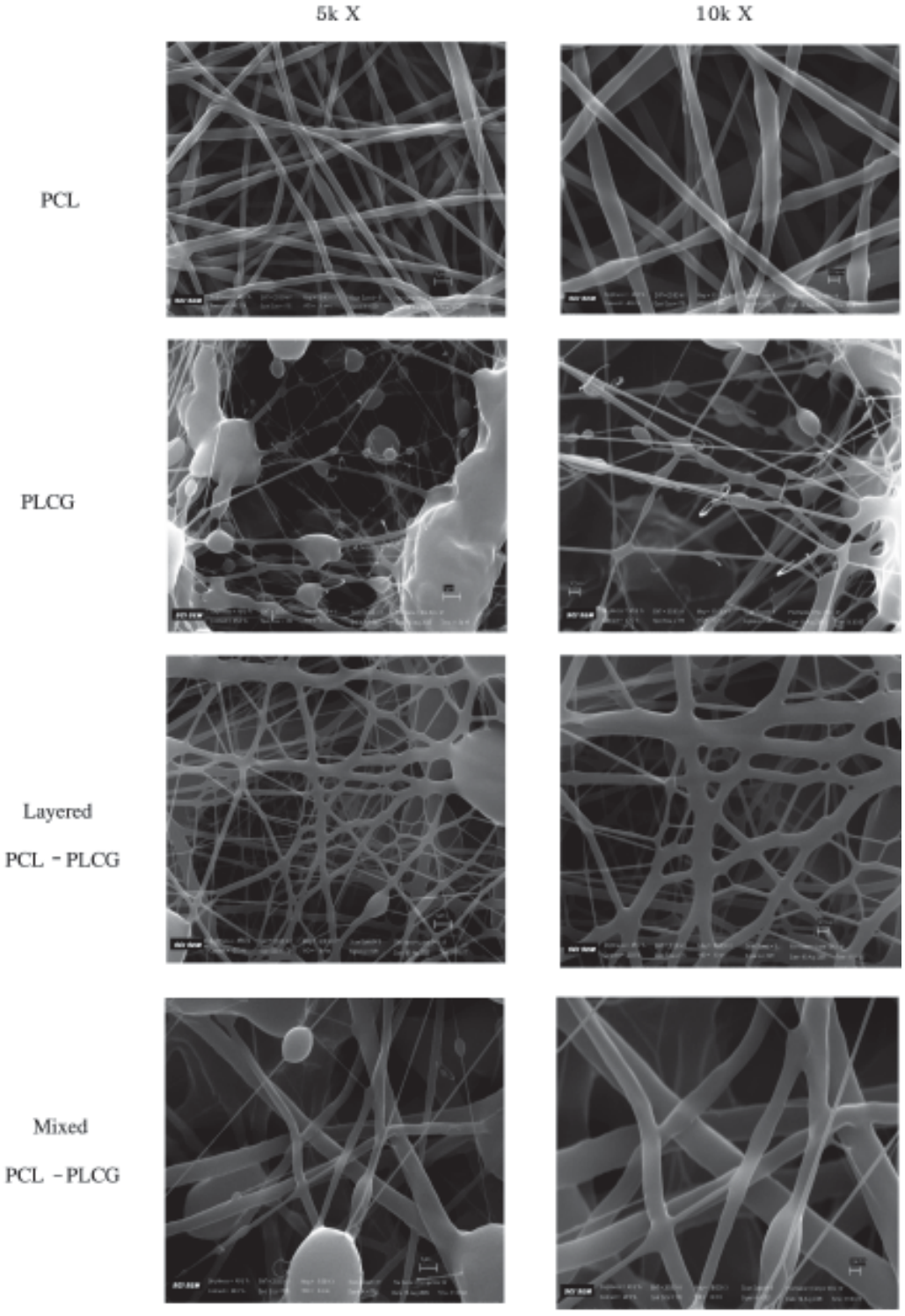

Figure 1. Morphology of fabricated PCL, PLCG, layered PCL-PLCG, and mixed PCL-PLCG nanofibers. The fiber morphology was observed under the scanning electron microscope at 5k X and 10k X.

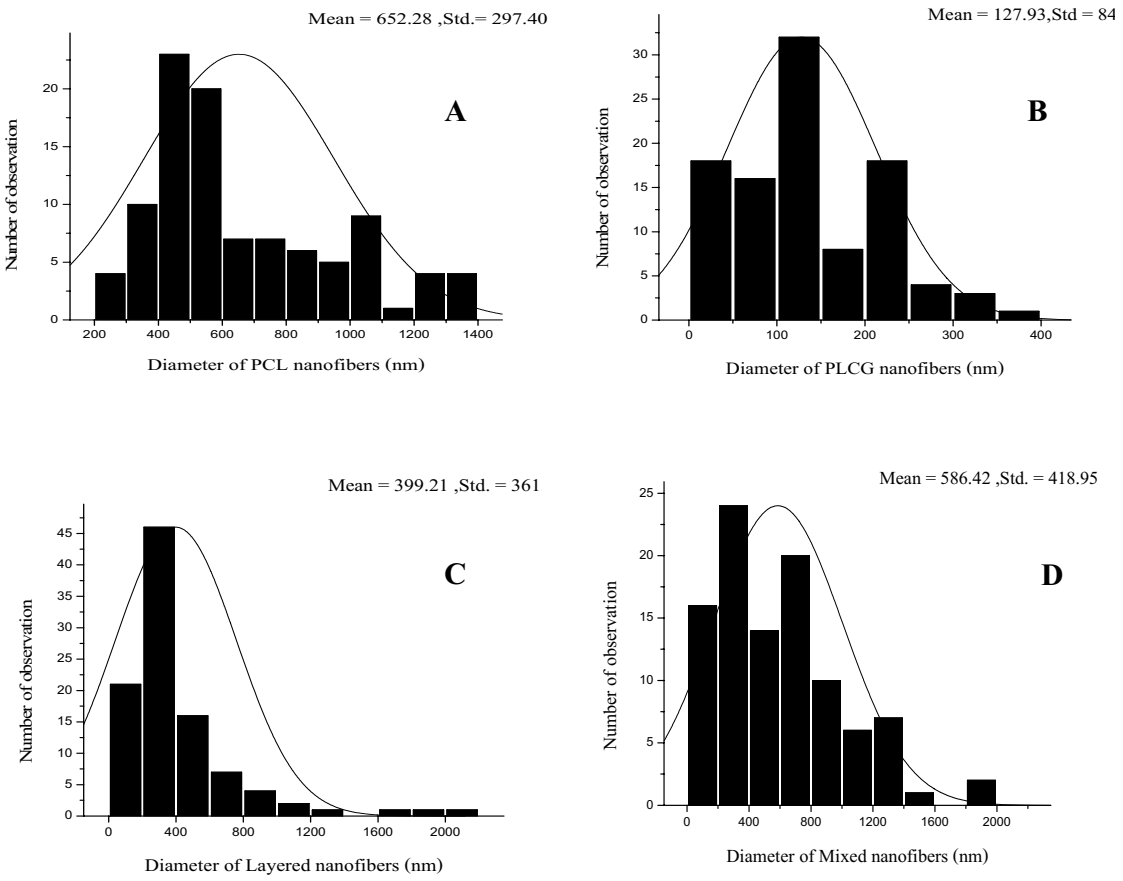

Figure 2. The distribution of fiber sizes. A) Fabricated PCL fibers. B) Fabricated PLCG fibers. C) Fabricated layered PCL-PLCG fibers. D) Fabricated mixed PCL-PLCG fibers. The sizes of fibers were measured from a randomly selected 100 areas of the SEM pictures.

Table 1. Distribution of polymer beads and drops of fabricated nanofiber sheets.

Nanofiber sheets	Bead density (beads/mm^2)	Area of polymer drops
PLCG	19.49x10^3	33.82 %
Layered PCL-PLCG	3.56x10^3	41.08 %
Mixed PCL-PLCG	2.02x10^3	18.53 %