Postprint: Electrospun Polycaprolactone-Collagen Composite Surgical Sutures Loaded with Basic Fibroblast Growth Factor and Their Sustained-Release Properties

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Abstract

Objective: To prepare a composite material for surgical sutures with sustained-release properties for basic Fibroblast Growth Factor (bFGF) and to investigate its mechanical properties and in vitro drug release behavior. Methods: Using electrospinning technology, encapsulation efficiency was optimized by investigating the ratio of material components in the composite. The influence of the polycaprolactone-collagen composite structure (PCL–Col) on the controlled release of bFGF was studied to prepare surgical sutures with biological activity and drug sustained-release properties. The microstructure of the sutures was observed, and the mechanical properties and drug loading capacity were measured. Results: Scanning electron microscopy (SEM) results demonstrated that the drug-loaded surgical sutures possessed an intact linear structure. Furthermore, tensile and tensile cyclic tests verified that the sutures exhibited favorable mechanical properties. Finally, enzyme-linked immunosorbent assay (ELISA) confirmed that the prepared surgical sutures possessed certain drug sustained-release properties. Conclusion: By optimizing the spinning parameters using an electrospinning apparatus, PCL–Col–bFGF surgical suture composite material was successfully prepared. The sutures meet the mechanical requirements for suturing while possessing certain bFGF sustained-release properties.

Full Text

Abstract

Objective: To prepare composite surgical sutures with controlled release of basic fibroblast growth factor (bFGF) and investigate their mechanical properties and in vitro drug release profiles. **Methods:** Using electrospinning technology,

we optimized the encapsulation efficiency by investigating the material composition ratios in the composite. The influence of polycaprolactone-collagen (PCL–Col) composite structure on bFGF release kinetics was examined to fabricate surgical sutures with both bioactivity and sustained drug release capability. The microstructure of the sutures was observed, and mechanical properties and drug loading capacity were measured. **Results:** Scanning electron microscopy confirmed that the drug-loaded surgical sutures maintained an intact fibrous structure. Tensile and cyclic tensile tests demonstrated excellent mechanical performance. Enzyme-linked immunosorbent assay (ELISA) verified that the prepared surgical sutures possessed sustained drug release properties. **Conclusion:** By optimizing electrospinning parameters, we successfully fabricated PCL–Col–bFGF surgical suture composites. These sutures meet the mechanical requirements for suturing while exhibiting sustained bFGF release performance.

Keywords: electrospinning; growth factor; mechanical property; sustained release

Introduction

Modern surgical practice demands increasingly sophisticated suture materials with enhanced tensile strength, handling characteristics, and therapeutic functionality. Recent strategies have focused on incorporating drug-loaded nanoparticles into sutures to create localized healing-promoting devices, demonstrating significant potential for effective local drug delivery.

Electrospinning technology offers excellent biocompatibility and biodegradability, making it suitable for implantable surgical suture applications. Electrospun nanofibers possess a high specific surface area and porosity, enabling their successful application in drug-controlled release, wound healing, and tissue engineering. Basic fibroblast growth factor (bFGF) is a therapeutic protein that plays crucial roles in cell self-renewal, tissue regeneration, and wound healing. However, its clinical utility is limited by rapid activity loss under normal physiological conditions.

To address these challenges, we developed a composite surgical suture by combining polycaprolactone (PCL) and collagen (Col) to encapsulate bFGF within a nanofiber bundle structure. This design leverages PCL' s excellent mechanical properties and collagen' s hydrophilicity to recapitulate extracellular matrix (ECM) architecture. The high specific surface area of electrospun nanofibers maintains drug stability under physiological conditions while providing sustained release, thereby extending bFGF' s therapeutic window.

Materials and Methods

1.1 Materials and Instruments

Human basic fibroblast growth factor (bFGF), polycaprolactone (PCL), and hexafluoroisopropanol were purchased from Sigma-Aldrich (USA). Collagen and

enzyme-linked immunosorbent assay (ELISA) kits were obtained from Shanghai Xitang Biological Technology Co., Ltd. The electrospinning apparatus (YFSP-G) was from Tianjin Yunfan Technology Co., Ltd. Mechanical testing was performed using an INSTRON universal testing machine (USA). Additional equipment included a freeze dryer (Beijing Boyikang Experimental Instrument Co., Ltd.), scanning electron microscope, multifunctional microplate reader (Shanghai Meirong Molecular Instrument Co., Ltd.), and contact angle measurement system (KRUSS, Germany).

1.2 Experimental Methods

The preparation of PCL–Col–bFGF nanofibers involved dissolving collagen in hexafluoroisopropanol under ice-bath stirring, followed by addition of bFGF solution and continued stirring for 24 hours to ensure complete encapsulation. PCL was then added to form a homogeneous polymer solution for electrospinning.

1.2.1 Optimization of Hexafluoroisopropanol/Water Ratio Collagen (226.3 mg) was dissolved in 7 mL of hexafluoroisopropanol/water mixtures with varying ratios under ice-bath stirring for 1 hour. After complete dissolution, 113 L of bFGF solution was added and stirred for 24 hours to ensure complete encapsulation within collagen. Polycaprolactone (0.45 g) was then added and stirred for 3 hours until homogeneous. The resulting milky, gel-like polymer solution was evaluated for uniformity and corresponding suture mechanical properties to optimize encapsulation efficiency.

1.2.2 Evaluation of PCL Content on Mechanical Properties Different amounts of polycaprolactone (0.45 g, 0.68 g, 0.91 g) were added to 7 mL of bFGF-loaded aqueous hexafluoroisopropanol mixtures. After 3 hours of ice-bath stirring, electrospinning was performed for 5 minutes. The uniformity of the mixture and mechanical performance of the resulting sutures were assessed to determine the optimal PCL concentration.

1.2.3 Effect of Flow Rate on Suture Formation Polymer solutions were loaded into 10 mL syringes and electrospun using a 20G needle. The spinning distance was set at 12 cm, collector rotation speed at 300 r/min, and voltage was controlled while varying the injection pump rates (1.08 mm/h, 2.16 mm/h, 3.24 mm/h). After 5 minutes of spinning, the uniformity and mechanical properties of PCL–Col–bFGF fibers were evaluated.

1.2.4 Effect of Voltage on Suture Quality Different voltage settings (6 kV, 12 kV, 18 kV) were tested using the optimal injection rate. Electrospinning was performed for 5 minutes to observe voltage effects on suture uniformity and mechanical properties, establishing the optimal voltage for bFGF-loaded sutures.

1.2.5 Scanning Electron Microscopy Approximately 2 cm segments of PCL, PCL–Col, and PCL–Col–bFGF sutures were mounted on copper plates, vacuum-treated, and gold-coated using a sputter coater. Microstructural characterization of bFGF-loaded fiber scaffolds was performed at various magnifications.

1.2.6 Mechanical Property Testing Using optimal composition and electrospinning parameters, sutures from all three groups were subjected to mechanical testing. Segments of 25–30 cm were mounted on a universal testing machine for tensile testing to generate stress-strain curves, elastic modulus plots, and maximum tensile stress diagrams. Cyclic tensile tests were performed at 20%, 40%, and 60% strain to calculate energy loss per cycle and compare elasticity and toughness among groups.

1.2.7 Hydrophilicity Assessment To investigate collagen' s effect on hydrophilicity, films were prepared using optimal parameters. Contact angles were measured using a DSA3D system with a novel model for determining effective contact angle stability on microstructured surfaces. Five replicate measurements were performed for each of the PCL, PCL–Col, and PCL–Col–bFGF groups.

1.2.8 bFGF Release Kinetics During electrospinning, bFGF and collagen were encapsulated within the PCL core solution. Release studies were conducted in both pure water and PBS buffer to simulate physiological conditions. Five-centimeter segments of bFGF-loaded sutures were placed in 1.5 mL centrifuge tubes with 300 L of release medium and incubated at 37°C. Release medium was replaced at 6, 12, 24, 48, 72, 96, 120, 144, and 168 hours. Collected bFGF was quantified by ELISA using a SpectraMax M2e microplate reader at 450 nm, with concentrations determined from standard curves to calculate cumulative release percentages.

1.2.9 Statistical Analysis Data were analyzed using GraphPad Prism software and expressed as mean ± standard deviation. One-way ANOVA was used for inter-group comparisons, with $P < 0.05$ considered statistically significant.

Results

2.1 Effects of Component Ratios on Composite Polymer Systems

bFGF stock solution exhibits poor solubility in hexafluoroisopropanol and tends to precipitate. Increasing water content improved bFGF solubility. As shown in Table 1, varying the hexafluoroisopropanol/water ratio revealed that in the absence of water, significant bFGF precipitation occurred, preventing homogeneous mixing. While 0.25 mL water yielded better mechanical performance than 0.5 mL, excessive water adversely affected fiber formation due to hexafluoroisopropanol' s superior polarity for electrospinning. Evaluation of PCL content demonstrated that 0.45 g provided insufficient mechanical strength, while 0.68

g markedly improved mechanical properties. However, further increasing PCL to 0.91 g resulted in excessive viscosity, poor mixing, and spinning difficulties. These findings indicate that while increasing PCL concentration enhances mechanical performance, an optimal range exists beyond which uniformity and spinnability are compromised.

Comprehensive evaluation identified Group 5 as the optimal formulation, producing the most uniform polymer system and highest mechanical strength sutures for subsequent studies.

2.2 Influence of Spinning Parameters on Composite Nanofiber Sutures

Solution flow rate critically affects material transfer and jet velocity. As shown in Table 2, flow rates of 1.08 mm/h, 2.16 mm/h, and 3.24 mm/h were tested. The 2.16 mm/h rate enabled stable polymer flow through the spinneret, producing the most uniform sutures. At 1.08 mm/h, insufficient solution supply prevented stable jet formation, while 3.24 mm/h produced a diffuse fiber web rather than concentrated jets.

Voltage also influences jet dynamics. Comparison of 6 kV, 12 kV, and 18 kV revealed that 6 kV provided insufficient drawing force, resulting in droplet formation and unstable, dispersed jets with poor mechanical properties. At 12 kV, stable jets formed with significantly improved mechanical performance. However, 18 kV caused excessive voltage, inadequate solvent evaporation, and droplet formation, preventing high-quality fiber production.

Optimal conditions were determined to be a flow rate of 2.16 mm/h and voltage of 12 kV (Group 5), producing sutures with superior uniformity and mechanical properties.

2.3 Synthesis and Characterization of Drug-Loaded Sutures

Using the optimal formulation, all three polymer solutions appeared as colorless, viscous liquids (Figure 2a). Electrospinning under optimal parameters produced uniform nanofibers with intact linear structures (Figure 2b). Scanning electron microscopy revealed that both PCL–Col and PCL–Col–bFGF solutions generated smooth, uniform nanofiber bundles oriented unidirectionally into dense, well-aligned linear structures. The addition of collagen and bFGF did not alter surface morphology compared to pure PCL, confirming that drug-loaded sutures maintained intact fibrous architecture composed of uniform nanofiber bundles (Figure 2c). Insoluble bFGF particles encapsulated within collagen were visible as scattered white granules on the suture surface.

2.4 Single Tensile Testing for Toughness Evaluation

PCL sutures inherently possess excellent mechanical properties. Single tensile tests were performed to assess mechanical changes after drug loading. All su-

ture groups exhibited strain-dependent stress increases, with no significant differences in mechanical performance among PCL, PCL-Col, and PCL-Col-bFGF groups ($P > 0.05$). Failure occurred at 65-75% strain with stress reaching approximately 0.0025 MPa (Figure 3). Analysis of elastic modulus, maximum tensile stress, and failure strain revealed similar values across groups: elastic modulus (5-10% strain) ~0.015 MPa, maximum tensile stress ~0.0025 MPa, and failure strain at 65-75% ($P > 0.05$). These results demonstrate that collagen and bFGF incorporation does not compromise mechanical strength or maximum tensile stress, preserving suture toughness while enabling drug release.

2.5 Cyclic Tensile Testing for Energy Loss

Three cyclic tensile tests were performed without suture failure. All groups exhibited mechanical energy loss that increased with cycle number. In the first cycle at 20% strain, maximum stress reached 0.0008 ± 0.0004 MPa; at 40% strain in the second cycle, 0.0012 ± 0.0003 MPa; and at 60% strain in the third cycle, 0.0015 ± 0.0004 MPa. Energy loss calculations yielded 0.8102 ± 0.0025 J/m³ in the first cycle, 2.1606 ± 0.0024 J/m³ in the second, and 3.0616 ± 0.0077 J/m³ in the third cycle (Table 4), with no significant differences among groups ($P > 0.05$). This confirms that bFGF loading and collagen addition do not alter post-stretching energy loss.

2.6 Hydrophilicity Assessment

Contact angle measurements evaluated surface hydrophilicity. Angles $< 90°$ indicate hydrophilic surfaces, with smaller angles representing greater hydrophilicity. Compared to PCL films, PCL-Col and PCL-Col-bFGF films showed significantly reduced contact angles (Figure 5), demonstrating that collagen incorporation effectively enhances polymer hydrophilicity.

2.7 Drug Release Kinetics from Surgical Sutures

ELISA quantification over 7 days demonstrated an initial burst release within 24 hours, followed by sustained, stable release through day 7 (Table 5). The PCL-Col composite structure prolonged release kinetics, with continued slow release observed beyond 7 days. Release studies in PBS buffer versus pure water showed no significant differences, confirming effective bFGF release under physiological conditions. Collagen' s hydrophilicity facilitates water absorption and bFGF diffusion, while the nanofiber' s three-dimensional porous structure creates a rate-limiting diffusion pathway that delays release. The sustained release profile, achieved through gradual degradation of PCL and collagen, overcomes bFGF' s aqueous instability and short half-life, establishing a foundation for in vivo applications.

Conclusion

This study successfully fabricated a novel PCL–Col–bFGF surgical suture composite using electrospinning technology with collagen-mediated physical encapsulation of bFGF. Optimization of material composition and electrospinning parameters yielded sutures with superior uniformity and mechanical performance. Mechanical testing confirmed that collagen and bFGF incorporation preserves excellent suture toughness while enabling sustained drug release. The nanofiber carrier system, combining collagen encapsulation and three-dimensional porous architecture, provides substantial drug loading capacity and prolonged release kinetics, addressing the limitations of bFGF aqueous instability and short duration of action. These findings establish a foundation for advancing bFGF-loaded surgical sutures toward clinical applications in tissue regeneration and wound healing.

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