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The Effect of Electrospinning Parameters on the Final Structure of the Electrospun PCL Fibers

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ABSTRACT

In the last decade, regenerating damaged tissues has been a primary focus in tissue engineering research. An ideal wound dressing can be produced from synthetic polymers, such as polycaprolactone (PCL), via electrospinning. The processing variables significantly affect fiber morphology and characteristics, including fiber size and porosity. These factors directly influence the properties of wound dressings. This study investigated how the electrospinning process variables—specifically needle-to-plate distance, flow rate, and applied voltage—affect the diameter and morphology of nanofibers. By adjusting these parameters, researchers can optimize the performance of this technique and enhance the properties of the resulting fibers. Initially, PCL solutions with varying compositions and concentrations were prepared. The results indicated that increasing the voltage from 12 kV to 16 kV across three samples resulted in a decrease in the nanofiber diameter from 205.28 ± 50 nm to 175.74 ± 41 nm. Conversely, changing the flow rate from 0.4 to 0.6 ml/h in two samples increased the average fiber diameter from 210.66 ± 43 nm to 223.18 ± 44 nm. Additionally, increasing the needle-to-plate distance also led to a reduction in fiber diameter. Scanning electron microscopy (SEM) images revealed that interconnected, thin, bead-free nanofibers could be achieved at high voltages, low flow rates, and longer distances. However, at voltages above 18 kV and distances greater than 18 cm, bead formation in the nanofiber structure became inevitable. Furthermore, the polymer solution containing a certain amount of salt exhibited high conductivity, which resulted in fiber breakage.

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1. INTRODUCTION

Tissue engineering represents a novel therapeutic approach for regenerating damaged tissues in living organisms (Siddiqui et al., 2021). This advanced field aims to develop innovative regeneration treatments by repairing and restoring various types of tissues, including skin, tendons, bone, cartilage, nerve tissue, maxillofacial tissue, and blood vessels. By combining cells, biomaterials, and biochemical factors, tissue engineering significantly enhances the quality of life for patients (Azimi et al., 2014; Ghaffarian et al., 2015; Siddiqui et al., 2021). Skin replacement stands out as one of the earliest successful applications of tissue regeneration,

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enabling the regrowth of damaged skin (Moniri Javadhesari, 2022).

The skin serves a crucial role in protecting the body from bacteria and regulating its physiological functions. Sudden contact with hard and rough foreign objects can damage the skin, necessitating immediate tissue regeneration to prevent pathogenic factors and adverse effects (Joseph et al., 2019). In cases where wound healing is compromised or conventional therapeutic methods are ineffective, appropriate skin substitutes must be available. These healing procedures aim to improve wounds either temporarily or permanently (Dias et al., 2018; Vyas & Vasconez, 2014). Alternative wound dressings, characterized by specific properties, are designed to accelerate the healing process by conforming to the wound's shape and maintaining a moist interface. Additionally, these dressings should absorb exudate without supporting bacterial growth and prevent bleeding and fluid leakage. Furthermore, they must protect the wound and surrounding tissues, promote healing, and be easy to remove with minimal trauma to the injury injury (Dias et al., 2017; Dickinson & Gerecht, 2016; Dong et al., 2020; Ferreira et al., 2021; Vig et al., 2017; Wang et al., 2011).

Recent investigations have explored both synthetic and natural polymers as functional skin substitutes (Dwivedi et al., 2019). These polymers can perform a variety of skin functions and are often in direct contact with cells and tissues (Joseph et al., 2019). Key advantages of polymer biomaterials include biocompatibility, suitable mechanical and physical properties, and good processability (Liu et al., 2012). Biodegradable polymers have gained significant attention for medical applications due to their rapid degradation rates (Dong et al., 2020).

A prominent class of biodegradable polymers includes polyesters such as polycaprolactone (PCL), polyglycolic acid (PGA), and polylactic acid (PLA). PCL, in particular, is a biocompatible polymer that has garnered extensive interest in tissue engineering (Joseph et al., 2019). With a melting point higher than normal body temperature (59–64 °C) and a glass transition temperature below 60 °C, PCL exhibits notable mechanical properties, including high toughness, at physiological conditions. As a non-toxic and tissue-compatible material, PCL is utilized in absorbable sutures, scaffolds, and drug delivery systems. However, its degradation under physiological conditions is relatively slow, occurring over a period of 2–3 years (Abrisham et al., 2020; Dwivedi et al., 2019; Gil-Castell et al., 2019; Linh et al., 2022; Loh & Choong 2013; Stratton et al. 2016).

Numerous techniques have been established for synthetic polymer scaffolds, with novel nanotechnology methods continually emerging. Among these, electrospinning is one of the most widely used techniques for producing wound dressings and scaffolds (Elkhouly et al., 2021). Compared to standard bandages, electrospun wound dressings exhibit unique characteristics, such as enhanced bleeding control, increased wound fluid absorption, and improved adaptability to the wound (Dias et al., 2017).

Electrospinning creates nano- or microfibers by applying electrostatic forces. By reducing fiber diameter from micrometers to nanometers, this technique results in a high surface-to-mass ratio, flexibility in surface functionalities, and superior mechanical performance (Abdollahi, & Bakhsheshi-Rad, 2018). Electrospun fibers are typically collected randomly, yielding a high surface area (Joseph et al., 2019; Yang et al., 2017). The process requires an upper voltage source, a collector plate, and a syringe pump. Initially, high voltage is applied to a syringe containing the polymer solution, held by surface tension at its tip. The electrical field generates mutual charge repulsion that counters the surface tension, leading to jet formation (Ginestra et al., 2016). Figure 1 illustrates the electrospinning process.

As the solvent evaporates, the fibers are deposited onto the collector plate after jet formation. The resulting fibers can exhibit a range of morphologies and pore structures, influenced by various parameters, including solution viscosity, conductivity, and process variables like applied voltage (Joseph et al., 2019). Therefore, precise control of these factors is essential for obtaining fibers with desirable morphological and biological characteristics.

Electrospinning enables the production of interconnected nanofibers, resembling the structure of the extracellular matrix (Elkhouly et al., 2021; Gil-Castell et al., 2019; Jun et al., 2018). This similarity enhances cellular function. Electrospun PCL layers can be employed as cell-free wound dressings or as cell-assisted skin substitutes. Significant research has focused on how different variables affect the morphology of electrospun PCL fibers. Consequently, researchers have developed predictive models for determining the final diameter of these fibers, as suggested in Equation 1 (Baji et al., 2010)

$$D = \left[\gamma\varepsilon\frac{Q^2}{I^2}\left(\frac{2}{\pi\left(2\left(ln\frac{l}{d}-3\right)\right)}\right)\right]^{\frac{1}{3}} \tag{1}$$

where ε is the dielectric constant, Q is the flow rate, I is the applied current, l is the initial length of the jet, and d is the needle diameter. A common morphology reported by several researchers is a combination of fibers and beads. Yet, the reason for bead formation is unknown. According to the results, the main factors controlling this behavior are the solution's viscoelasticity and surface tension.

Beachley et al. investigated the impact of various processing parameters on the morphology of polycaprolactone (PCL) fibers (Beachley & Wen, 2008).

Applied voltage plays a crucial role in determining fiber structure; as voltage increases, both fiber length and diameter tend to decrease due to heightened tension on the surface of the electrospinning jet. This finding contrasts with the study by Dustgani, which indicated that higher voltage could result in increased solution injection from the syringe, subsequently leading to larger fiber diameters (Doustgani, 2015). Moreover, elevated voltage has been observed to influence fiber morphology by reforming Taylor Cone jets and facilitating bead formation within the electrospun fibers (Chinnappan et al., 2022). Conversely, another study reported that a decrease in voltage could also lead to bead formation (Jarusuwannapoom et al., 2004).

The concentration of the polymer solution is another critical factor affecting fiber spinning ability. Insufficient polymer concentrations often result in the breakdown of electrospun fibers, preventing proper formation. Conversely, an increase in polymer concentration typically leads to an increase in fiber diameter (Chinnappan et al., 2022; Liverani & Boccaccini, 2016). Additionally, the incorporation of ionic salts, such as NaCl and KH_2PO_4, can enhance the electrical conductivity of polymer solutions, resulting in the formation of nanofibers with smaller diameters (Chinnappan et al., 2022).

Flow rate is a vital parameter as well, as it influences the properties of the newly synthesized polymer solution passing through the syringe. A high flow rate tends to produce fibers that contain beads and exhibit larger diameters. Furthermore, adjusting the needle-to-plate distance can significantly alter fiber structure; shorter distances can prevent fibers from solidifying before collection, while excessively long distances may induce bead formation (Baji et al., 2010; Ginestra et al., 2016; Liverani & Boccaccini, 2016).

This study aims to explore the effects of various processing parameters on the morphology of electrospun PCL fibers. As highlighted, the electrospinning process is significantly influenced by these variables, which ultimately affect the chemical composition, fiber size, porosity, and overall morphological characteristics essential for scaffold performance in tissue engineering. By examining these attributes, researchers can enhance the efficacy of the electrospinning technique. Therefore, this study investigates how different variables impact the morphology of electrospun fibers and seeks to identify optimal parameters for producing the most desirable fiber characteristic.

2. MATERIALS AND METHODS

2. 1. Materials

This study utilized polycaprolactone (PCL) sourced from the Solar Bio brand, characterized by an average molecular weight of 80,000 g/mol, as a natural biopolymer. To enhance the conductivity of the polymer solution and prevent blockage in the syringe, dichloromethane (DCM) and dimethylformamide (DMF) were employed as solvents. DCM, with a concentration exceeding 99% and a molecular weight of 84.3 g/mol, and DMF, of Extra Pure Grade with a concentration greater than 99.5% and a molecular weight of 73.09 g/mol (DrMojallali brand), were both selected for their efficacy in improving solution performance.

2.2. Preparation of Solution

Three types of polymer solutions with varying concentrations and compositions were prepared. Solution (1) was created by dissolving 1 g of polycaprolactone (PCL) in 8 ml of dichloromethane (DCM) and 1 ml of dimethylformamide (DMF). Solution (2) comprised 1.5 g of PCL in 8 ml of DCM and 1 ml of DMF. Solution (3) was identical to Solution (2), but included an additional 0.01 g of lithium chloride (LiCl). Initially, DMF and DCM were mixed, after which PCL was incorporated into the solution. The resulting polymer mixture was stirred for 12 hours to ensure complete dissolution.

2.3. Electrospinning

For this study, the ES1000 device from Nanoscale Technologies was utilized. The PCL solution was placed in a 5 ml syringe fitted with a 22-gauge needle. The solution flow rate was adjusted between 0.1 and 0.3 ml/h. Upon applying voltage, a fluid jet was ejected from the needle. Each experiment lasted for 5 minutes per sample, after which the samples were analyzed using a Scanning Electron Microscope (SEM). Experiments were conducted under various conditions to examine the effects of several variables on the morphology of the PCL fibers. Specifically, the influence of applied voltage, needle-to-plate distance, flow rate, and the presence of salt in the polymer solution was investigated. The distance was measured from the tip of the needle to the top of the collecting plate. Table 1 summarizes the parameters used for each sample.

2.4. Morphological examination

The results were evaluated to assess how variations in processing parameters affect the diameter and morphology of the nanofibers. For this purpose, Scanning Electron Microscopy (SEM) images were analyzed to measure the diameter of both the fibers and beads. The average diameter of 50 fibers and the maximum average diameter of 45 beads were calculated using ImageJ software.

3. RESULTS

3.1. Applied Voltage

The applied voltage is a critical parameter influencing the morphology and diameter of the fibers. Generally, a voltage exceeding 6 kV is necessary to generate polymer solution jets from Taylor cones (Ifegwu & Anyakora, 2018). Figure 2 displays the SEM images of samples S6, S7, and S8, which were subjected to different voltages while maintaining the same solution. The needle-to-plate distance and flow rate were fixed at 13 cm and 0.6 ml/h, respectively. Sample S6, with an applied voltage of 12 kV, exhibited an average fiber diameter of 225.28 ± 88 nm. Conversely, S8 and S7, subjected to 14 kV and 16 kV, yielded average diameters of 205.28 ± 50 nm and 175.74 ± 41 nm, respectively.

A reduction in fiber diameter correlated with an increase in applied voltage. To enhance the analysis, additional sets of samples were tested: S9 and S10 received voltages of 16 kV and 12 kV, while maintaining a needle-to-plate distance of 13 cm and a flow rate of 1 ml/h. Their average fiber diameters were recorded as 194.4 ± 41 nm and 231.1 ± 76 nm, respectively. For S12 and S13, voltages of 18 kV and 17 kV were applied, with a flow rate of 0.4 ml/h and a needle-to-plate distance of 20 cm, resulting in average diameters of 385.6 ± 149 nm and 424.6 ± 125 nm. Further, S16 and S17 were subjected to 19 kV and 18 kV, producing average fiber diameters of 335.1 ± 181 nm and 423.28 ± 130 nm, respectively. In S18 and S19, voltages of 20 kV and 19 kV resulted in average diameters of 385.18 ± 183 nm and 506.62 ± 149 nm. Overall, fiber diameter consistently decreased with increasing voltage, as illustrated in Figure 3. These findings align with results reported by Beachley et al., which noted a reduction in diameter as voltage increased (Beachley & Wen, 2008). The increase in applied voltage enhances the electric field between the needle and the collector plate, leading to elevated surface tension due to heightened coulombic forces. Consequently, the nanofiber diameter decreases with increased voltage (Can-Herrera et al., 2021).

As depicted in SEM images in Figures 2 and 4, the morphology of the nanofibers consists of both fibers and beads. Figure 5 illustrates how increasing voltage affects fiber morphology; specifically, the average diameter of beads in the fibers diminishes with higher voltage. Increased voltage can eliminate the beaded structure within the nanofibers, consistent with observations by Jarusuwannapoom et al. (Jarusuwannapoom et al., 2004). Bead formation may result from viscosity-related forces and surface tension, as the number of charge carriers in the jet rises with increasing electrostatic fields. This increase leads to stronger electrostatic and coulombic forces, which in turn elevate surface tension and enhance repulsion between the fibers, reducing the likelihood of bead formation.

3.2. Flow Rate

The flow rate significantly influences the morphology and diameter of the fibers by controlling the volume of the electrospinning solution. In samples S4 and S5, where the voltage was set at 12 kV and the needle-to-plate distance at 12 cm, changing the flow rate from 0.4 to 0.6 ml/h resulted in an increase in average fiber diameter from 210.66 ± 43 nm to 223.18 ± 44 nm.

When the flow rate was increased under a voltage of 16 kV and a needle-to-plate distance of 13 cm, the average fiber diameters for samples S7 and S9, with flow rates of 0.6 and 1 ml/h, were 175.74±41 nm and 194.4±41 nm, respectively. Further testing with additional sample groups (S6 and S10) showed that increasing the flow rate from 0.6 to 1 ml/h led to fiber diameters of 225.28 ± 88 nm and 232.4±74 nm. Similarly, for samples S16 and S19, an increase in flow rate from 0.6 to 0.8 ml/h resulted in average fiber diameters of 335.1 ± 118 nm and 506.62 ± 142 nm, respectively. Figure 6 illustrates the impact of flow rate on fiber diameter.

Previous research has indicated a direct correlation between fiber diameter and flow rate (Zargham et al., 2012). At higher flow rates, a larger volume of solution exits the needle, requiring more time for solvent evaporation. If the flow rate is too high, there may not be enough time for the solvent to evaporate completely, causing the remaining solvent to either draw the fibers together or create droplets at the needle tip. This results in thicker fibers often exhibiting a beaded structure. As shown in Figure 7, samples contain a mixture of fibers and beads. Figure 8 further highlights how lower flow rates yield fibers with smaller beads. Additionally, insufficient time for solvent evaporation can lead to other defects, such as branched fibers.

3.3. Needle-to-plate distance

The needle-to-plate distance is another critical variable in the electrospinning process. For samples S4 and S3, where the voltage was set at 12 kV and the flow rate at 0.4 ml/h, an increase in distance from 12 to 15 cm resulted in a decrease in fiber diameter, with average diameters reported at 210.66 ± 43 nm and 181.62±37 nm, respectively. Similarly, in samples S15 and S13, increasing the distance from 18 to 20 cm led to a reduction in average fiber diameter from 457.5 ±140 nm to 424.6±130 nm. Previous studies have also demonstrated a decrease in fiber diameter with increased needle-to-plate distance (Ginestra et al., 2016).

A longer distance allows the polymer solution more time for solvent evaporation, which contributes to a reduction in fiber diameter. However, contrasting results were observed in samples S6 and S10; as the distance increased from 11 to 13 cm, fiber diameters were reported at 201.92±35 nm and 225.28±38 nm, respectively. Yogendra Pratap et al. (Singh et al., 2020) noted that while increasing the needle-to-plate distance initially reduces fiber diameter due to extended solvent evaporation time, a further increase can lead to larger diameters because of a diminished electrostatic field. Figure 9 illustrates the effect of varying the needle-to-plate distance on the diameter of electrospun fibers. SEM images in Figure 10 reveal a beaded structure in the electrospun fibers. A short needle-to-plate distance may hinder complete solvent evaporation, resulting in non-dried fibers being deposited on the collector plate. If solvent remains in the final solution, the fibers can merge or form droplets at the needle tip. Figure 11 shows that the diameter of the beads decreases as the distance increases, with a significant reduction observed for samples S3 and S4.

3.4. Solution conductivity

The conductivity of the polymer solution is influenced by the choice of solvents, salts, and polymers. An increase in the solution's electrical conductivity significantly correlates with a decrease in the diameter of electrospun nanofibers. This phenomenon occurs because the repulsive forces between the charges on the surface of the electrospinning jet enhance the stretching of the solution. As the conductivity of the solution rises, the charge on the polymer jet increases, leading to a reduction in fiber diameter. Additionally, incorporating small quantities of salt compounds, such as NaCl, into the polymer solution can help prevent the formation of beaded fibers, resulting in more uniform structures. However, achieving a high solution conductivity can complicate the electrospinning process, even at elevated voltages (Jarusuwannapoom et al., 2004).

In this study, samples S20 and S21 were electrospun with flow rates of 0.6 ml/h and 0.5 ml/h, voltages of 11.5 kV and 16 kV, and needle-to-plate distances of 18 cm and 16 cm, respectively. Solution 4, which contained a small amount of LiCl salt, produced fragile and bead-free fibers, as confirmed by SEM images, owing to the high conductivity of the solution. Nevertheless, while increased conductivity can enhance fiber uniformity, it also poses challenges in fiber collection. Figure 12 displays SEM images of S20 and S21, illustrating fractured and separated fibers due to the high conductivity of the solution.

4. DISCUSSION

Studies have indicated that multiple variables influence the morphology of scaffolds in the electrospinning process. This study demonstrated that increasing the voltage reduces the diameter of electrospun fibers, aligning with previous findings. However, some researchers argue that higher applied voltage can lead to an increase in fiber diameter due to reduced solvent evaporation time (Dickinson & Gerecht, 2016). Notably, smaller beads were observed within the fiber structure at elevated voltages. The effects of other variables—such as flow rate, needle-to-plate distance, and solution conductivity—were also examined.

SEM images from samples S12 to S21 revealed bead-free fibers. The high conductivity of the solution, resulting from the addition of LiCl salt in samples S20 and S21, facilitated the formation of these bead-free fibers. Table 1 summarizes the processing conditions for each sample. Samples S12 to S19 exhibited higher applied voltages and longer needle-to-plate distances, with beaded structures observed at voltages below 18 kV. Bead-free fibers were predominantly found in samples with lower flow rates. The effect of distance on fiber morphology was also investigated, revealing that the presence of beads is inevitable at distances less than 18 cm. Fibers characterized by thicker diameters and a bead-free structure were found to be superior.

As highlighted, understanding the simultaneous effects of various parameters is crucial for identifying optimal conditions. For instance, while increasing the distance generally reduces nanofiber diameter, an optimal distance can further decrease fiber diameter (Singh et al., 2020). It is essential to recognize that each parameter has a specific optimal value.

In summary, several processing variables significantly impact the morphology of nanofibers in the electrospinning process. Achieving a desirable structure of electrospun fibers requires careful control of these parameters, which is vital for applications in healthcare. The use of polymers in wound dressings has garnered considerable attention, with polycaprolactone (PCL) emerging as a preferred choice due to its remarkable properties. However, its hydrophobic nature can result in poor cellular responses. These findings indicate that adjusting electrospinning parameters can facilitate the creation of an ideal fiber structure.

5. CONCLUSION

PCL is highly regarded in medical applications due to its exceptional properties. Electrospinning PCL can create an ideal wound dressing with excellent characteristics. The processing conditions significantly impact the structure of electrospun fibers, and this research aims to develop interconnected, bead-free PCL fibers. By accurately and concurrently controlling processing variables, it is possible to achieve such a desired structure.

The results indicated that smooth, bead-free fibers can be produced at low flow rates, high voltages, and longer distances. However, excessive conductivity in the solution can lead to fiber breakage. Additionally, the semi-crystalline and hydrophobic nature of PCL results in slow degradation (2 to 4 years), which can limit its application as a wound dressing. Therefore, further research on the electrospinning process of PCL is necessary to enhance its hydrophobicity.

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