HYBRID ELECTROSPINNING APPROACHES FOR TUBULAR NANOFIBER SCAFFOLD FABRICATION

Josef BULIR[1], Ondrej BATKA[1]

[1]*Technical University of Liberec, Liberec, Czech Republic, EU, josef.bulir@tul.cz*

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Abstract

This work focuses on fabricating tubular nanofiber scaffolds using DC and AC electrospinning combined with electrohydrodynamic (EHD) technology. Experiments were performed with a rotating collector to evaluate the influence of applied high voltage, needle-to-collector distance, and polymer solution dosage on process stability and fibre deposition. Suitable processing parameters were identified for each technique, and their mutual compatibility was demonstrated. For AC electrospinning, the needle-to-collector distance was shown to have a critical impact on fibre deposition, resulting in the formation of two distinct structural types. These findings highlight the potential of parameter tuning to precisely control scaffold structure, supporting their application in tissue engineering and related biomedical fields.

Keywords: Scaffolds, AC electrospinning, DC electrospinning, EHD printing

1. INTRODUCTION

Nanofiber scaffolds produced by electrospinning represent a modern approach to fabricating structures with controlled nanoscale features, applicable in tissue engineering and other biomedical fields. This method employs a high-voltage electric field to stretch a polymer solution into fine fibres, which are subsequently deposited onto a collector to form spatially organised layers. The resulting scaffold properties, such as porosity, fibre density, and orientation, are strongly influenced by process parameters including applied voltage, solution dosage, needle-to-collector distance, and the type of collector used.

For the preparation of tubular scaffolds, relevant, for example, as vascular graft models, a rotating mandrel was employed to enable cylindrical fibre deposition. The experiments focused on DC [1,2] and AC electrospinning [3, 4], as well as EHD printing technology [5, 6], with particular attention to the effects of key parameters on process stability and fibre continuity. By optimisation of these conditions, the uniform fibrous layers were established, which create the foundation for functional scaffolds with well-defined geometry. The findings will lead to the development of an open-source device for the production of combined tubular nanofibrous structures.

2. EXPERIMENTAL SETUP

A rotating drum collector (1), mounted on a stepper motor shaft and grounded, was used for the fabrication of tubular structures. A needle electrode (2) was applied for electrospinning, with the polymer solution supplied by a syringe pump (3). The experimental setup is shown in **Figure 1**. A series of experiments was carried out to examine the influence of several parameters on the spinning process. The effects of applied voltage, needle-to-collector distance, and solution dosage on fibre formation were systematically investigated.

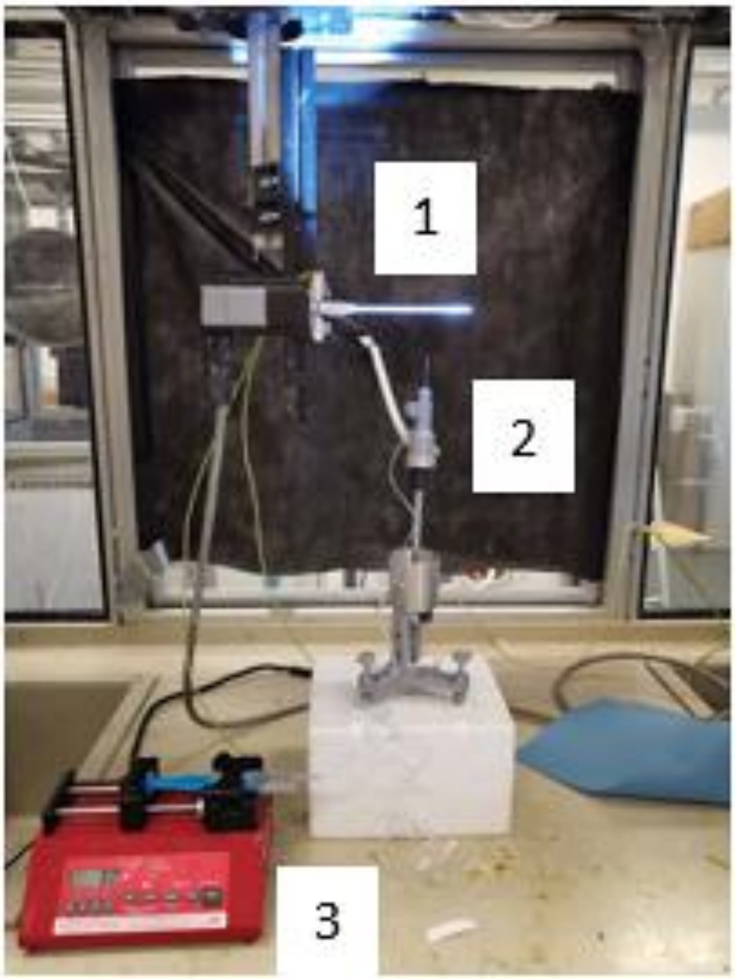

Figure 1 Experimental setup, drum collector (1), needle (2), syringe pump (3)

3. DC ELECTROSPINNING

The initial experiments focused on optimizing the solution dosage and geometric parameters of the DC electrospinning process. A rotating drum collector with a radius of 6 mm was used. The needle-to-collector distance was initially set to 5 cm, the collector rotation speed to 3 rpm, and the applied voltage to 5 kV. In the first experiment, a dosage of 130 µL/h was applied; however, this value proved insufficient, as the needle dried out and stable fibre formation could not be achieved. Increasing the dosage to 150 µL/h resulted in stable and long-term sustainable electrospinning, indicating that this value represents the minimum dosage required for continuous fibre formation under the given conditions. In subsequent experiments, the needle-to-collector distance was gradually reduced. When the distance reached 0.5 cm, isolated fibres were deposited onto the drum surface rather than forming a continuous fibrous layer. Under these conditions, a higher dosage of 250 µL/h was found to be suitable, indicating that short working distances require increased material flow to maintain process stability. These parameters were identified as appropriate for EHD printing rather than conventional electrospinning. **Table 1** summarizes all technological parameters and observed outcomes of the DC electrospinning experiments, including dosage, needle-to-collector distance, voltage, and process stability. From the results presented in **Table 1**, the most efficient conditions for stable DC electrospinning were identified at a distance of 5 cm and a dosage of 150 µL/h, which were therefore selected as reference parameters for further device development. **Figure 2** shows the data from experiment no. 2, while the results of the remaining experiments are summarized in **Table 1**.

Figure 2 Stable fibre formation using the DC electrospinning method

4. AC ELECTROSPINNING

The AC electrospinning experiments were conducted at a fixed frequency of 50 Hz using a rotating drum collector with a radius of 6 mm. The initial needle-to-collector distance was set to 4 cm, the collector rotation speed to 3 rpm, and the applied voltage to 1.77 kV_{RMS}. Under these conditions, the influence of solution dosage on fibre formation was investigated. In the first experiment, a dosage of 250 µL/h was applied; however, stable fibre formation was not achieved. The dosage was therefore gradually increased. At 3250 µL/h, fibre spinning occurred but was unstable over time, whereas a dosage of 6250 µL/h resulted in stable and reproducible fibre deposition. This indicates that AC electrospinning requires significantly higher solution throughput compared to DC electrospinning to achieve stable operation. After establishing a suitable dosage, the needle-to-collector distance was reduced. In experiment no. 4, the distance was decreased to 3 cm, and the voltage was increased to 2.47 kV_{RMS} to maintain the electric field strength. Further reduction of the distance to 2 cm led to unstable and strongly fluctuating fibre deposition, indicating that the collector was already too close to the needle. In experiment no. 7, the distance was reduced to 1 cm and the voltage increased to 3.88 kV_{RMS}, which resulted in electrical breakdown between the needle and the collector **(Figure 3c),** defining the lower operational limit of the system. **Table 2** provides a comprehensive overview of the technological parameters and outcomes of all AC electrospinning experiments, including dosage, distance, voltage, and process stability. Based on the results summarized in **Table 2**, the most efficient and stable AC electrospinning conditions were identified at a distance of 4 cm with a dosage of 6250 µL/h, which were selected for subsequent experiments and device design. Records of the individual experiments are shown in **Figure 3**, while the resulting fibrous structures are presented in **Figure 4**. An interesting observation was that at distances of 4 cm and 3 cm, the fibres tended to cluster and wind around the collector due to their inherent elasticity **(Figure 3a)**. These wound fibres are shown in detail in **Figure 4**. At shorter distances, the fibres lacked sufficient space for controlled winding, resulting in deposition over a broader area of the collector surface **(Figure 3b).**

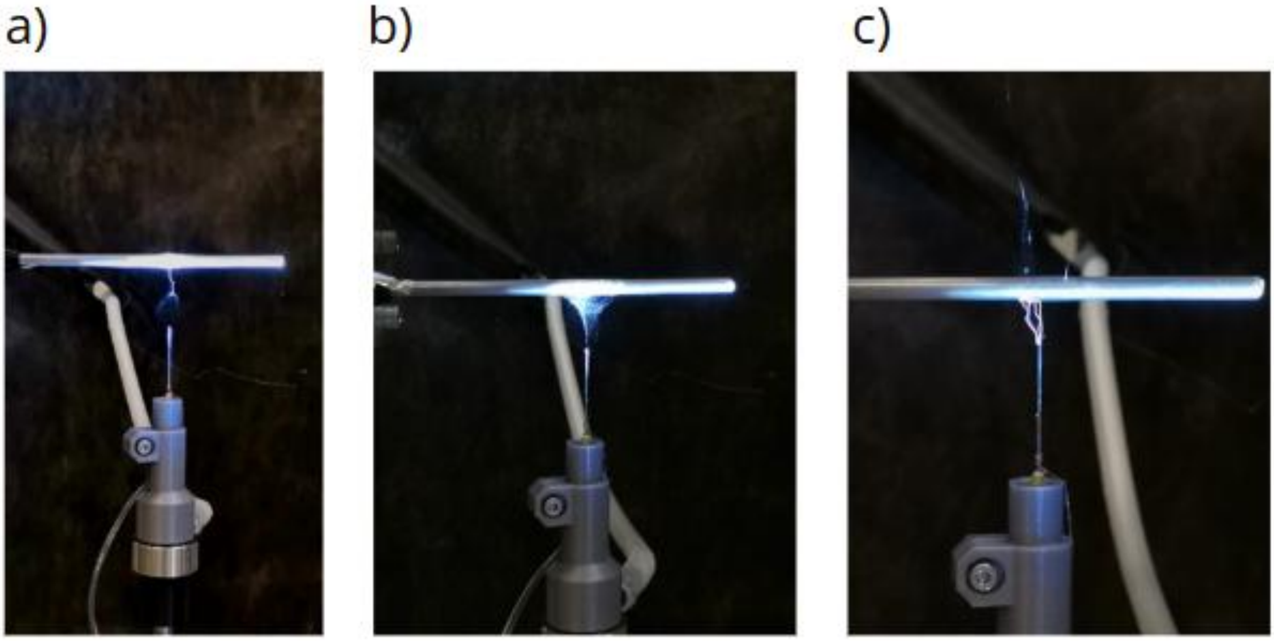

Figure 3 a) experiment no. 4, b) experiment no. 6, c) experiment no. 7

Figure 4 Final product - 1. layer: DC - 2. layer: AC

Table 1 Overview of the DC electrospinning experiments, listing the experiment number, applied voltage, needle-to-drum distance, solution dosage, drum rotation speed, and drum diameter.

DC Electrospinning					
Material: PVB, 10% solution					
Experiment number	Voltage [kV]	Needle-to-drum distance [cm]	Dosage [μl/h]	Drum rotation [rpm]	Drum diameter [mm]
1	5	5	130	3	6
2	5	5	150	3	6
3	5	4	250	3	6
4	3.75	3	250	12	6
5	3.75	2	250	12	6
6	3.75	0.5	250	12	6
7	4.75	4	250	12	3
8	4.25	3	250	12	3
9	4.15	3	250	12	8

Table 2 Overview of the AC electrospinning experiments, listing the experiment number, applied voltage, needle-to-drum distance, solution dosage, drum rotation speed, and drum diameter.

AC Electrospinning					
Material: PVB, 10% solution					
Experiment number	Voltage [kV]	Needle-to-drum distance [cm]	Dosage [μl/h]	Drum rotation [rpm]	Drum diameter [mm]
1	1.77	4	250	12	6
2	1.77	4	3250	12	6
3	1.77	4	6250	12	6
4	1.77	3	6250	12	6
5	2.47	3	6250	12	6
6	1.77	2	6250	12	6
7	3.88	1	6250	12	6
8	1.77	4	6250	12	3
9	1.77	3	6250	12	3
10	1.77	3	6250	12	8

5. CONCLUSION

In conclusion, this work successfully demonstrated the feasibility of combining AC electrospinning, DC electrospinning, and EHD technology. Suitable process parameters for fibre formation using these techniques were determined, and their mutual compatibility was confirmed. Furthermore, it was observed that AC electrospinning enables the formation of two distinct fibre structures depending on the electrode-to-collector distance, highlighting the potential for precise control of scaffold structure through geometrical and electrical conditions. These findings represent an important step toward optimising the fabrication of tubular scaffolds with tailored properties, suitable for applications such as tissue engineering and the development of vascular grafts. The results also confirm the potential of combining different electrospinning approaches to design and manufacture nanofiber systems with defined functionality effectively.

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