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A battery-operated portable handheld electrospinning apparatus

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Received 00th January 20xx,
Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

www.rsc.org/

Electrospinning (e-spinning) still has certain limitations in flexible practicability for its conventional setup which is usually quite bulky and excessively dependent on a plug (electric supply). In this article, we report on a battery-operated electrospinning apparatus (BOEA) based on miniaturization and integration. The new device gets liberated from the conventional heavy power supply, achieves the tight integration of functional parts and can be operated by a single hand for its small volume ($10.5 \times 5 \times 3 \text{ cm}^3$) and light weight (about 120 g). Different polymers such as polyvinylpyrrolidone (PVP), polycaprolactone (PCL), polystyrene (PS), poly (lactic acid) (PLA) and poly (vinylidene fluoride) (PVDF) were electrospun into fibers successfully, which confirms the stable performance and good real-time control capability of the apparatus. These results demonstrate that the BOEA could be potentially applied in many fields, especially in biomedical fields such as skin damage, wound healing and rapid hemostasis, etc.

1 Introduction

At present, nanofibers are considered as the optimal candidates for many important applications such as nano-electronic devices,^{1,2} air filtration and liquid filters,³ protective clothing⁴ and bio-medical materials (e.g. tissue engineering,⁵⁻⁸ wound dressing,⁹⁻¹¹ drug delivery^{12,13} and many others) for several inherent outstanding properties including high surface-to-mass ratio, flexible surface functionality and superior mechanical performance (e.g. stiffness and tensile strength). As an efficient technique for fabricating ultrafine fibers, electrospinning (e-spinning) has attracted much attention for its simple structure, low cost, ambient operating conditions and various raw materials.¹⁴⁻¹⁶

E-spinning is a process caused by the application of an electric force on the surface of a liquid with appropriate viscosity¹⁴. As shown in Fig. 1a, there are three basic elements in a typical e-spinning setup: a high voltage power supply (HVPS), a needle-like spinneret and a grounded metal collector. In the e-spinning process the polymer solution overcomes the surface tension to form charged jet in the presence of a strong electric field, and then the jet undergoes an instability, elongation and splitting process along with the solvent

evaporating and finally solidifies into charged polymer fibers on the collector. Besides the general characteristics of nanofibers, these electrospun ultrafine fibers also have a good one-by-one continuity and uniformity in diameter. Nevertheless, it's far from enough for the extensive commercial applications of electrospun fibers.^{14,15}

Over the last two decades, various modifications have been made on conventional e-spinning setup, especially on the collector and spinneret parts. For example, Yarin et al.¹⁷ fabricated successfully compound core-shell nanofibers by an e-spinning setup with a coaxial needle instead of the common spinneret, which has promising application in the fields of micropackaging and drug delivery.¹⁸⁻²⁰ In order to increase the yield of electrospun nanofibers, multi-needle and needleless e-spinning techniques have been proposed and developed by different research groups.²¹⁻²⁴ Furthermore, Xia et al.²⁵ demonstrated that specially designed collectors could control the alignment and assembly of the electrospun fibers, which is of interest for many potential applications. Chang et al.^{26,27} successfully got the electrospun mats with complex ordered architectures and various patterns via patterned electrodes.

As mentioned above, these modifications on e-spinning setup are mainly focused on realizing the controllability of fiber morphology, structure and assembly, or enhancing production efficiency of nanofibers to an industrial scale. However, there still exist two inextricable problems: (1) excessive reliance on a plug (electric supply) and (2) large bulky device with high cost and difficult transportability. That is to say, these modified e-spinning setups cannot work after a power failure, or in remote area where electricity is not

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accessible, which greatly reduces the practical application scope of e-spinning technique. Several attempts have been made to exploit new power supply system or to miniaturize the e-spinning setup. For example, Pirrie and Coffee²⁸ proposed a battery-powered device aimed at electrospinning and then Smith et al.²⁹ applied power-supply mechanism to the e-spinning with a battery pack and successfully fabricated composite fibers. Recently, a self-powered e-spinning apparatus based on a hand-operated Winshurst generator was reported by Long and collaborators, which makes the e-spinning possible without electric supply.³⁰ However, these devices are mainly limited to theoretical level and few developed technical details. They have remained unexploited and there has few follow-up work on the potential applications of actual uses.

In this paper, a battery-operated portable handheld e-spinning apparatus (BOEA) is reported for the first time, of which two AAA batteries and one high-voltage converter are employed to provide a high voltage instead of the typical HVPS. After a shell encapsulation, this entire apparatus has light weight (about 120 g), small volume ($10.5 \times 5 \times 3 \text{ cm}^3$) and low cost. As the name implies, the BOEA is able to work with the installed battery and no longer dependent on the power plug. It largely relaxes the restricted conditions of e-spinning and hopefully contributes to promote e-spinning technique for practical day-to-day applications such as personal healthcare device, standard medical equipment, and cosmetic tool due to its real time.

Table 1. Polymers to be electrospun in solution form

Polymer	Details	Solvent	Concentration
Polyvinyl pyrrolidone, PVP	Mw = 1300,000 g mol ⁻¹ , ACROS	Anhydrous ethanol	15 wt%
Polycaprolactone, PCL	Mw = 100,000 g mol ⁻¹ , ACROS	Acetone	15 wt%
Polystyrene, PS	Mw = 250,000 g mol ⁻¹ , ACROS	Tetrahydrofuran (THF)	18, 20 wt%
Poly(vinylidene fluoride), PVDF	Mw = 275,000 g mol ⁻¹ , ACROS	Dimethylformamide (DMF): acetone (1:1)	15 wt%
poly(lactic acid), PLA	Mw = 100,000 g mol ⁻¹ , ACROS	Acetone	15 wt%

2 Experimental

2.1 Materials

The materials used for preparation of polymer solutions in this work are presented in Table 1. These polymers were dissolved in corresponding solvents at room temperature under constant stirring. All solutions were kept for half an hour prior e-spinning and all the experiments were carried out at room

temperature with ambient humidity of about 25-50% RH (relative humidity).

2.2 E-spinning apparatus

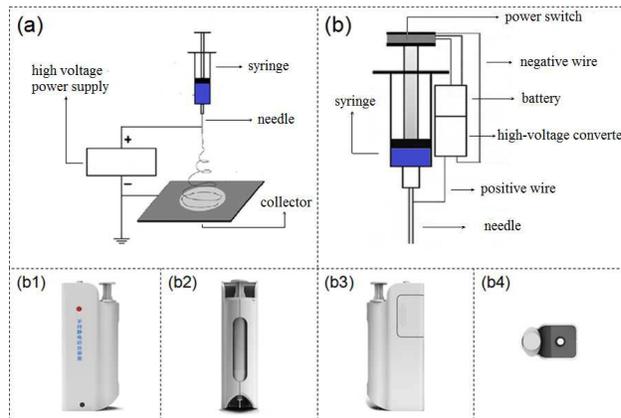


FIG. 1 Schematic diagrams of (a) a conventional e-spinning setup using a high voltage power supply (HVPS) and (b) a battery-operated portable handheld e-spinning apparatus (BOEA, China Patent ZL201210229010.3). The exploded views of the BOEA: (b1) left view (b2) front view (b3) right view (b4) top view (China Patent ZL201230642660.1).

As shown in Fig. 1a and b, there exist many creative changes in the power mode and performance of the new apparatus when compared with the conventional e-spinning setup. Two mercury-free alkaline AAA batteries (LR03, Fujian Nanping Nanfu Battery, China) and one high-voltage converter are employed to provide a high voltage instead of the typical HVPS of 220 V-working voltage. Batteries installed in the BOEA provide a 3 V DC voltage, which is connected to the converter. The voltage (3 V) is amplified up to 10 kV under the action of converter and then is applied to spinning needle by positive wire. This power source can make BOEA continuously work for more than 15 h with a negligible current. The negative electrode of the converter is connected to a conductive metal foil. In this way, the charge can be transferred out through the body (hand) touching the metal foil to avoid charge accumulation. To obtain a good spinning effect, the e-spinning distance between the needle and collector usually in the range of 2 to 10 cm. The stereograms of the apparatus (designed with Autodesk AutoCAD 2012 software) are presented in Fig. 1(b1-b4). The BOEA has a weight of about 120 g and a precise size of 5 cm in length, 3 cm in thickness and 10.5 cm in height, which makes the portable handheld e-spinning setup a reality.

2.3 Characterization

An optical microscope (BX-51, Olympus) and scanning electron microscope (SEM, TM-1000, Hitachi) were used to characterize the morphology of the electrospun fibers. In addition, the e-spinning process was recorded by a high-speed digital video camera (FASTCAM Mini UX100, Photron).

3 Results and discussion

3.1 Performances of the BOEA

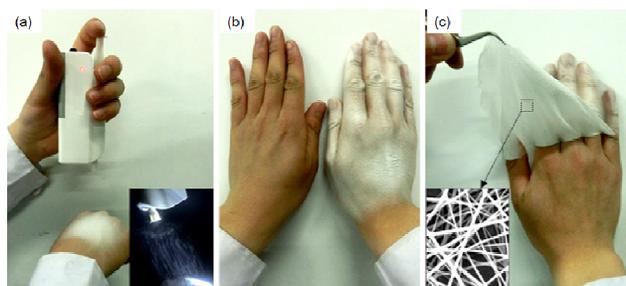


FIG. 2 Optical images showing the process of PLA fibers directly electrospun onto the skin using the BOEA in two minutes. (a) BOEA was operated by one hand and the inset shows the spinning process of the BOEA in dark environment. (b) A PLA fibrous membrane was fabricated on another hand within two minutes. (c) The electrospun fibrous membrane has good flexibility and compactness. The inset is the SEM image of the electrospun fibers.

The combination of battery and high-voltage converter, as a new power supply system, makes the device have low cost, light weight and small volume. Moreover, the e-spinning device is easier and safer to operate. As shown in Fig. 2a, hold the apparatus and press the power switch, and then the device works. Unlike the conventional bench-top device, it is more flexible and portable (a fixed position is not needed). More importantly, this apparatus completely gets rid of the outer power supply and can be used when there is no electric supply. Namely, this portable hand-held device hopefully allows the e-spinning technique to be applied anywhere and anytime. In addition, its working life can be prolonged by battery change.

Fig. 2 shows the direct e-spinning of PLA fibrous membrane onto a hand by the BOEA (The vivid details can be found in supplementary 1). The BOEA works very steadily in spinning process and exhibits a good spinning effect. The inset in Fig. 2a clearly shows the working process of the BOEA in dark environment. It has an exactly similar e-spinning process to the conventional e-spinning setup (The related video can be found in supplementary 2). The polymer solution jet undergoes an elongation and/or split process, which allows the jet to become very long and thin. Meanwhile, the solvent evaporates, leaving behind ultrathin polymer fibers.¹⁴ Moreover, the apparatus has a decent production rate, which can be demonstrated by the PLA fibrous membrane (Fig. 2b) fabricated within two minutes. This PLA membrane has good flexibility and compactness. When using a tweezer to peel off the PLA membrane from the skin, there is no breakage and residual fibers on the skin. Furthermore, the inset in Fig. 2c shows that the electrospun fibers have small diameters ranging from hundreds of nanometers to several micrometers, which has no obvious difference with the conventional electrospun PLA fibers.

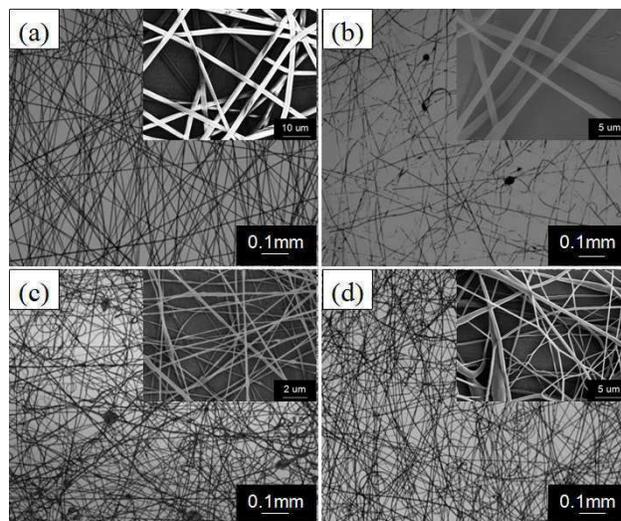


FIG. 3 Optical images of (a) PVP, 20 wt%, 10 cm; (b) PS, 20 wt%, 7 cm; (c) PVDF, 15 wt%, 5 cm; and (d) PCL, 15 wt%, 5 cm fibers, which were fabricated by the BOEA. The inset in each image is SEM image of the corresponding fibers.

3.2 E-spinning materials and parameters of the BOEA

In order to further test the applicability of this apparatus, various polymer materials including PVP, PS, PVDF and PCL have been successfully electrospun into fibers by the BOEA. These polymers are commonly used in e-spinning for biomaterial and non-biomaterial applications. Fig. 3 shows the optical images of the four kinds of fibers fabricated under specified conditions such as solution concentration and spinning distance. These fibers were fabricated smoothly and had good fibrous morphology with even thickness. Through diameter analysis, the fabricated PVP, PS, PVDF and PCL fibers have an average diameter of about 1.8 μm , 1.6 μm , 170 nm and 266 nm, respectively. It is also observed that there are some droplets and fibrous breakages in the optical image of the PS fibers, which may be ascribed to low concentration or short spinning distance.

To study the morphology of electrospun PS fibers, the e-spinning distance, an important influence factor of fiber morphology, was explored by fabricating PS fibers under different distances: 3, 5, 7 and 9 cm, respectively. As shown in Fig. 4a-d, there are some beads in the fibers and the beads gradually disappeared with the spinning distance increasing. Furthermore, Fig. 4e indicates that the average diameter of PS fibers reduces from 1.358 to 1.076 μm with the spinning distance increasing from 3 to 9 cm. It can be ascribed to longer fiber-stretching distance or time in the electric field. All the results in Figs. 3 and 4 demonstrate that the BOEA has strong versatility and can be used to fabricate various polymer micro/nanofibers.

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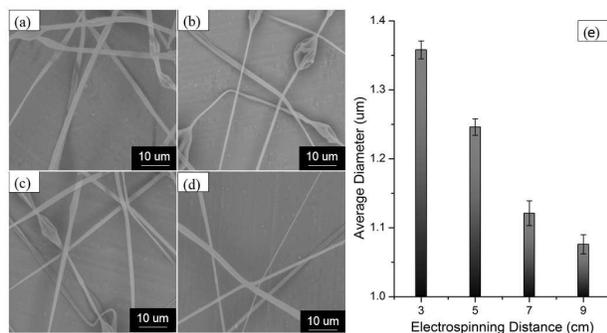


FIG. 4 SEM images of the PS fibers (18 wt%) fabricated under different e-spinning distances: (a) 3 cm, (b) 5 cm, (c) 7 cm, and (d) 9 cm; (e) The relationship between the average diameter and the e-spinning distance.

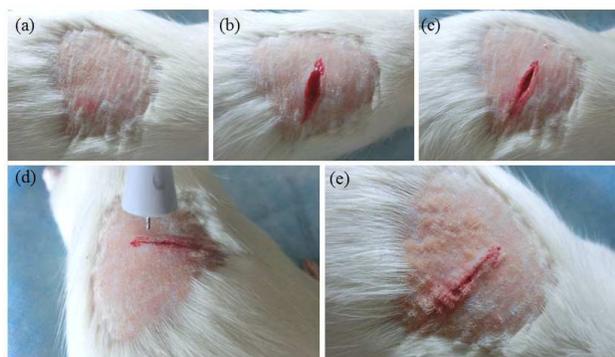


FIG. 5 Diagrams and optical images of depositing medical adhesive fibers onto the wound of a rat by the BOEA to stop bleeding. (a) The rat had a pre-operative skin preparation of operation site. (b) A gash of about 2 cm in length was made and the wound oozed blood. (c) The blood was cleaned by sterile gauze. (d) The gash was then rapidly covered by a layer of medical adhesive using the BOEA. (e) No blood was observed.

3.3 Potential applications of the BOEA

Owing to the aforementioned performances, the BOEA has many potential applications including education, cosmetic and medical treatment. For example, it can serve as a teaching demonstration device or be introduced into the personal family as a medical or makeup tool. Fig. 5 shows an example of applying this handheld apparatus to *in vitro* trauma care. One laboratory rat was selected to cut a gash on its back, and then the BOEA was used to spin medical glue (N-octyl-2-cyanoacrylate) fibers on the gash to stop bleeding in 15 s. The detailed operation processes are shown in Fig. 5a-e. Here, it is noted that Long and his co-workers³¹ performed a rapid hemostatic operation via a modified airflow-directed *in situ* e-

spinning setup. In comparison, the BOEA is portable, easy to operate and can realize real-time secure even in the case of no electric supply.

As mentioned above, the BOEA can fabricate some biopolymer fibers. If these polymers have special medical functions like antibiosis, hemostasis, anti-inflammation and analgesic, this portable BOEA will become more meaningful in outdoor activities, disaster rescue, especially in battlefields. It is expected to greatly save rescue time by using the small BOEA to directly deposit biomedical functional dressing onto the wound.

4 Conclusions

In this work, we present a unique e-spinning apparatus using battery and high-voltage converter instead of the typical HVPS to provide a high voltage. Based on the battery-operated mechanism, the encapsulated apparatus has small volume, light weight, convenient and deft use and can be operated by a hand. Above all, it gets liberated from a plug (electric supply) and makes the e-spinning feasible anywhere and anytime. We demonstrated its applicability for various polymers, stable performance and good real-time control capability. In addition, we showed an instance for its potential applications in medical treatment. All these performances reveal that this portable handheld battery-operated apparatus has good application prospects in many fields, especially in bi-medical fields such as skin damage, wound healing and rapid hemostasis, etc.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (51373082), the Taishan Scholars Program of Shandong Province, China (ts20120528), the Natural Science Foundation of Shandong Province for Distinguished Young Scholars (JQ201103), and the National Key Basic Research Development Program of China (973 special preliminary study plan, 2012CB722705).

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