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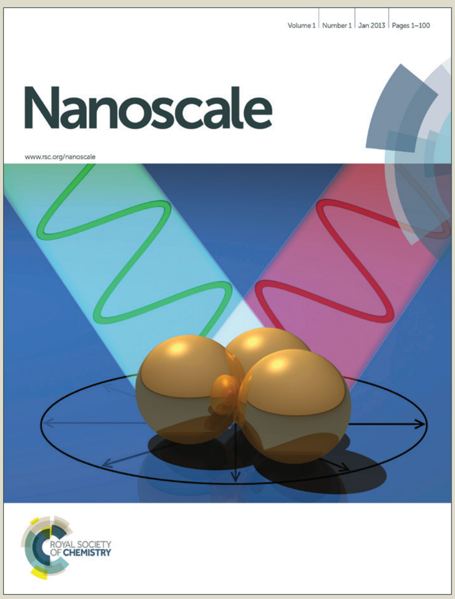

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COMMUNICATION

A self-powered electrospinning apparatus based on a hand-operated Wimshurst generator†

Cite this: DOI: 10.1039/x0xx00000x

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Received 00th January 2015, Accepted 00th January 2015

DOI: 10.1039/x0xx00000x

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Conventional electrospinning setup cannot work without a plug (electric supply). In this article, we report on a self-powered electrospinning setup based on a hand-operated Wimshurst generator. The new device has better applicability and portability than typical conventional electrospinning setup because it is lightweight and can work without external power supply. Experimental parameters of the apparatus such as the minimum number of handle turns to generate enough energy to spin, rotation speed of the handle and electrospinning distance were investigated. Different polymers such as polystyrene (PS), poly(vinylidene fluoride) (PVDF), polycaprolactone (PCL) and polylactic acid (PLA) were electrospun into ultrathin fibers successfully by this apparatus. The stability, reliability, and repeatability of the new apparatus demonstrate that it can be used as not only a demonstrator for electrospinning process, but also beneficial complement to the conventional electrospinning especially where or when without power supply, and may be used in wound healing and rapid hemostasis, etc.

1 Introduction

In the recent years, electrospinning has attracted much attention as an effective technique for fabricating ultrathin fibers and non-woven mats with remarkable properties such as high surface-to-mass ratio, high porosity, flexibility, extensive selection of polymer materials, etc.[1-3] However, typical commercial electrospinning equipment is often too large/heavy to transport, limiting its some potential uses and slowing down the development of new applications. As shown in Fig.1a, a typical conventional electrospinning setup consists of a high voltage power supply (HVPS), a syringe pump unit and a metal collecting screen. In the electrospinning process a high voltage is applied to the solution, and then a charged jet is ejected from Taylor Cone and rushes onto the grounded collector under the driving force of an electric field. The solid fibers with uniform diameter are randomly deposited on the collector after solvent evaporation.[4-7] Over the past two decades many improvements have been investigated on electrospinning setup for getting unique structure fibers (core–shell structure, fiber alignment, three-dimensional (3D) scaffolds, etc.) or improving the rate of production. For example, Sun et al.[8] fabricated successfully curled architectures nanofibers by a reciprocating-type electrospinning setup with a spinneret in straight forward simple harmonic motion. In order to prepare core–shell nanofibers and hollow nanotubes, coaxial electrospinning (co-electrospinning) rapidly gained popularity and was implemented by a number of groups[9-14] that a coaxial needle attached to a two-compartment syringe was used to take the place of the common spinneret to induce a core–shell droplet in co-electrospinning process. Recently, many researchers have studied the electrospinning process to manufacture aligned nanofibers which have many excellent properties and larger application range. For example, Huang et al.[7] demonstrated that a rotating multi-frame structure could be used as collector to get fiber alignment. Li et al.[15] and Ishii et al.[16] prepared the highly aligned nanofibers by using a parallel electrode collector system. At the same time, such as multiple-jet electrospinning system,[17-19] rotary cone electrospinning setup,[20] and many kinds of needleless electrospinning system[21-26] etc. have been developed to improve the production rate of electrospun ultrathin fibers.

As mentioned above, the modification of conventional electrospinning setup was mainly focus on spinneret, collector or auxiliary system (e.g. auxiliary electric field, magnetic field and airflow). Nevertheless, so far there are almost no reports on the replacement of the HVPS part, but not to say it is perfect either. For example, as shown in Fig. 1a, the HVPS part of typical conventional electrospinning setup must be equipped with a plug which is used to connect with power grid. It means that the conventional commercial electrospinning setup cannot work once power cut or unable to connect with power grid, which greatly reduces portability and application scope of conventional electrospinning setup. So, it is still a challenge to design a self-powered portable electrospinning setup.

In the present work, a self-powered electrospinning apparatus (SPEA) based on a hand-operated generator was designed and manufactured for the first time, of which the expensive HVPS part was replaced by a Wimshurst machine to generate a high voltage. As the name implies, the SPEA can still work without power supply which leads to better applicability and portability. It can be taken for the beneficial complement to the conventional electrospinning setup especially where or when without power supply and has some favorable applications such as electrospinning demonstrator, wound healing, and rapid hemostasis.

2 Apparatus and Experiments

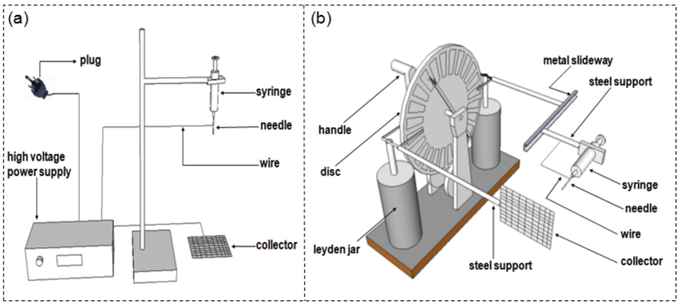

FIG. 1 Schematic diagrams of (a) a conventional electrospinning setup, and (b) a new self-powered electrospinning apparatus (SPEA).

The schematic diagram of the SPEA is shown in Fig. 1b, compared with typical traditional electrospinning equipment, the HVPS part is taken place of a typical Wimshurst machine which can generate high voltage about dozens of kilovolts. Though the machine was invented as early as 1883,[27] it is extensively used for demonstration of electrostatic induction, lightning simulation experiments, and cutting-edge discharge until now. The Wimshurst machine operates when the two discs are counter-rotating by turning the handle as shown in Fig. 1b in the clockwise direction. Due to electrostatic induction, the positive and negative charges are generated on different regions of discs and stored in the two Leyden jars separately. The charges accumulated more and more along with continuously rotating the handle, and then, the high voltage can be generated between the needle and collector. The metal chute is used to obtain suitable electrospinning distance between the needle and collector, which is a critical factor about the diameter of the electrospinning fibers. The electrospinning distance can be changed range from 10 to 30 cm in this work.

In order to verify the spinning efficacy and determine the experimental parameters of the SPEA, we try to prepare polystyrene (PS) nanofibers by it at first. PS solution was prepared by dissolving 2.0 g PS (average molecular weight of 250,000, ACROS) into 8.0 g tetrahydrofuran. After stirred for 4 h at room temperature, the PS solution was kept at room temperature for 0.5 h before electrospinning. All experiments were carried out at room temperature, and the ambient relative humidity was 25%. The optical images were obtained by an optical microscope (BX-51, Olympus) and the microscale morphologies of the fibers were characterized by a scanning electron microscope (SEM, TM-1000, Hitachi). In addition, the accurate and vivid electrospinning process was recorded by a high-speed digital video camera (FASTCAM Mini UX100, Photron) running at nearly 10,000 frames per second, and the static voltage between the needle and collector was measured by a digital multimeter (BM905, BRYMEN) assembled with a high voltage probe (HVP-40, PINTEK).

3 Results and Discussion

3.1 Outstanding performances of the SPEA

The electrospinning process by using the SPEA is shown in Fig. 2a-b (The vivid details can be found in supplementary 1). The spinning process of the SPEA is very smooth and it has a comparable production rate with the typical conventional electrospinning equipment used in laboratory. As shown in Fig. 2c, the fabricated PS nanofibers have relatively uniform morphologies with diameter ranging from hundreds of nanometers to several micrometers. It demonstrates that the SPEA can be used in laboratory for preparing ultrathin fibers. In addition, several-centimeter-high 3D stacking structure of PS nanofibers (Fig. 2d) can be formed in less than two minutes. So it is very suitable for application in the teaching demonstration of electrospinning process. As mentioned above, those all verified that the SPEA have an outstanding performance in electrospinning filed.

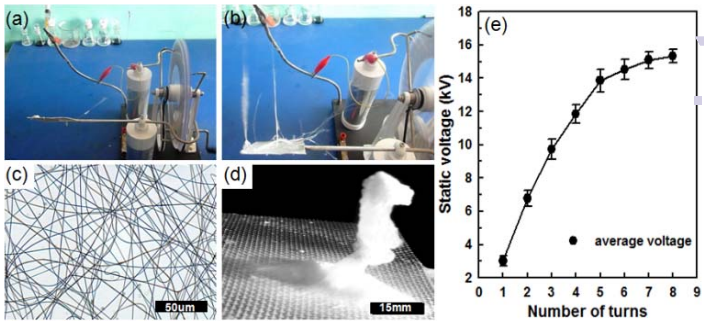

FIG. 2 (a-b) The electrospinning process by using the SPEA; (c) Optical microscope image of the PS fibers; (d) 3D stacking structure of PS fibers. (e) The relationship between the number of turns and the generated static voltage between needle and collector of the SPEA.

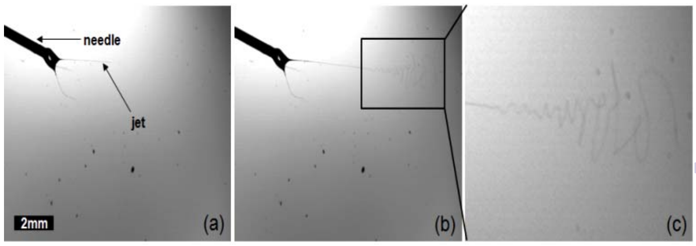

FIG. 3 The images of electrospinning process which were recorded by using a high speed camera: (a) the moment of jet initiation, and (b) a moment of elongation process of the jet. (c) Magnified image of the region indicated by a solid square in (b).

In order to prove the actual electrospinning process of the SPEA, the vivid details was recorded by a high-speed digital video camera running at nearly 10,000 frames per second (The video can be found in supplementary 2). As shown in Fig. 3, it exactly similar to the electrospinning process by using typical traditional setup.[13,28-30] Firstly, a droplet at the cone tip overcomes its surface tension to eject into the electric field between the needle and collector, and a straight solution jet is generated. As the diameter of the straight segment part decreases monotonically with distance from the tip, the electrical bending instability increases gradually, which causes bending of the head of the solution jet, and the solution jet formed in the helical structure finally as shown in Fig. 3c.

3.2 Experimental parameters of the SPEA

As we know that a high voltage (typically from several to 20 kilovolts) is used to create an electrically charged jet of polymer solution or melt out of the pipette in the electrospinning process. However, the high voltage between the needle and collector in this SPEA can be created not as simple as the conventional electrospinning setup of which just needs to plug in the HVPS part. It needs a process for reaching the minimum spinning voltage through the accumulation of electrostatic induction charges when begins to turn the handle of the SPEA in the clockwise direction. The relationship between the number of turns and the static voltage created between needle and collector of the SPEA can be found in Fig. 2e. It indicates that the static voltage increases linearly alone with the number of turns before turn the handle less than five rounds, and the static voltage will reach a saturation point nearly 15 kV after the number of turns exceeds six, because the Leyden jars of the SPEA can't save more charges. The deviations of each measurement from the average voltage are shown in Fig. 2e as the error bars because the rotation speed of the handle may be slightly different in our experiments of ten times. The good phenomenon is that the static voltage between the needle and collector can be reached nearly 7 kV just need to turn the handle two rounds. In the experiments for preparing PS fibers by the SPEA, we found that it begins to spin just need to turn the handle in the range of one cycle to two cycles. And the minimum number of turns needed for spinning increases monotonically with the electrospinning distance between the needle and collector. It means that more charges need to be accumulated to get the minimum spinning voltage when the electrospinning distance increases because the electric field strength is inversely proportional to the distance.

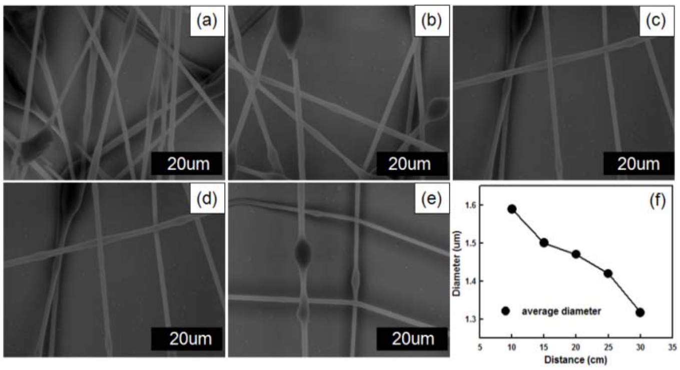

FIG. 4 SEM images of the PS fibers fabricated under different electrospinning distance: (a) 10 cm, (b) 15 cm, (c) 20 cm, (d) 25 cm and (e) 30 cm; (f) The relationships between the average diameters and the electrospinning distance.

In addition, it was found that the spinning process was stable and efficient when the rotation speed of the handle was about 100 revolutions per minute (rpm) by using the SPEA. Then the influence of electrospinning distance on the morphology of fibers was explored when the rotation speed of the handle was fixed at 100 rpm. As shown in Fig. 4a-e, the PS fibers have been fabricated by using the SPEA under different electrospinning distances: 10, 15, 20, 25 and 30 cm, respectively. The average diameters of those electrospun fibers were obtained from the SEM analysis. As shown in Fig. 4f, the average diameter reduced from 1.589 to 1.317 μm alone with the electrospinning distance increased from 10 to 30 cm because the fiber tensile curing time lengthened in the electric field. The result is consistent with the spinning process by using the conventional electrospinning setup.

3.3 Electrospinning of other polymers by using the SPEA and potential application

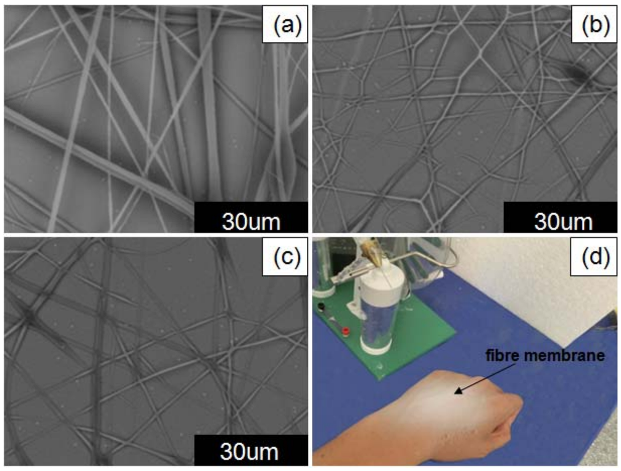

FIG. 5 SEM images of (a) PVDF (b) PCL and (c) PLA fibers which were fabricated by using the SPEA; (d) An optical image showing the process of PLA fibers electrospun directly onto skin by using the SPEA.

In order to further validate the performance of the apparatus, we tried to spin other materials by using the SPEA. As shown in Fig. 5a-c, such as poly(vinylidene fluoride) (PVDF), poly(caprolactone) (PCL) and polylactic acid (PLA) fibers were also prepared successfully by the SPEA. In the electrospinning process, the rotation speed of the handle was about 100 rpm and the spinneret-to-collector distance was 15 cm. And the parameters for the spinning solutions: PVDF (20 wt.%, solvent: N,N-dimethyl formamide), PCL (15 wt.%, solvent: acetone), and PLA (15 wt.%, solvent: acetone). These demonstrate that the SPEA can be used as the beneficial complement to the conventional electrospinning setup.

In addition, as shown in Fig. 5e, the PLA fibers could be *in situ* electrospun onto skin and form a fibrous membrane quickly by using the SPEA. Recently, Long and his co-works[31] have illustrated that a kind of FDA-approved medical glue could be spun directly to the wounds by using a modified electrospinning technology to realize rapid hemostasis in dozens of seconds. If the materials of electrospinning solutions have the functions like wound dressing/healing, rapid hemostasis, and cosmetic, the SPEA maybe has favorable applications in healthcare filed especially for the situation when or where without electric supply.

Conclusions

A self-powered portable electrospinning apparatus was designed and manufactured by using a hand-operated Wimshurst machine to replace the usually used high-voltage power supply of the conventional electrospinning setup. The experimental parameters of the new apparatus such as the minimum number of turns (~1-2 circles) to begin to spin, rotation speed of the handle (~100 rpm) and the electrospinning distance (10-30 cm) have been investigated and optimized. The electrospinning process has also proved by a high speed camera. Furthermore, different polymer materials can be electrospun into submicron fibers by this new setup. These all reveal that the new self-powered setup has good stability, reliability and repeatability, and can be used as not only demonstration equipment, but also laboratory apparatus for scientific research. In addition, the setup maybe has potential applications in wound healing and rapid hemostasis because of its better applicability and portability.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (51373082 and 11404181), Taishan Scholars Program of Shandong Province, China (ts20120528), Natural Science Foundation of Shandong Province for Distinguished Young Scholars (JQ201103), National Key Basic Research Development Program of China (973 special preliminary study plan, 2012CB722705), and Natural Science Foundation of Shandong Province (ZR2013EMQ003).

Notes and references

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† Electronic Supplementary Information (ESI) available: [The video of the electrospinning process by this new self-powered electrospinning apparatus and the vivid details were recorded by a high-speed digital video camera]. See DOI: 10.1039/b000000x/
‡ These two authors contributed to this work equally.

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