SPIDER-INSPIRED MICROFLUIDIC CHANNEL FOR TUNABLE PHYSICOCHEMICAL ENCODING OF MATERIAL COMPOSITION AND TOPOGRAPHY IN CONTINUOUS MICROFIBERS

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ABSTRACT

In this paper, we describe a method to continuously fabricate microfibers with tunable physicochemical characteristics using a microengineered platform. By introducing active functional modulations, such as by switching the flow through the use of a digital control scheme, we produced microfibers along which diverse chemical compositions, structure (e.g.: hydrophilic and hydrophobic), gas, live cells and morphologies.

KEYWORDS: Microfiber, Digital Microfluidics, Encoded Microfibers

INTRODUCTION

Biocompatible micro and nano fibers are useful for various biological applications, including the delivery of cells, guided cell culture and tissue engineering. For this purpose, several methods have been developed, such as electrospinning and microfluidic spinning [1-2]. Most recently, we reported the simultaneous production of multiple fibers, each of differing composition, using coaxial PDMS microfluidic channels [3]. Although these methods permit the simple and cost-effective production of uniformly sized microfibers without clogging, they have potential problems to generate fibers with complex morphologies and tunable composition to the same extent as those present in nature.

In this paper, we propose a spinning method that uses a microfluidic chip combined with a digital fluid control. Using this method we demonstrated microfibers encoded with diverse chemical compositions, structures, live cells, gas and morphologies.

THEORY

The fiber-spinning mechanism of spider provided critical clues to addressing artificial fiber generation and coding mechanism. A spider produces fibers by using special glands according to its own specialized composition in its abdomen as shown in Figure 1(a). At the end of spinning duct, a valve acts as a clamp to grip the thread or as a ratchet to restart spinning after internal rupture. Based on the ideas of spider’s spinning system, we fabricated a combination of rectilinear and cylindrical channels, with multiple micro-valves, on a single microfluidic platform and the sample fluid volume of each channel was tightly controlled by a computer controlled pneumatic valve as shown in Figure 1(b).

![Figure 1: Concept of encoded microfiber production; (a) Anatomy of spider’s silk spinning system; (b) Photograph of the microfluidic spinning chip](image)

EXPERIMENTAL

To encode various composites periodically into fibers, we employed active functional modulations, such as by switching the flow through the use of a digital control scheme. Figure 2 shows the complex encoding of morphology and composition in
the fiber. Diameter of fiber could be periodically tapered by controlling valve operation, and figure 2(a) show the control scheme to produce tapered fibers and SEM image. Instead of chemical composition, gas could be encoded along the fiber. By the injection of gas and detergent into the alginate solution channel, microfibers entrapping gas bubbles were produced. By using valve operation, gas could be distributed either periodically or uniformly throughout the fibers (Figure 2(b)). Also, the periodic modulation of fiber diameter and the encoding of varying composition were performed simultaneously. Figure 2(c) shows the fluorescent image of fiber indicating that fibers with spatiotemporal variations in morphology and chemical composition could be produced by using a single microfluidic platform and digital control scheme. To operate the small pneumatic valves, compression and vacuum pumps were employed. Continuous air pressure (around 200kpa) or vacuum were supplied, and the ‘on–off’ switching of air flow was controlled using solenoid valves. The ‘open’ and ‘closed’ operations of the solenoid valve were controlled using a program written in Lab View (NI Lab View 8.6.1, NATIONAL INSTRUMENTS). Communication between the Lab View routine and the solenoid (ST2001-15DN, DKC, KOREA) proceeded through a DAQ board (NI DAQ-PAD 6015/6016, NATIONAL INSTRUMENTS). In most experiments, alginate was used since it has been approved by the FDA for certain biomedical applications, although a range of other materials (e.g., PEG, chitosan, etc.) can also be used.

RESULTS AND DISCUSSION

We demonstrated the feasibility of fibers to biological applications. The fiber diameter and length of spindle-knots can be modulated by the valve operation only and heterogeneous structure (e.g.: porosity) was encoded to the longitudinal direction by alternatively changing the material. With the current setup the smallest length of the serial coding was ~800μm although this is expected to improve with more advanced valves. To test the engineered fibers to mimic the water collecting behavior of spider silk, drops of water were added on the fiber [4]. As expected the water droplets self-collected at the spindle-knots (Figure 3(a)). To construct a porous spindle-knot, we injected an alginate solution containing salt (0.5 % w/w) with high flow rate in one of sample channels. It is noteworthy that the length of spindle-knot could be controlled by altering the time that the valve was kept open. We further demonstrated the feasibility of fibers for tissue engineering by generating 3D structures with controlled cellular organization. As shown in figure 3(b), we encapsulated primary rat hepatocytes and L929 fibroblasts along the length of the fiber either individually or as co-cultures. Interestingly, the fraction of viable cells in hepatocyte only cultures decreased throughout the 5 day experiment; whereas the cells in co-cultures better maintained their viability. This result indicates that the spatiotemporal control of co-culturing within the scaffold is of potential benefit in tissue engineering applications or cell biology studies. To further demonstrate the use of functionally modified fiber,
neuron alignment on grooves fiber were achieved as illustrated in figure 3(c) Such controlled alignment is of great importance in directing the extension of axons and controlling their subsequent connection with other cells with important implications in tissue regeneration after spinal cord or peripheral nerve injury. Figure 4 shows a confocal image of the stained cells in fiber encoded parallelly (illustrated in Figure 3(b)) at the different depth, and cells were uniformly distributed along the vertical direction.

![Confocal image of mixture region embedding stained at the different depth of fiber](image)

*Figure 4: Confocal image of mixture region embedding stained at the different depth of fiber. (Red arrow: Hepatocyte, Blue arrow: Fibroblast) (Scale bar: 100 µm)*

**CONCLUSION**

In summary, we presented spinning method for the versatile tuning of chemical and morphological properties in micrometer scale. The coding of diverse materials in microscale may be used to generate a range of useful functions in materials, such as artificial tissue and fabric. Nature also utilizes spatial patterning of existing materials to generate new functionality. The proposed method can be used to fabricate many other materials in a spatially regulated manner to generate functional fibers of benefit for a variety of applications, such as tissue engineering and drug delivery.

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**REFERENCES**


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