ABSTRACT

In this paper, we report the development of a biologically inspired fluidic diode motivated by xylem pores in plants. The biologically inspired fluidic diodes allow to design large-scale microfluidic circuits and simple fluidic controls. It requires only a single-layered device and a single pressure source to regulate flow through the entire platform. The operational conditions are precisely estimated based on a fully developed analytical model, which considers the hysteresis of contact angles and effects of fabrication limitations. Using biologically inspired fluidic diodes, we have demonstrated a large-scale spontaneous droplet-patterning and microfluidic co-culture array.

KEYWORDS: biological inspiration, surface tension, microfluidic diode, passive valve, co-culture chip

INTRODUCTION

Nature provides an abundant source of inspiration and creativity to foster innovation while challenging us to elucidate them in greater depth. The systematic study and abstraction of functional design from nature generate novel solutions for technological barriers and appreciation of the beauty of nature. Particularly, compartmented xylems maintain water transport even in the presence of gas embolism (or ‘xylem embolism’) by utilizing the physics of surface tension at the xylem pores [1]. Understanding the mechanism behind the regulation of xylem embolism in plants might provide us insights to accomplish simple and effective microfluidic systems without using mechanical valves.

THEORY

Just as xylem pores prevent the movement of the meniscus within a critical xylem pressure range, the bidirectional fluidic diodes regulate the flow with the applied pressure (Fig. 1). The mechanism of regulation is due to the pinning effect of a meniscus at the fluidic diode edge via surface tension by dropping the liquid contact angle below a critical contact angle required for bursting. The meniscus remains pinned until the meniscus angle surpasses the critical contact angle or the pinning force reaches its maximum value. An increase in the meniscus angle results in a decrease in curvature radius, which consequently causes an increase in the surface tension pinning the meniscus at the edge of diodes. Therefore, the fluidic diode can regulate flow via surface tension by the structural properties.

Figure 1: Xylem embolism isolation and biologically inspired bidirectional fluidic diode. (a) Pseudocolor SEM images show xylems (upper), a xylem wall including pits (middle) [2], and a pit membrane (PM, lower) in a plant [3]. (b) Schematics illustrate the embolism isolation via surface tension in xylem conduits (upper) and a pit with a pit membrane (lower). (c) A characteristic curve and photos detail a bidirectional fluidic diode. Inset presents zoomed-in views of the diode. Scale bars are 50/10/2 µm in upper/middle/lower figures of panel 'a', respectively, and 5 µm in panel 'c'.
RESULTS

Using the microfluidic circuit of fluidic diode arrays, we accomplished a droplet-patterning fluidic network. The fluidic diodes were differentiated as either uni-directional or bi-directional diodes depending on the edge angle of the diodes, which determined the bursting pressures at either side of the diodes and, thus, controlled the flow direction under certain operational pressures (Fig. 2). For example, uni-directional fluidic diodes burst at lower operational pressure in a certain direction because it was designed with a dull edged-structure on one side, which created a low bursting pressure in that one direction; whereas, bi-directional diodes held the meniscus in both directions under the same high bursting pressure.

Figure 2: Characteristic curves of uni- and bidirectional fluidic diodes. (a) Unidirectional diodes have low and high operational pressures in forward and backward directions, respectively. (b) Bidirectional diodes have a high operational pressure in both directions. Scale bars are 5 µm.

We demonstrated a droplet-patterning in chambers equipped with eight different microfluidic diodes on each side, in which each type of diodes regulated the flow direction. Ultimately, we designed a microfluidic circuit composed of the arrayed droplet chambers that utilized the designed uni- and bi-directional diodes to form self-patterned letters (Fig. 3, a - c, 1). The lettering involves two steps: liquid-filling with forward flow and liquid-removal with backward flow. Firstly, under a positive operational pressure, liquid filled the chambers in the forward direction by passing through uni-directional diodes with low forward bursting pressure. However, the meniscus was pinned at bidirectional diodes, as well as at uni-directional diodes with a high forward bursting pressure (Fig. 3, a - c, 2). Secondly, under a negative operational pressure, only the meniscus at the uni-directional diodes with low backward bursting pressure were released and flowed in the reverse direction, resulting in the removal of liquid in “unselected” chambers (Fig. 3, a – c, 3). However, the meniscus pinned at the bi-directional diodes, as well as uni-directional diodes with a high backward bursting pressure, maintained their pinning status in “selected” chambers, ultimately resulting in the patterning of droplets in selective, “letter-forming” chambers (Fig. 3, a - c, 4). These steps were illustrated in zoomed-in schematic representations (Fig. 3a), zoomed-in views of photos (Fig. 3b), and zoomed-out views of photos (Fig. 3c). In addition, the lettering was done with two different color dyes, demonstrating multiplex patterning (Fig. 3d). Moreover, it may be important to note that meniscus-pinning failed under an excessive positive operational pressure that exceeded the high bursting pressure of all fluidic diode types.

Figure 3: Droplet-patterning fluidic network by uni- and bidirectional fluidic diodes. Each letter chamber is designed with eight different fluidic diodes, making the letter chambers equivalent to an electric circuit with eight electric diodes (1). Lettering is accomplished through two steps: forward flow to fill letter chambers under a positive operational pressure (2) and backward flow to remove liquid from unselected chambers under negative operational pressure (3), ultimately achieving droplet patterning to form letters (4), as seen in the schematics (a), and photos of zoomed-in (b) and zoomed-out (c) views of arrayed letter chambers. (d) A photo shows letters composed of droplets in two different colors of blue (upper row) and green (lower row). Scale bars are 30 µm (b) and 300 µm (c and d), respectively.
The co-culturing platform mimics in vivo cancer environment: clustered tumor cells localized in a 3D microvessel network for the study of angiogenesis triggered by insufficient nutrients and mediated with over-expressed growth factors (Fig. 4). The platform is provided with thousands of chambers with the variations of inter-cellular distances, the size of clustered tumors, and the amount of nutrients in the culturing media. The co-patterning is programmed by uni- and bidirectional fluidic diodes, which can regulate gel flowing in a large scale only with a single pump but no complicated tubing. The co-patterning was visualized by showing multi-colored liquids in chambers with a variation of chamber sizes and an array. Furthermore, the technique was applied to pattern breast cancer cells inside localized chambers and endothelial cells in line channels.

**CONCLUSION**

The understanding of water flow through xylem pores in plants has inspired the development of bidirectional fluidic diodes that can regulate liquid flow upon structural design. The constructed analytical model provides a guideline for the design of microfluidic circuits. It also helps us to understand the mechanism behind water transport in plants. The utility of the single-layered fluidic diodes was successfully demonstrated by selective patterning in the well-organized arrayed microfluidic network and co-culture array chip.

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