Fast-Flow Paper-Based Fluidic Channels

Conor Camplisson

Department of Chemistry & Biochemistry, California Polytechnic State University,

San Luis Obispo, CA 93401

Abstract

This project focused on the development of paper-based microfluidic channels that wick fluids faster than conventional paper-based channels and a new model to describe the wicking in these fast-flow channels. My contributions to this project included developing and optimizing a method of fabricating fast-flow channels, measuring the wicking rates of fast-flow channels and standard channels, and fitting the results of the model to the experimental data.

Introduction

Point-of-care diagnostic devices have the potential to improve global healthcare by enabling the diagnosis and monitoring disease in remote settings without access to trained medical personnel. Paper-based microfluidic devices, also known as microPADs, are a promising new platform for the development of simple and low-cost point-of-care diagnostic devices for four principal reasons: [1] i) the devices are inexpensive (microPADs can be fabricated for less than one cent);[2] ii) the devices are portable (a typical device has dimensions of approximately 2 cm × 2 cm × 0.2 mm and has a mass of less than one gram); iii) the devices are easy to use (paper wicks fluids by capillary action so all the fluid processing can be handled automatically by the device);[3] iv) the devices are easy to make so they could be fabricated locally.

Unlike conventional microfluidic devices made from glass or plastic that typically require computer-controlled pumps to move fluids through the device, microPADs contain channels patterned into a sheet of paper that wick fluids by capillary action so no pumps, computers or

power sources are required to control fluid movement in these devices (Figure 1).[1] With the appropriate design, a microPAD can automatically process a sample of fluid and combine it with reagents in specific sequences to, for example, detect an analyte such as malaria antigen.[4] In conventional microPADs, the distance that a fluid is wicked along a channel is proportional the square root of time as described by the Washburn equation:[5]

$$L = \sqrt{\frac{\gamma D t \cos\theta}{2\mu}} \quad (1)$$

where L is the distance penetrated by a liquid flowing under capillary pressure into a capillary, t is time, γ is the surface tension, D is the average diameter of the capillary, θ is the contact angle, and μ is the viscosity of the liquid. For channels patterned in paper, the value of √(γr cosθ /2μ) was measured experimentally under controlled conditions of 100% humidity.[6] Based on these results, equation 1 can be simplified to:

$$L = 1.48 \frac{cm}{min^{1/2}} \sqrt{t} \quad (2)$$

Equation 2 can be used to estimate the amount of time it will take fluid to wick across a channel of a given length under conditions of 100% humidity. For example, a fluid will take approximately four minutes to wick across a 3-cm-long channel and eleven minutes to wick across a 5-cm-long channel. Under lower humidity conditions, as would be encountered in the real world, evaporation slows down the capillary wicking significantly. At 53% relative humidity, fluid was found to wick across a 3-cm-long channel in five minutes, and it virtually stopped advancing past 5 cm. This slow wicking of fluids across paper channels represents a significant problem for microPADs as it puts a practical limit on the length of channels that can be used in a device, which in turn limits the complexity and function of the device.

We developed fast-flow channels that wick fluids faster than conventional channels in order to overcome the limitations of slow wicking. Fast-flow channels significantly decrease the

amount of time required for operation of microPADs and increase the functions that a microPAD can complete as they allow for longer channels to be incorporated into microPADs so that additional functions can be added such as filtration, separation and mixing. Since the surface tension (γ), contact angle (θ) and viscocity (μ) terms in equation 1 are all constant for a given system, the only way to make the channels wick fluid faster is by increasing the average diameter of the capillary (D). We increased the average diameter of the capillary in paper-based channels by stacking two channels on top of each other to generate fast-flow channels (Figure 2). In doing so, a small space between the layers of paper is generated that acts as a capillary with a much larger diameter compared to the capillaries in paper and draws fluid into the channel rapidly (Figures 3 and 4). We foresee that fast channels will bring new capabilities to microPADs and extend the applications of this class of devices.

Experimental Design and Details

Fabricating fast-flow channels. Fast-flow channels were fabricated in three steps. (1) Two sheets of Whatman no. 1 Chr chromatography paper were patterned by wax printing,[7] using a Xerox Phaser 8560 printer. The paper was then heated for two minutes in a convection oven set to 195 °C to melt the wax into the paper. (2) After allowing the paper to cool for five minutes, four layers of toner were printed onto one face of one of the sheets of patterned paper using a Samsung CLP-680ND printer. (3) The two sheets of paper were stacked on top of each other—with the layer of toner sandwiched between the two sheets of paper, and the stack was passed through a Purple Cows 3015c laminator set to the 5 mil setting in order to bond the two layers of paper together with the toner acting as a thermal adhesive.[8]

Evaluating the wicking properties of fast-flow channels. Devices were prepared with six straight channels—three standard single-layer channels and three fast-flow double-layer

channels—each 8 cm long and 2 mm wide. The devices were dipped vertically to a depth of 2 mm into a fluid reservoir containing aqueous blue dye, and the fluid fronts were tracked over time as fluid wicked up the channels.

Modelling the wicking properties of fast-flow channels. Two models were used to describe the wicking properties of fast-flow channels. The first was the Washburn model described by Equation 1. While this model is typically used for describing capillary wicking, it does not account for the effects of evaporation. We developed a second model to include loss of fluid to evaporation. Darcy's law (Equation 3) provided the basis for the derivation of the second model, which we called the evaporation model:

$$\frac{\partial P}{\partial z} = -\frac{\mu}{k} \times \frac{dl}{dt} \quad (3)$$

Where P is pressure, z is distance, μ is dynamic viscosity of the fluid, k is permeability, l is the position of the fluid front and t is time. From Equation 3 and the approximation that the permeability (k) equals $D^2/12$, where D is the average diameter of the capillaries in paper, it is possible to derive an expression relating the position of the fluid front (l) to time (t):

$$l(t) = \sqrt{\frac{\gamma D^2}{6\mu q_0}\left(1 - e^{-\frac{q_0}{D}t}\right)} \quad (4)$$

Where γ is the surface tension of the fluid being wicked and q_0 is the evaporation of fluid from the surface of the paper (Figure 4). For water, γ is 0.0728 N/m and μ is 0.001 Ns/m^2 so equation 4 can be simplified further to the following expression:

$$l(t) = \sqrt{\frac{12.133\,D^2}{q_0}\left(1 - e^{-\frac{q_0}{D}t}\right)} \quad (5)$$

Results and Discussion:

Wicking rates of fast-flow vs. standard paper channels. The fast-flow channels wicked water to twice the distance of the conventional single-layer channel in any given amount of time (Figures

3 and 5). The wicking of fluid in conventional single-layer channels effectively stopped after 20 minutes, with the fluid having wicked a distance of 4.5 cm on average. The double-layer channels reached the end of the 10-cm long devices after 20 minutes, and had not shown signs of significantly slowing down by that point, which suggests they would continue to wick fluids to an even greater distance. An alternative way to evaluate the wicking properties of the two types of channels is to compare the amount of time required for a single-layer channel and a double-layer channel to wick a fluid a distance of 4.0 cm. The single-layer channels, on average, required 12 minutes to wick water a distance of 4.0 cm, while the double-layer channel required only 2.5 minutes to wick water the same distance. This result suggests that the fast double-layer channel wicks fluids almost five times faster than the conventional single-layer channel.

Modelling the wicking properties of fast-flow channels. The experimental data was fit with both the traditional Washburn equation and the evaporation model (Figure 6). As expected, the Washburn model appears to describe the experimental results accurately during the initial portion of the experiment, when the effects of evaporation are less significant, but tends to deviate significantly from the experimental data during later time points. The evaporation model provides an excellent fit to the experimental data throughout the duration of the experiment.

Conclusions

We developed a method for fabricating fast-flow channels in microPADs that wick fluids faster than conventional single-layer channels and allow for the fabrication of larger devices with increased capabilities. We also introduced a mathematical model to describe the wicking properties of the fast-flow channels, which will be used in the future to help design paper-based point-of-care diagnostic devices.

Appendix

Figures

Figure 1. A) Schematic of an open paper-based microfluidic channel. The channel comprises a porous matrix of hydrophilic cellulose fibers that wick fluids along the path defined by the channel. The sides of the channel are bounded by hydrophobic barriers, and the top and bottom of the channel are open to atmosphere. B) Schematic diagram of the fabrication a paper-based microfluidic device by wax printing. During the heating step, the wax melts and wicks into the paper creating the hydrophobic barriers. C) A paper-based microfluidic device fabricated by wax printing.

Figure 2. Schematic of a standard single-layer paper-based channel (A) and a fast-flow channel (B).

Figure 4. Schematic diagram of water wicking along a longitudinal section of a fast-flow channel. The water wicks quickly along the central capillary between the two pieces of paper and the leaks into the paper channels, before it evaporates from the surface of the paper.

Figure 3. A standard channel and a fast-flow channel wicking an aqueous blue dye.

Figure 5. Plot of the height of the fluid front wicked along a channel versus time for fast-flow channels and standard channels. Data points represent the mean of nine experiments. Error bars represent one standard deviation from the mean.

Figure 6. Modelling the wicking properties of the fast-flow channels. The black diamonds depict the experimental results while the blue dashed line represents the modelled wicking properties of the channel using the Washburn model and the red dashed line represents the modelled wicking properties of the channel using the evaporation model.

References

[1] A. K. Yetisen, M. S. Akram and C. R. Lowe, *Lab Chip*, 2013, **13**, 2210-2251.

[2] A. W. Martinez, S.T. Phillips, E. Carrilho, S. W. Thomas, H. Sindi and G. M. Whitesides, *Anal. Chem.*, 2008, **80**, 3699−3707.

[3] Martinez, A. W., *et al. Anal. Chem.* **2010**, 82, 3-10.

[4] Fu, E. *et. al. Anal. Chem.* **2012**, 84, 4575-4579

[5] Washburn, E. W. *Phys. Rev.* **1921**, 17, 273−283.

[6] Schilling, K. M. *et. Al. Anal. Chem.* **2012**, 84, 1579-1585.

[7] E. Carrilho, A. W. Martinez and G. M. Whitesides, *Anal. Chem.*, 2009, **81**, 7091−7095.

[8] K. C. Schilling, D. Jauregui and A. W. Martinez, *Lab Chip*, 2013, **13**, 628-631.