# PAPER MICROFLUIDICS GOES DIGITAL

**R. Fobel[1*], A.E. Kirby[2], A.R. Wheeler[1,2]**
*[1]Institute for Biomaterials and Biomedical Engineering, University of Toronto, CANADA*
*[2]Department of Chemistry, University of Toronto, CANADA*

## ABSTRACT

We report the first example of so-called "digital microfluidics" (DMF) implemented on paper, thus combining the power and flexibility of DMF with the low-cost benefits of paper-based microfluidics. Devices were fabricated by inkjet printing of conductive features on a paper substrate followed by standard dielectric and hydrophobic coatings. We demonstrate an automated serial dilution and homogeneous chemiluminescence assay as an example of a complex, multi-step protocol that would be difficult or impossible to achieve with capillary-driven paper microfluidics. Furthermore, we show that paper-based DMF devices have comparable performance to photolithographically patterned chromium-on-glass DMF devices at a fraction of the cost.

**KEYWORDS:** digital microfluidics, paper microfluidics, inkjet printing, low-cost diagnostics

## INTRODUCTION

Paper microfluidics [1], [2] has recently emerged as simple and low-cost paradigm for fluid manipulation with potential applications in diagnostic testing in the developing world. Passive, capillary-driven flow is a benefit of these devices since it does not require any external instrumentation; however, it also limits these devices to relatively simple assays. Here we report an alternative strategy: the first example of so-called "digital microfluidics" implemented on paper. Compared to traditional capillary-driven paper microfluidics, these methods facilitate complex, multi-step experiments.

Digital Microfluidics (DMF) is a technology for manipulating liquid drops on an array of electrodes using electrostatic forces. While DMF has been applied to a wide range of applications [3], a significant challenge has been the lack of a scalable and economical method of device fabrication. We propose that inkjet printing of DMF devices can greatly expand the complexity of experiments that can be implemented on paper-based microfluidic platforms.

## EXPERIMENTAL

Paper DMF devices were printed using a Dimatix DMP-2800 printer and SunTronic silver nanoparticle-based ink. The paper is coated with a thin layer of latex and kaolin making it suitable for inkjet printing [4]. The silver ink ws sintered using a 1500 W infrared lamp and coated with Parylene-C and Teflon-AF via chemical vapour deposition and spin coating respectively. Glass devices were fabricated as in Ref. [5]. The instantaneous velocity of deionized (DI) water drops was measured on paper- and glass-based DMF devices through capacitive sensing [5] for actuation voltages of 100, 110 and 120 $V_{RMS}$. A serial dilution and homogeneous chemiluminescence assay was performed by dispensing drops of horseradish peroxide (HRP) and mixing them with buffer to form a dilution series (1x, 2x, 4x). Drops at each concentration were subsequently mixed with drops of luminol/$H_2O_2$ and the emitted light was quantified with a photomultiplier tube.

## RESULTS

Figure 1A shows a sheet of printed devices. The test pattern in Figure 1B demonstrates horizontal and vertical feature capabilities as small as 30 µm and gaps of 60 µm.

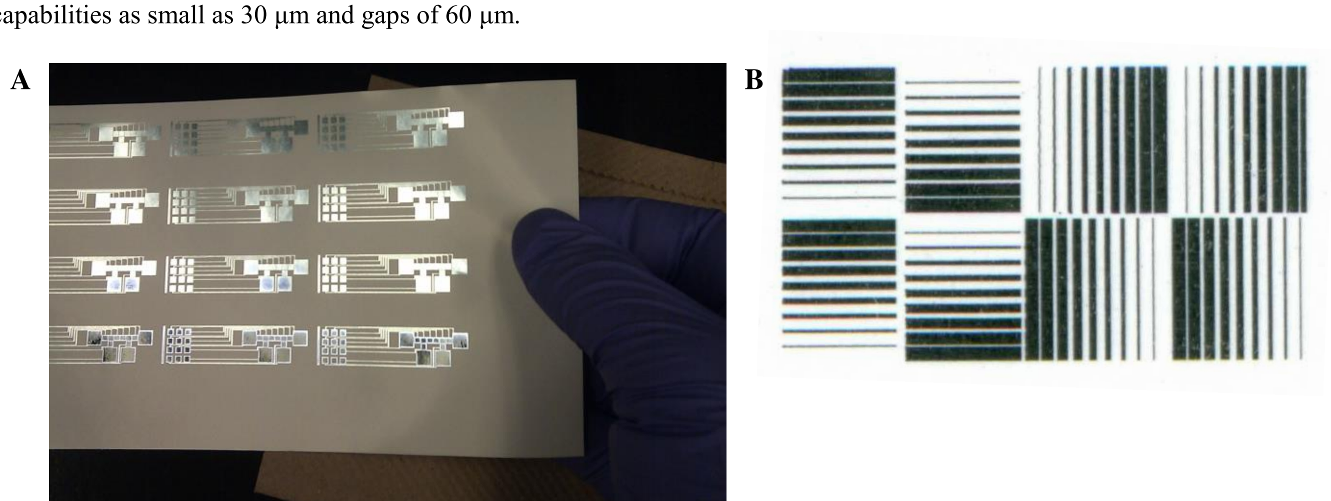


*Figure 1: Printing resolution and device design. (A) Photo of printed devices. (B) Photo of printed test pattern showing gradients of line/gap widths in horizontal and vertical directions.*

Figure 2A shows the resistance of a 150 µm wide trace after sintering for 5, 10 and 15 s. The resistance of traces on the paper devices (after sintering for 10 s) was about 500 times lower than that of an identical design fabricated by standard photolithographic methods (i.e., chromium on glass). Figure 3A shows a sequence of video frames demonstrating the ability to move DI water on a paper DMF device. Figure 3B is a plot of the instantaneous velocity of DI water drops as a function of actuation voltage on paper and glass DMF devices. These results suggest that the functional performance of glass- and paper-based devices is comparable. Figure 4B shows the calibration curve for a serial dilution and homogeneous chemiluminescence assay performed on a paper DMF device.

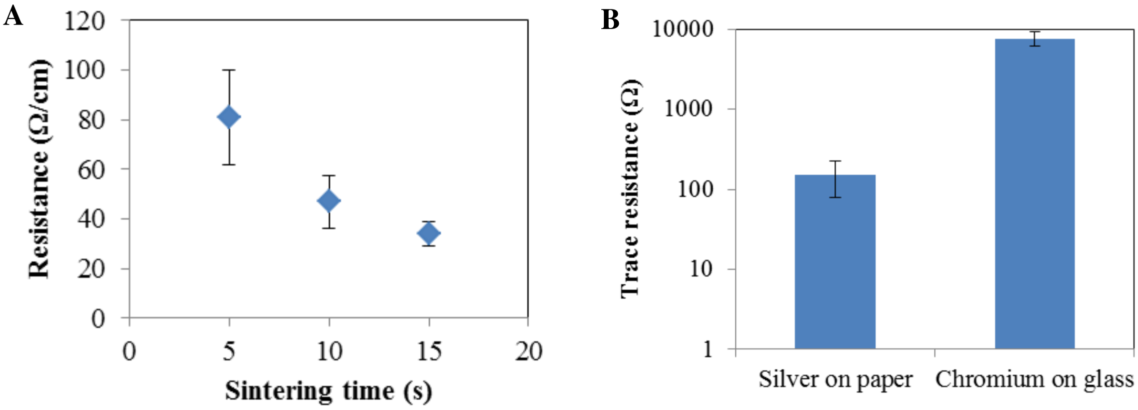


*Figure 2: Conductivity of silver ink on paper. (A) Effect of sintering time on the resistance of 150 µm wide traces. (B) Average resistance of all traces for the DMF device design fabricated by inkjet (silver on paper) and by standard photolithography (chromium on glass). Error bars are +/- 1 standard deviation.*

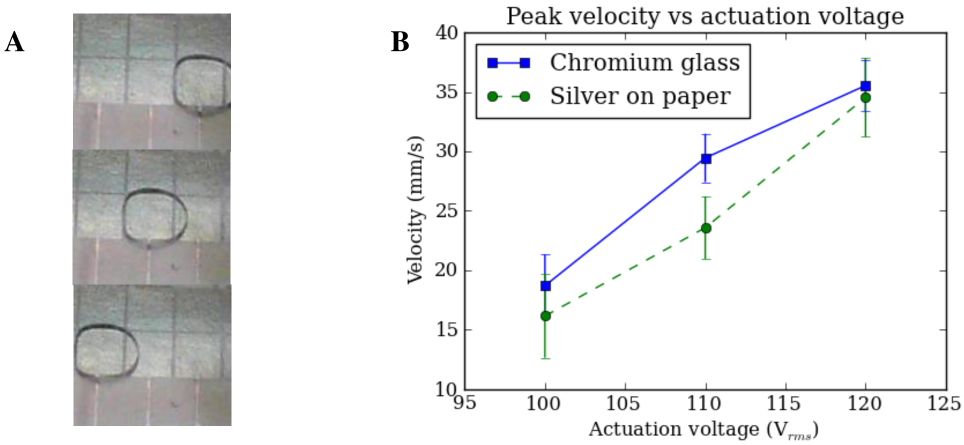


*Figure 3: Velocity of DI water on a DMF device. (A) Series of video frames demonstrating translation of a drop of DI water on a paper device. (B) Peak velocities of DI water drops on a paper DMF device (blue squares) relative to those of a standard device fabricated by photolithography (green circles). Error bars are +/- 1 standard deviation.*

**DISCUSSION**

Complex multiplexing and multi-step assays (e.g., sandwich ELISA) have traditionally been a challenge for paper-based microfluidics. Sandwich ELISA has been implemented using paper "well-plates" and manual pipetting [6], but the major drawback to this class of devices is that they require skilled laboratory technicians and the associated assays are time-consuming to implement. On the other hand, DMF is emerging as a useful tool for implementing fully automated, low-volume magnetic particle-based immunoassays [7], and we propose that paper-based DMF devices could make this diagnostic method feasible for resource-poor settings. As a step towards this goal, we have tested the compatibility of paper DMF devices with a homogeneous chemiluminescence assay (Figure 4). This experiment requires 22 discrete steps (8 dispense, 6 mix, 8 split) and would likely be difficult or perhaps impossible to perform on a capillary-driven paper device.

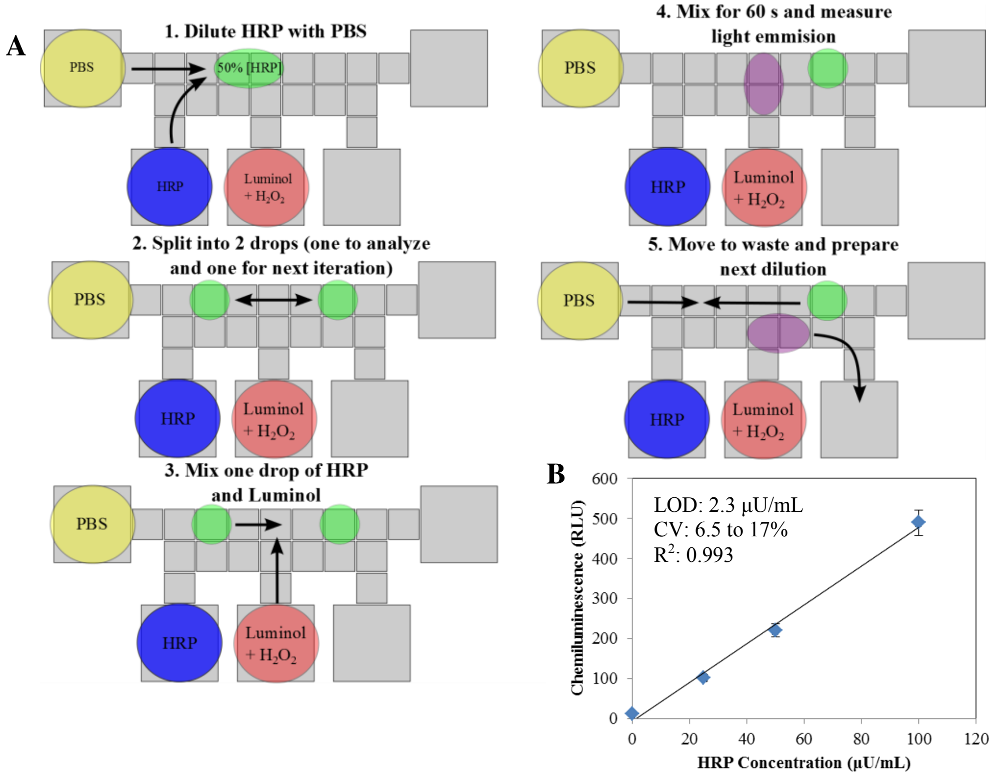


*Figure 4: Homogeneous chemiluminescence assay generated on a paper DMF device though on-chip serial dilution of HRP mixed with Luminol/$H_2O_2$. (A) Cartoon showing individual steps in the assay. (B) Generated calibration curve (n=3). Error bars are +/- 1 standard deviation.*

## CONCLUSION

In summary, we introduce an exciting new paper-device format for DMF. In the future, inkjet fabrication may be scaled to a roll-to-roll process for commercial production, or alternatively, it may appeal to researchers interested in rapid prototyping new device designs.

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## CONTACT

*R. Fobel, tel: +1-416-946-5702; ryan.fobel@utoronto.ca