FORWARD OSMOSIS COUPLED WITH ELECTROCHEMISTRY FOR CONCENTRATION OF FLUID SAMPLES AND IN-LINE PROCESS MONITORING

Martin Kimani[1], Rachel Loo[1], and Edgar D. Goluch[1,2*]
[1] Department of Chemical Engineering, Northeastern University, Boston, MA 02115, USA
[2] Department of Bioengineering, Biology, Civil & Environmental Engineering, Northeastern University, Boston, MA 02115, USA

ABSTRACT

This paper presents an integrated microfluidic system that uses dialysis membranes coupled with electrochemical sensing to concentrate bodily fluid samples up to a hundred fold while simultaneously monitoring the process in-line. Sensors measure both the conductivity and the sucrose concentration in the sample while it is being concentrated using impedance spectroscopy and voltammetry, respectively. This sample concentration technique can be coupled with many microanalysis systems to process samples and improve the limit of detection. We have concentrated samples up to 100x by using two forward osmosis concentrators in series.

KEYWORDS: Osmotic concentration, impedance measurement, electrochemistry

INTRODUCTION

Previous work in our lab focused on improving the limit of detection by increasing the production of quorum sensing molecules using amino acids that up-regulated the metabolic pathway involved in biosynthesis of these molecules [1]. While innovative, this approach relied on bacterial cells to increase the concentration of the target molecule in the sample. Electrokinetic techniques are often used for sample concentration at the micro scale, however they require optimization based on the properties of the molecule being concentrated [2]. Paper-based concentration is a promising concentration approach for some applications, but it can be difficult to control and monitor [3]. Concentration using forward osmosis overcomes these limitations.

THEORY

Forward osmosis is routinely used in large scale water purification systems where millimeter thick membranes with high salt rejection are utilized alongside high pressure systems but in our design, we are using the osmotic driving force for controlled water removal from small scale samples. The water removal rate (water flux) is controlled by maintaining a maximum solute concentration outside a cellulose ester membrane (Figure 1). However, since the solute can also migrate slowly across the membrane, a solute concentration gradient internal to the membrane reduces the water flux. In this work, we characterized water flux decay and also introduced an inline monitoring system that provides feedback during process operation to optimize microscale volume reduction.

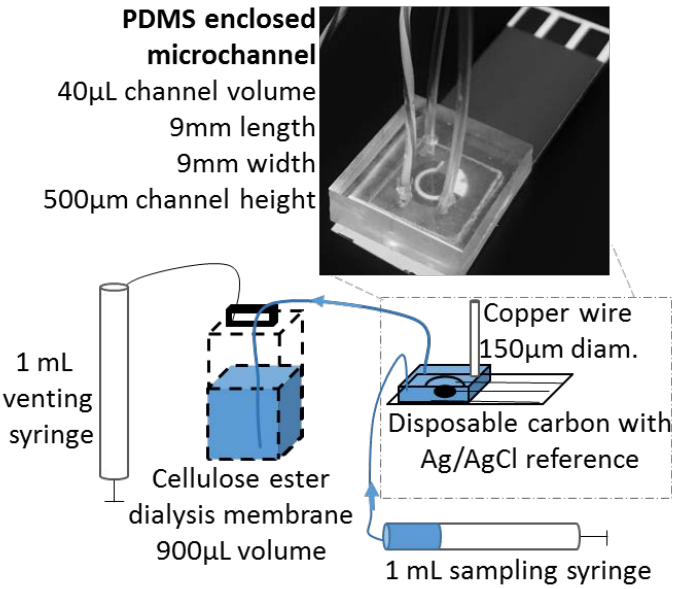

Figure 1: Disposable carbon & copper working electrodes were used in electro-chemical sensors in parallel with a forward osmosis cellulose ester membrane. The sample is introduced and recovered using the sampling syringe.

EXPERIMENTAL

Our system utilizes copper and carbon electrodes coupled with cellulose ester dialysis membranes in a draw solution to accurately

concentrate biological fluid samples, which all contain millimolar concentrations of salts. We used cellulose ester dialysis membranes with 100–500 Dalton molecular weight cutoff (MWCO) to concentrate 1 mL samples using salt or sucrose as draw solutions. The schematic of the system is shown in Figure 1. Copper electrodes detect the presence of reverse flux sugar into the sample by voltammetry to provide feedback of membrane performance. Disposable carbon electrodes detect the changing sample conductivity by impedance spectroscopy to provide in-line feedback of the extent of sample concentration. The sample does not need to be removed from the system, which allows controllable stopping points for concentrating different samples. The syringes were used to move the sample between the concentrator and the sensors.

RESULTS AND DISCUSSION

We tested both potassium chloride (KCl) and sucrose as the draw solution on the outside of the membrane starting with the same applied osmotic pressure. Deionized water was used as the initial sample for evaluating the efficacy of the two draw solutions. Each experiment contained only KCl or sucrose in the draw solution. The graph in Figure 2 shows the concentrations of KCl or sucrose that is present in the deionized water sample at different time points during the water removal process. KCl concentration in the samples increased much faster than the sucrose concentration. As the draw chemical migrates through the membrane into the sample, the concentration gradient decreases and the water flux rate decreases. Sucrose performed better because it did not permeate the membrane as rapidly as KCl, thereby maintaining a larger chemical gradient during the sample concentration process.

Extent of sample concentration was then monitored by measuring the volume at set time intervals using a syringe. The volume change was then compared against changes in salt concentration in the sample using impedance measurements. 50 mM phosphate buffered saline (PBS) was used as the sample for this set of experiments. Figure 3 shows the relationship between the two measurement approaches. The error bars in the graph represent the standard deviation of the mean obtained from three separate experiments. This data shows that the impedance method used to determine PBS salt concentration can be used for determining the extent of sample concentration without removing the sample for volume measurements.

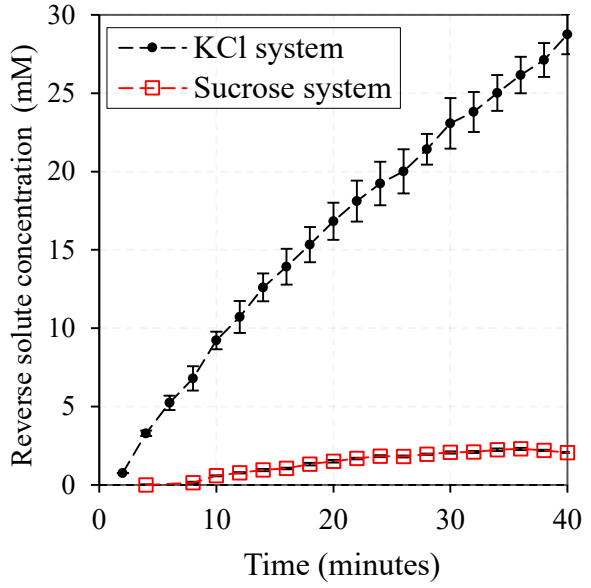

Figure 2: In-line profiles of total reverse flux of KCl and sucrose when they are used to concentrate solutions. Error bars represent the standard deviation of three separate experiments.

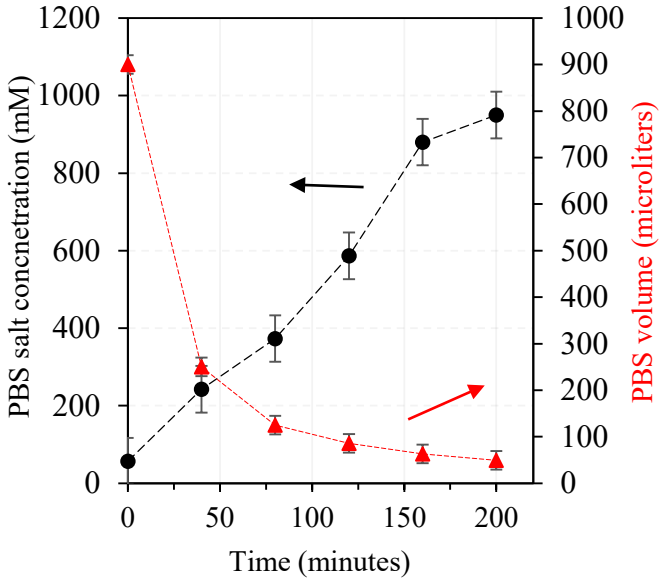

Figure 3:The amount of water in the PBS sample decreases while the salt concentration present in the sample increases proportionally. Error bars represent the standard deviation from three separate experiments.

CONCLUSION

Our forward osmosis concentration system, using sucrose, was able to concentrate a representative bodily fluid sample (PBS) ten-fold in under 2 hours, with minimal reverse flux of sucrose into sample. The results indicate the feasibility of using the microfluidic assembly for quantitatively concentrating 1 mL volumes of bodily fluid with a design that can be easily integrated into existing point-of-care diagnostic methods for improved sensitivity. We are using this approach to measure the concentration of pyocyanin, a redox-active virulence factor produced by *Pseudomonas aeruginosa*, spiked into urine samples using existing electrochemical sensor technology.

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REFERENCES

[1] H.J. Sismaet, T.A. Webster and E.D. Goluch "Up-regulating pyocyanin production by amino acid addition for early electrochemical identification of Pseudomonas aeruginosa." Analyst 139(17), 4241-4246, 2014.

[2] C.-H. Han, S.Y. Woo, A. Sharma, and J. Jang. "Rapid and selective electrokinetic concentration of bacteria using AC signal superposition on two coplanar electrodes." Proceedings of Micro Total Analysis Systems, 2017.

[3] D.G. Rackus, R.P.S. de Campos, C. Chan, M.M. Karcz, B. Seale, T. Narahari, C. Dixon, M.D. Chamberlain, and A.R. Wheeler. "Pre-concentration by liquid intake by paper (P-CLIP): A new technique for large volumes and digital microfluidics." Proceedings of Micro Total Analysis Systems, 2017.

CONTACT

* E. D. Goluch; phone: +1-617-373-3500; email: e.goluch@northeastern.edu