

A Miniature, Nongassing Electroosmotic Pump Operating at 0.5 V

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S Supporting Information

ABSTRACT: Electroosmotic pumps are arguably the simplest of all pumps, consisting merely of two flow-through electrodes separated by a porous membrane. Most use platinum electrodes and operate at high voltages, electrolyzing water. Because evolved gas bubbles adhere and block parts of the electrodes and the membrane, steady pumping rates are difficult to sustain. Here we show that when the platinum electrodes are replaced by consumed Ag/Ag₂O electrodes, the pumps operate well below 1.23 V, the thermodynamic threshold for electrolysis of water at 25 °C, where neither H₂ nor O₂ is produced. The pumping of water is efficient: 13 000 water molecules are pumped per reacted electron and 4.8 mL of water are pumped per joule at a flow rate of 0.13 mL min⁻¹ V⁻¹ cm⁻², and a flow rate per unit of power is 290 mL min⁻¹ W⁻¹. The water is driven by protons produced in the anode reaction 2Ag(s) + H₂O → Ag₂O(s) + 2H⁺ + 2e⁻, traveling through the porous membrane, consumed by hydroxide ions generated in the cathode reaction Ag₂O(s) + 2 H₂O + 2e⁻ → 2Ag(s) + 2 OH⁻. A pump of 2 mm thickness and 0.3 cm² cross-sectional area produces flow of 5–30 μL min⁻¹ when operating at 0.2–0.8 V and 0.04–0.2 mA. Its flow rate can be either voltage or current controlled. The flow rate suffices for the delivery of drugs, such as a meal-associated boli of insulin.

Solutions of drugs can be subcutaneously infused at modest, typically <1 kPa, pressures. A small and simple pump, having no moving parts, of a cost low enough to be replaced daily with its associated drug reservoir, might be used for parenteral delivery of drugs like insulin. The first electroosmotic insulin pump was reported in 1977 by Luft, Kuehl, and Richter.¹ Their refillable pump consisted of a polymeric ion-exchange membrane sandwiched between two Ag/AgCl electrodes. The pumped solution was saline water, which pushed a mobile separator to move the insulin solution so as to avoid insulin fouling of the electrode or the membrane. The nongassing pump delivered only 0.7 μL min⁻¹ at 1 mA cm⁻². This pump and later insulin-delivering electroosmotic pumps^{2,3} failed to reach their intended users. More recently Guzman et al. reported low-voltage gel electrophoresis of large polyanions in microchannels with rechargeable Ag/AgCl electrodes and 40–100 mM NaCl solutions,⁴ showing that electrolysis, resulting in gassing, can be avoided in electrophoretic systems. However, in 40 and 100 mM electrolytic solutions the electroosmotic flow rate and efficiency are reduced, respectively,

about 50- and 100-fold (Figure S1, Supporting Information, SI). This makes the delivery times of meal-associated fast-acting insulin boli, typically averaging about 160 μL, unacceptably long and the required pumps sizes excessively large.

High pressure and therefore greater power requiring electroosmotic pumps are presently applied in compact bioanalytical systems and microfluidic devices.^{5,6} Most have ceramic, e.g., silica, membranes, and platinum electrodes.^{7–10} Because their operating voltages are usually high enough to electrolyze water, trapped O₂ and H₂ bubbles insulate electrode and membrane areas from the liquid, making the flow irregular. For this reason, commercial pumps, such as those made by Nano Fusion Technologies (NFT, Tokyo) are built with a feedback loop, which comprises a flow meter and a constant flow rate-maintaining circuit.¹¹ Efficient low voltage, but still water electrolyzing, pumps were recently reported. Ai et al. built a pump with a platinum-coated 60 μm thick nanoporous alumina membrane operating at 1–5 V with a maximum flow rate of 0.074 mL min⁻¹ V⁻¹ cm⁻².¹² Lister et al. described an efficient plastic sheet-separated two-liquid pump made with a porous glass membrane and platinum mesh electrodes operating at 3 V, having a flow rate of 10 μL min⁻¹ at 25 μA. In the absence of feedback loops, the adverse effects of trapped bubbles were avoided by incorporating a catalyst for recombining the evolved H₂ and O₂¹³ or by AC-driving the flow,^{9,14,15} either of which increases the size or complexity of the system.

Here we show that by using reactive Ag/Ag₂O electrodes, which are consumed in the pumping process, nongassing, low DC voltage miniature pumps can be built. A small and simple pump of 2 mm thickness and 0.3 cm² cross-sectional area produces a flow rate of 14.5 ± 1.5 μL min⁻¹ when operating at 0.5 V and 0.1 mA. Its flow rate suffices for the delivery of drugs, such as a meal-associated boli of insulin. Because its electrodes are consumed, its operating life is limited but suffices, nevertheless, for use in a miniature, daily or twice-weekly replaced system, comprising the infused drug, e.g., the insulin solution, and the pump itself. The Coulombic capacity of its Ag of the anode is 2.6 C as is the Coulombic capacity of its Ag₂O cathode. These capacities suffice for 7.2 h continuous operation at 0.1 mA and for the pumping of as much as 6.3 mL of water, about 10 times the average daily infused insulin volume, typically 0.64 mL. To avoid fouling of the membrane, only pure water passes the pump. The drug solution is separated by a water-insoluble droplet, e.g., of silicone oil, which is pushed by the pumped water.

The 0.1 cm³ pump, of 8 mm outer diameter and 2 mm thickness, has a 1.3 mm thick 8 mm diameter membrane, formed

Received: November 13, 2010

Published: February 7, 2011

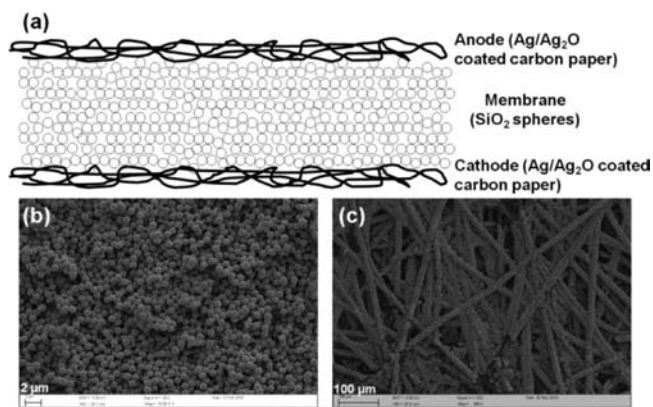


Figure 1. (a) Schematic diagram of the pump. The 1.3 mm thick 8 mm diameter membrane consists of fused, randomly packed, phosphosilicic acid-coated 1 μm diameter monodisperse silica microspheres. It is sandwiched between 280 μm thick, 78% porosity carbon paper electrodes, coated with 2.6 C equiv of Ag and Ag_2O . Scanning electron micrographs of (b) the membrane and (c) the silver plated, then electrooxidized carbon paper electrode (top-down view).

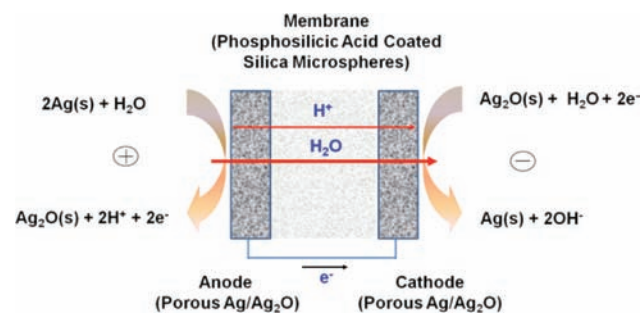


Figure 2. Electrode reactions and flow in the $\text{Ag}/\text{Ag}_2\text{O}$ /phosphosilicic acid on $\text{SiO}_2/\text{Ag}_2\text{O}/\text{Ag}$ pump formed by sandwiching the ceramic membrane between two $\text{Ag}/\text{Ag}_2\text{O}$ coated carbon paper electrodes.

by fusing phosphosilicic acid-coated silica microspheres and two identical flow-through $\text{Ag}/\text{Ag}_2\text{O}$ electrodes (Figure 1a). The membrane is made by pelletizing phosphosilicic acid-coated monodisperse silica microspheres of 1 μm diameter and firing for 4 h at 700 $^\circ\text{C}$. The microspheres are randomly packed; the void fraction is 47%, and the water-volume in the membrane is 18 μL (Figure 1b). The Si:O:P ratio, estimated from the Si_{2p} , O_{1s} and P_{2p} electron spectroscopy for chemical analysis peaks, is 31.5:64.8:3.7, from which the thickness of the 1:1 Si:P phosphosilicate surface layer is estimated at 1.4 nm, equivalent to about five monolayers. The zeta (ζ) potential of the coated microspheres is -34 mV. The flow-through $\text{Ag}/\text{Ag}_2\text{O}$ electrodes are formed of 280 μm thick 78% porosity carbon paper, on which silver is plated, followed by anodizing half of the silver. The Coulombic capacity of both the Ag and the Ag_2O is 2.6 C. The pores of the carbon paper are not blocked by the plated and half anodized silver (Figure 1c). With 1 mm of the membrane's rim covered in the pump's assembly, the pump's active, water-contacting area is 0.3 cm^2 , and its diameter is of 6 mm. For contacting, two gold foil lips are inserted between the electrodes, and the membrane and the assembly are epoxy encapsulated. Further details of the membrane and electrode preparations are provided in the SI.

Figure 2 shows the reaction and transport scheme of the pump. At the porous $\text{Ag}/\text{Ag}_2\text{O}$ anode, Ag is electrooxidized to

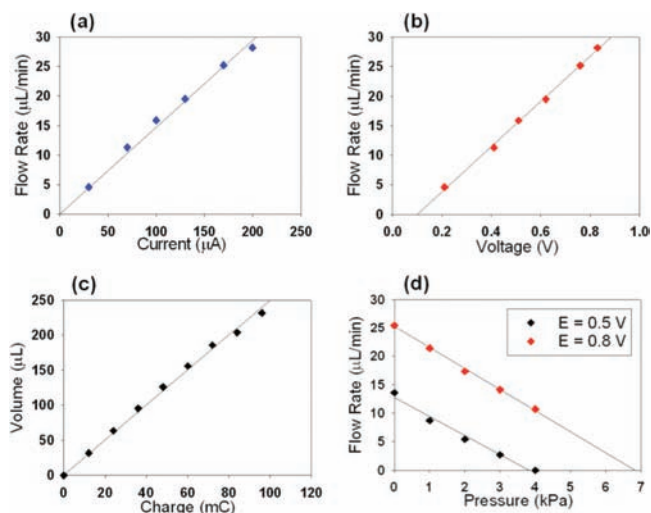
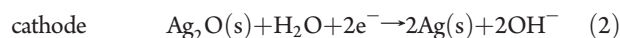
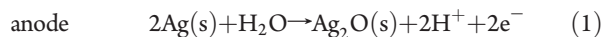


Figure 3. Dependence of the flow rate on the (a) applied current and (b) operating voltage. (c) Dependence of the delivered volume on the charge at 0.1 mA constant current. (d) Dependence of the flow rate on the flow opposing pressure at 0.5 and 0.8 V constant voltage at 24 $^\circ\text{C}$; 2 mm thick and 0.3 cm^2 active cross-sectional area pump.

Ag_2O , and a flux of protons is generated through reaction 1. After passing the membrane, the protons combine with hydroxide anions, generated by reaction 2, the electroreduction of Ag_2O to Ag:



A flow rate of $14.5 \pm 1.5 \mu\text{L min}^{-1}$ is maintained when a constant current of 0.1 mA is applied. The potential difference between the anode and the cathode is 0.5 V, i.e., the power consumption is 50 μW . Then 4.8 mL of water are pumped per joule at a rate of 290 $\text{mL min}^{-1} \text{W}^{-1}$, and 13 000 water molecules are pumped per reacted electron. The flow rate increases linearly with the applied current (Figure 3a), the slope being $150 \text{ mL min}^{-1} \text{A}^{-1}$; the line relating the flow and the current passes through the origin, showing that there is no flow in the absence of a current. The dependence of the flow rate on the voltage is also linear (Figure 3b), with flow starting at 0.12 V. The slope is $38 \mu\text{L min}^{-1} \text{V}^{-1}$, i.e., $0.13 \text{ mL min}^{-1} \text{V}^{-1} \text{cm}^2$. The ohmic resistance, calculated from the data in Figure 3, is 3.6 $\text{k}\Omega$, close to the 3.4 $\text{k}\Omega$ value obtained independently by measuring the AC impedance. The volume of the pumped water increases linearly with the passed charge (Figure 3c). In 24 h tests, during which 0.1 mA current is applied intermittently for 10 min periods, boli of $130 \pm 6 \mu\text{L}$ are delivered. The flow rate decreases linearly with the flow-opposing pressure, dropping to nil at 4 kPa at 0.5 V constant applied voltage and at 7 kPa at 0.8 V constant applied voltage (Figure 3d).

Upon adding a nonreacting electrolyte, such as KNO_3 , the resistance decreases from 3.5 $\text{k}\Omega$ at 0.01 mM, to 3.2 $\text{k}\Omega$ at 0.1 mM, to 2.0 $\text{k}\Omega$ at 1 mM, and to 0.6 $\text{k}\Omega$ at 10 mM. The flow rate also decreases (Figure S1, SI). An increase in KNO_3 concentration from 0 mM to 1 mM halves the flow rate and causes the voltage to drop from 0.50 to 0.35 V at 0.1 mA.

Independent measurement of the potential of each electrode in 0.5 mM KNO_3 with a three electrode potentiostat at 0.1 mA applied current shows that the anode potential is +0.41 V vs Ag/AgCl

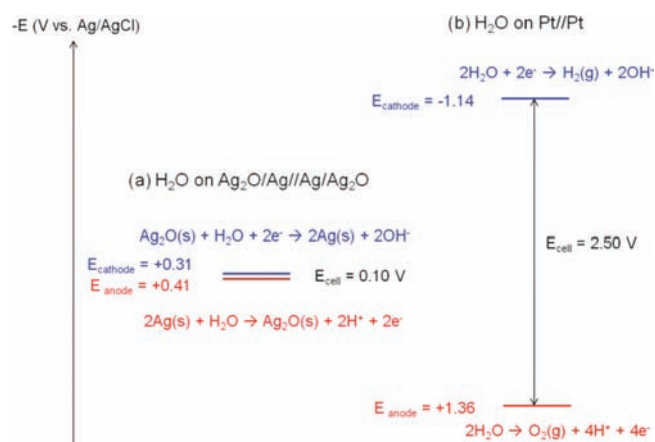


Figure 4. Electrode potentials of the Ag/Ag₂O pump (left) and of the NFT RPSA-RL-N610 pump, having Pt electrodes (right).

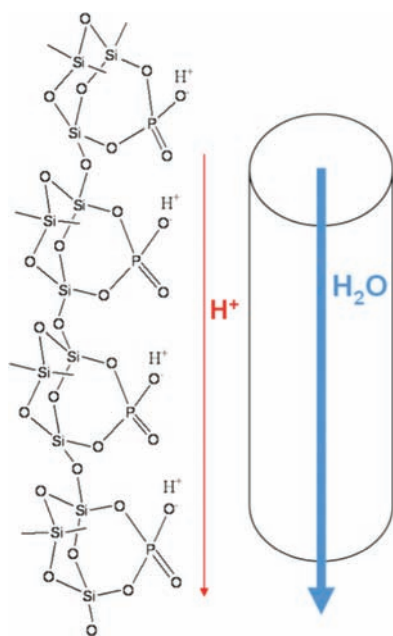


Figure 5. Model showing the water flow inducing proton transport through the interfacial phosphosilicic acid layer.

and that the cathode potential is +0.31 V vs Ag/AgCl (Figure 4a). Because the cell resistance is 3.4 k Ω , the ohmic drop for the applied 0.1 mA current is 0.34 V, about 70% of the 0.5 V operating voltage; the small residual voltage, associated with the potential difference between the anode and cathode, shows that reactions 1 and 2 are close to reversible and that it is the near reversibility that allows the pump to operate at a low voltage. Measurement of the potentials of the NFT RPSA-RL-N610 pump's O₂ and H₂ evolving platinum electrodes, at the same current density, shows that the anode potential is +1.36 V vs Ag/AgCl and that the cathode potential is -1.14 V vs Ag/AgCl (Figure 4b). A 2.9 V operating voltage is required for a 9 $\mu\text{L min}^{-1}$ flow rate. The cell resistance is 3.5 k Ω , and the ohmic drop is 0.35 V. Thus, most of the voltage is consumed in the electrolysis of water, not in driving the flow, reducing the energy efficiency of the pump.

Protons are hydrated only by 2–8 water molecules,¹⁶ and the mobility of hydrated protons in bulk water does not explain the

flux of 13 000 water molecules per reacted electron. In the absence of physical contact between the Ag/Ag₂O anode and the ceramic membrane or between the membrane and the cathode, we observe no measurable flow, even if the gap is small. We explain the high power efficiency of 290 mL min⁻¹ W⁻¹ at 0.5 V, about twice the highest reported,¹⁷ as well as the necessity for physical contact between both electrodes and the membrane by fast transport of protons at the solid electrode and membrane surfaces. Accordingly, protons generated at the anode (reaction 1) and consumed by OH⁻ ions generated at the cathode (reaction 2) propagate not in the water bulk but through the surface of the anionic phosphosilicic acid (-34 mV ζ -potential), dragging the proximal water sheet. Flow is induced by momentum transfer from the sheet to the water bulk (Figure 5). Proton transport through water-bounded P-OH and Si-OH surfaces is well-known. It underlies, for example, the very high proton conductivity of porous phosphosilicate glasses.^{18,19}

In summary the utilization of a consumable, nongassing, nearly reversible proton-producing anode and a similar proton-consuming cathode enables efficient electroosmotic pumping at a very low voltage. A simple pump built with such electrodes, 2 mm thickness and 0.3 cm² cross-sectional area, produces a flow sufficient for the delivery of drugs, such as a meal-associated bolus of insulin.

■ ASSOCIATED CONTENT

S Supporting Information. Experimental details and Figure S1. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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■ ACKNOWLEDGMENT

This study was performed at the University of Texas, Austin, while W.S. and J.M.L. were on leave from the Sogang University. R.K.N. and A.H. thank the Welch Foundation (grant no. 1131) for support. W.S. thanks the National Research Foundation of Korea (NRF-2009-C1AAA001-2009-0093879) for travel support.

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