Integration of paper-based microfluidic devices with commercial electrochemical readers†

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Received 24th July 2010, Accepted 14th September 2010
DOI: 10.1039/c0lc00237b

The combination of simple Electrochemical Micro-Paper-based Analytical Devices (EμPADs) with commercially available glucometers allows rapid, quantitative electrochemical analysis of a number of compounds relevant to human health (*e.g.*, glucose, cholesterol, lactate, and alcohol) in blood or urine.

Introduction

This article describes a simple, electroanalytical system—based on the combination of a commercial hand-held glucometer with easily fabricated Micro-Paper-based Analytical Devices (μPADs)—that is useful in quantitative analysis of metabolites such as glucose, cholesterol, and lactate in human plasma or whole blood, and ethanol (or acetaldehyde) in aqueous solution. These electrochemical devices (which we call Electrochemical μPADs or EμPADs) provide fluid handling and support sensing electrodes; an inexpensive, commercial electrochemical reader (a glucometer) carries out electrochemical analyses and displays the results in digital format. The glucometer is an amperometer that is used to measure the quantity of an electroactive species formed by the reaction of glucose with reagents stored in the test strips.[1] The EμPADs include microfluidic channels, electrodes, and electrical interconnects fabricated in chromatography paper using wax printing and screen printing (Fig. 1A and B). The wires were printed using silver ink, and four electrodes (a working electrode, a counter electrode, and two internal reference electrodes) were printed using graphite ink.

The chemical reagents needed for the assays of glucose and alcohol were stored in the detection zone of the EμPAD. To use this system, we usually inserted the dry EμPAD into the port of the glucometer. After applying a drop of fluid to the exposed end of the EμPAD, and allowing liquid containing the analytes to wick to its sensing region, the glucometer initiated amperometric measurement, and displayed the electrochemical readout on its LCD screen (Fig. 1C). In some reactions (*e.g.*, those for lactate and cholesterol), when the time interval required to complete the enzymatic reactions was greater than the 10 second waiting-time set in the glucometer, we mixed the solution of analytes with the chemical reagents needed for the assays in a small centrifuge tube (the mixing can also be conducted on any clean substrate such as a plastic thin film or the surface of a table), and allowed the reaction to proceed to completion. We then inserted a dry EμPAD into the port of the glucometer, and dipped the exposed end of the EμPAD into this reacted solution to perform the analysis.

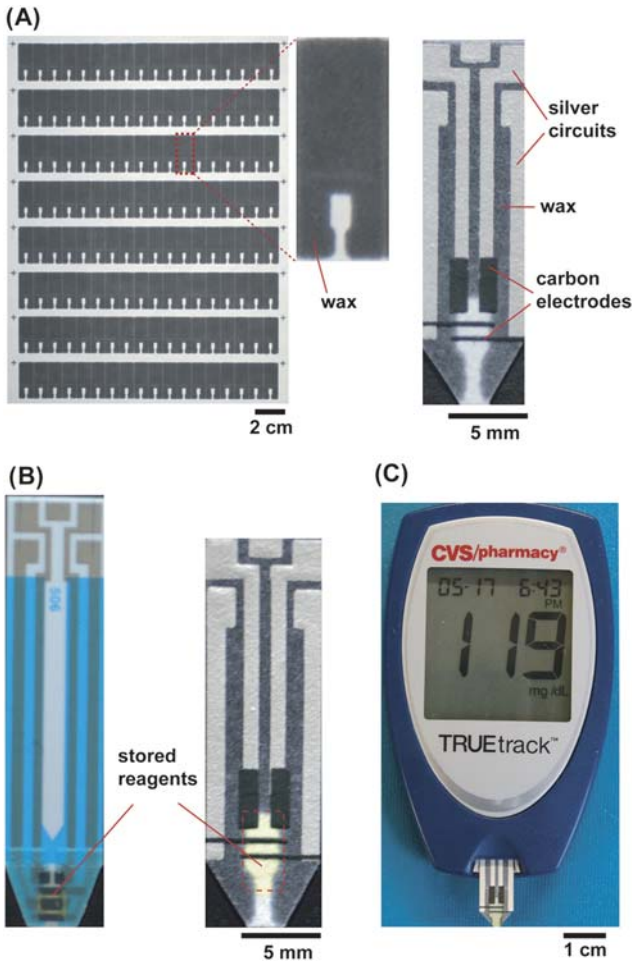

Fig. 1 Components of an EμPAD-based system that uses a commercial glucometer as an electrochemical reader. (A) Arrays of microfluidic paper channels fabricated in chromatography paper using wax printing, and an enlarged image of one paper channel (left) and a representative microfluidic paper device with electrodes and electronic wires fabricated using screen printing (right). The number of devices that could be fabricated on one US letter-sized page was approximately 150–200. (B) A photograph of a commercial test strip made from plastic (left) and an EμPAD made from a single layer of paper (right); chemical reagents were stored in dry form in the detection zone in the dashed square. (C) The glucometer used as a reader. An EμPAD was inserted into the test port with the contacts and the display facing up. After applying an aqueous solution containing analytes, the glucometer displayed the electrochemical readout on its LCD screen.

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† Electronic supplementary information (ESI) available: fabrication of EμPADs, measurement of analytes in EμPADs using glucometers, assays, electrochemical behavior of EμPADs, and performance of two-layer EμPADs. See DOI: 10.1039/c0lc00237b

This work is part of a broad effort to develop high-quality, low-cost biomedical analyses appropriate for use in the developing world and in resource-limited settings.[2–8] Here we take advantage of a highly developed and commercially successful technology—the electrochemical quantification of glucose in blood—for other applications. We believe that these electrochemical systems possess the characteristics required to be useful in a range of applications, including human, animal and plant diagnostics, food-quality control, and environmental monitoring.[9,10]

The technology used in the currently available glucometer is based on the quantitation of electron-transfer mediators (*e.g.*, ferrocyanide) generated by the enzyme-catalyzed oxidation of glucose (eqn (1), GOx is glucose oxidase).[1,11,12] Glucometers are designed to combine specificity based on enzymes and electrochemistry for quantitation. Amperometry makes the device relatively insensitive to variations in the catalytic activity of the GOx.[11]

$$\text{D-glucose} + H_2O \xrightarrow[2e^-]{\text{GOx}} \text{Gluconic acid} + 2H^+ \qquad (1)$$
$$2Fe(III)CN_6^{3-} \quad 2Fe(II)CN_6^{4-}$$

Our objective here is to demonstrate that glucometers have the combination of characteristics needed in a broad range of assays in resource-limited environments. We take the advantage of three facts. (i) The market for blood testing devices is sufficiently large that the costs for development of this successful and robust technology have already been absorbed. (ii) These electrochemical devices integrate smoothly with Micro-Paper-based Analytical Devices (μPADs)[6,13] that we are developing, and can thus be adapted to analyze a broad range of analytes. (iii) The output of these systems can be read directly, or coupled to cell phones, for telemedicine-based applications.

EμPADs

We[14] and others[15–17] have recently developed microfluidic paper-based electrochemical devices capable of quantitative analysis of a range of substances (*e.g.* glucose, enzymes, serum proteins, and heavy metal ions) in aqueous solutions. Although electrochemistry provides an enormously powerful set of analytical methods, electrochemical systems of the types used in research, industrial, and clinical laboratories are too expensive and cumbersome to be practical for use in resource-limited environments. Glucometers provide, we believe, a way to bridge the gap between laboratory use and field use of electrochemistry.

Commercially available electrochemical glucose test strips are typically made on a plastic substrate and their price (including margin) in the US, ~$0.5 to 1.0 per strip,[1,18] is impractically high for applications in the developing world. Test strips that would be produced at lower cost, and that would assay analytes other than glucose, might fit a range of uses. Glucose testing for diabetes control is currently the dominant application of glucometers, but we believe that this technology can be extended to a large group of substances other than glucose.

The electrochemical analytical system described in this article has at least five advantages. (i) It is simple, fast (<60 s for detection, for systems that develop most rapidly), and low-cost (at current stage of development, ~$0.014 per strip for the materials and use of equipment[19] for a glucose test). There are clear opportunities to lower this cost further, and to fabricate a glucometer for substantially less than $10. (ii) The strips are lightweight, portable, rugged, and safely disposable by incineration.[20] (iii) It does not require professional medical personnel or complicated instruments. (iv) The same reader can be adapted to a range of different analytes. (v) Electrochemical methods are insensitive to light, dust, and insoluble particulates, and are thus applicable to dirty environments, and to samples containing suspended solids (where optical methods might fail). This system has three disadvantages: (i) It requires batteries (one 3 V lithium battery is capable of carrying out approximately 1100 measurements). (ii) Its assays are susceptible to interferences from electrochemically active substances. (iii) Certain assays may be sensitive to temperature.

Experimental design

Fabrication of the devices

We fabricated paper-based microfluidic channels by patterning chromatographic paper (Whatman 1 Chr) by wax printing, as described previously.[21] We screen-printed wires and contact pads using silver ink, and four electrodes from graphite ink, on a piece of patterned paper.[10] The external circuits do not contact the solution of analytes being measured, and less expensive conducting inks (*e.g.*, copper or aluminium ink) could be used to lower the cost of the test strips further. The silver wires and carbon electrodes firmly attached to the paper device due to the penetration of binding reagents in the inks into the paper matrix. The silver wires and carbon electrodes do not break or peel off from the device upon folding.

Glucometers

We chose the True Track™ blood glucometer[22] (CVS/Pharmacy) as the electrochemical reader. This glucometer has two attractive characteristics. (i) Its cost is low (the meter retails for about $20 for each; however, it is usually supplied free with the test strips), and it is simple to use. (ii) It is easy to reverse engineer the format used in its test strips into a format that fits our needs. Other glucometers could also be used. The design required differs with the test: one that requires concentration—for example, for the analysis of water—might be different from one that works with blood, and one that required removing cells from blood by filtration might be different from the one used with whole blood or urine.

Since commercial test strips may vary from batch to batch, this model of glucometer requires the user to enter a code on a code chip that comes with the test strips. Inserting the code chip into the glucometer calibrates it for that batch of test strips (Fig. S2†). We have not tried to replicate this level of calibration in our present work.

Design of paper-based electrochemical devices

We designed the EμPADs to fit into the port of the glucometer. We fabricated the circuits of the EμPAD to mimic the format of

the test strips sold for this device. We treated the detection zones of the EμPAD with a solution of 2 wt% 3-aminopropyldimethylethoxysilane (APDES) in water to enhance the hydrophilicity of the paper channels, and of the electrodes.[23,24]

Methods and principles of detection

We measured concentrations of D-glucose, cholesterol, L-lactate, and ethanol on the EμPADs using amperometry, utilizing the glucometer as an electrochemical reader. Eqn (2) generalizes the reactions for the amperometric detection of D-glucose, cholesterol, and L-lactate.[1,10,12,25]

$$\text{Substrate(CHOH or CH=O)} + H_2O \xrightarrow{\text{Enzyme}} \text{Substrate(CH=O or } COO^-) + 2H^+$$
$$2Fe(III)(CN)_6^{3-} \xrightarrow{2e^-} 2Fe(II)(CN)_6^{4-} \quad (2)$$

In the enzyme-catalyzed step, glucose oxidase (GOx), or another oxidase, catalyzed the oxidation of glucose (or cholesterol or lactate) to gluconic acid (or cholest-4-en-3-one or pyruvate) with concomitant reduction of Fe(III) to Fe(II) (eqn (2)); The $Fe(II)(CN)_6^{4-}$ ions generated were detected amperometrically.

Eqn (3) and (4) describe the mechanism of enzymatic detection of ethanol in the presence of β-NAD^+.[10] The oxidation of ethanol to acetaldehyde in a reaction catalyzed by alcohol dehydrogenase reduced β-NAD^+ to NADH (eqn (3)). The electron-transfer mediator ferricyanide present in the solution rapidly oxidized the NADH to β-NAD^+ with concomitant reduction of Fe(III) to Fe(II) (eqn (4)); the $Fe(II)(CN)_6^{4-}$ ions generated were detected amperometrically.

$$CH_3CH_2OH + NAD^+ \xrightarrow{\text{Alcohol dehydrogenase}} CH_3CHO + NADH + H^+ \quad (3)$$

$$NADH \xrightarrow{2e^-} NAD^+ + H^+$$
$$2Fe(III)(CN)_6^{3-} \quad 2Fe(II)(CN)_6^{4-} \quad (4)$$

Results and discussion

Optimization of the design of EμPAD

We used EμPADs made from a single layer of paper (as opposed to two or more layers; even though multilayer designs may be useful or even required in some complex assays). These EμPADs incorporated channels patterned with hydrophobic walls to control the flow of liquids and to support the electrochemical measurements (Fig. 1A and B). A single-layer platform has at least three advantages. (i) It allows reproducible conformal contact between the electrodes and the paper channels. (ii) Its fabrication can be scaled to large numbers (10^{3-4} strips per day by hand or 10^{7-8} strips per day by machine). (iii) It requires a smaller quantity of solution of analytes than multilayer devices.

It was important to treat the detection zone of the EμPADs with APDES or another agent that enhanced wetting, in order to: (i) increase the hydrophilicity of the surface of the graphite electrodes, and thus the effective area of contact of the electrode surface with the solution of analytes (Fig. S3†), and (ii) increase the rate of wicking of the solution of analytes in the paper channel. If the rate of mass transport of fluids is not sufficiently rapid to deliver the fluids to wet all electrodes, the glucometer displays an error message.

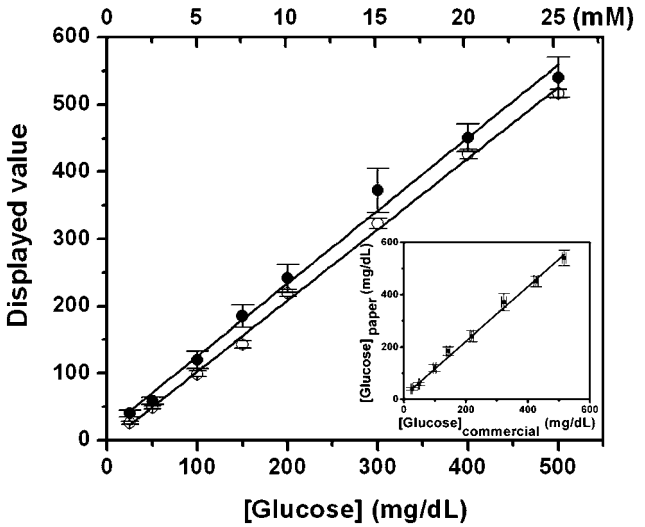

Fig. 2 Calibration plots for the analysis of glucose in human plasma in commercial test strips (○) and in EμPADs (●) made from a single layer of paper, using a commercial glucometer. The solid lines represent linear fits to experimental data with regression equations: $y = -2.9 + 1.05x$ ($R^2 = 0.997$, $n = 7$) (○) and $y = 17.0 + 1.09x$ ($R^2 = 0.993$, $n = 7$) (●). Inset shows the readings of glucose concentration in EμPADs plotted as a function of glucose concentration measured by commercial test strips. The solid line in the inset represents a linear fit to experimental data with a regression equation: $y = 11.9 + 1.05x$ ($R^2 = 0.995$, $n = 7$). $[Glucose]_{paper}$: the displayed concentration of glucose in EμPADs. $[Glucose]_{commercial}$: the displayed concentration of glucose in commercial test strips.

Evaluation of the meter for the use in EμPAD

In order to fit the capability of the glucometer to our electrode geometry, we adjusted the dimensions of the electrodes of the EμPAD to make the measured currents fit the desired range of concentrations.[26] Based on the Cottrell equation, the electrical current, i, of the system is linearly proportional to the surface area, A, of electrode ($i \propto A$).[27] In principle, the same objective might be achieved by reprogramming the code chip that comes with the glucometer; but to do so would require more understanding of the design, circuiting, and control of the device than we have.

To evaluate the compatibility of the commercial glucometers with our EμPADs, we generated a calibration curve for the measurement of glucose in human plasma (Fig. 2). The value of glucose concentration displayed by the glucometer increased linearly with the concentration of glucose, [glucose]; the slope of this plot was 1.09 unit per mg dL^{-1} (intercept, 17.0, correlation coefficient, 0.993). The analysis of glucose in human plasma in commercial plastic-based test strips produced a similar linear calibration curve with a slope of 1.05 unit per mg dL^{-1} (intercept, −2.9, correlation coefficient, 0.997) (Fig. 2).

The range of linear concentrations in EμPADs (from 0 to 500 mg dL^{-1}) covers the medically relevant range of glucose concentrations (~70 to 120 mg dL^{-1}).[1] A wider linear range of concentrations—for example in food testing—could be achieved by optimizing the geometry of the device and the surface area of working electrode, although the precision of the device might suffer.

Table 1 summarizes the comparison between the performance of the analysis of glucose in EμPADs with that in commercial test strips. The limit of detection (LOD) was calculated as the concentrations which produced three times SD_0, where SD_0 is the value of the standard deviation as the concentration of the analyte approaches zero. The lower LOD of 26 mg dL^{-1} glucose obtained using EμPADs is slightly larger than the LOD of 15 mg dL^{-1} glucose achieved with commercial test strips. The mean coefficient of variation in these analyses in EμPADs was 9.1%. This value is approximately twice the 4.1% of the commercial glucose test strips.[22] We attribute the higher value of this coefficient of variation in EμPADs to variations in the width of paper channels fabricated by wax printing, and to variations in the width of electrodes fabricated by screen printing; the reproducibility of measurements in our system could certainly be increased by improved engineering and standardized fabrication.

The minimum volume of samples required to wet the paper channel completely was approximately 1.0 μL for the design of the EμPAD used for this specific assay; this quantity can be decreased further by shortening the length of paper channel, or by using a thinner paper. This EμPAD is probably sensitive to temperature, due to rates of evaporation and wicking of solutions.

We compared the analysis of glucose in human whole blood using EμPADs with commercial test strips. We brought the inlet of an EμPAD into contact with a small droplet of blood obtained from a fingerprick. The blood containing blood cells rapidly filled the paper channel by wicking (this way does not require the paper to remove cells), and the glucometer initiated the electrochemical measurement, and displayed the result of measurement. The levels of glucose in whole blood are generally 10–15% lower than glucose in plasma;[28] and the concentrations of glucose in blood, $[glucose]_{blood}$, can be approximated to the measured values of plasma glucose, $[glucose]_{plasma}$ ($[glucose]_{blood} = [glucose]_{plasma}/1.14$).[29] The calibration curves for the analysis of glucose in human plasma (Fig. 2) were therefore used to determine the concentration of glucose in blood. The corrected concentration of glucose in blood was 95 ± 9 mg dL^{-1} ($n = 8$) measured in EμPADs; this value was about 4.4% lower than the value 99 ± 3 mg dL^{-1} ($n = 3$) obtained in commercial test strips.

We conclude that—at this stage of the work (laboratory prototype)—the performance of the EμPADs is roughly equivalent to that of commercial test strips. Since we are using the same chemistry as that used commercially, the agreement is not surprising. It does, however, validate EμPADs as electrochemical sensors for use—in conjunction with commercial glucometers—in biomedical sensing.

Applications in analyzes other than glucose

We evaluated the feasibility of using EμPADs and this glucometer to measure the concentration of analytes other than glucose. We demonstrated the analysis of cholesterol and L-lactate in human plasma as well as ethanol in aqueous solutions.

Clinical diagnostics: analysis of cholesterol and L-lactate in body fluids

The concentration of cholesterol in human plasma is less than 5.2 mM (200 mg dL^{-1}).[30] The analysis of cholesterol in human plasma using cholesterol oxidase yielded a linear calibration plot in the concentrations ranging from 20–200 mg dL^{-1} (0.5–5.2 mM);[31] these values cover the clinically relevant range of cholesterol concentrations (Fig. 3A).[30] The limit of detection was 13 mg dL^{-1} (0.34 mM) and the sensitivity was approximately 0.8 unit per mg dL^{-1}. The mean coefficient of variation of these analyses was about 6.2% ($n = 7$).

The clinically relevant range of L-lactate concentrations is from 0.5 to 15–20 mM in serum or plasma.[32,33] Commercial lactate meters have a range of 0.8–23.3 mM with a 60 s sampling time, and require 5 μL of sample. We demonstrated the use of the glucometer to analyze the concentration of L-lactate in human plasma. The calibration curve for the measurement of L-lactate shows that the values displayed are linearly proportional to the L-lactate concentrations in the range of 1–11 mM with a sensitivity of 2.8 units per mg dL^{-1} (~25.5 units per mM) (Fig. 3B). The concentration range for quantitative detection is, therefore, slightly narrower than the clinically relevant range at this stage of development of EμPADs. The reliable lower limit of detection was 9.8 mg dL^{-1} (~1.1 mM).[34] Both assays of cholesterol and L-lactate on these specific EμPADs require approximately 1.2–1.5 μL of fluid; this value is determined by the quantity required to wet the paper channels completely. Although it would be straightforward to tune the geometry of EμPADs to adjust the displayed values closer to actual concentrations of analytes, we

Table 1 Comparison of the performance of EμPADs with commercial plastic-based glucose test strips

Substrate	Linear dynamic range/mg dL^{-1}	Limit of detection/mg dL^{-1}	Mean coefficient of variation (%)[b]	Minimum volume of sample/μL	Test for blood samples/mg dL^{-1}[c]
Commercial test strips	~0 to 550[a]	~15	4.1	~1.0	99 ± 3[d]
Paper strips	~0 to 500	~26	9.1	~1.0	95 ± 9[e]

[a] The linear dynamic range reported previously was 0–600 mg dL^{-1}.[22] [b] The mean coefficient of variation was calculated by averaging relative standard deviations of the measurements of standard solutions with glucose concentration of 25, 50, 100, 150, 200, 300, 400, and 500 mg dL^{-1}. [c] For the analysis of blood samples with unknown concentration of glucose, a small drop of blood was obtained by pricking the skin with a steel lancet. [d] Three measurements were averaged. [e] Eight measurements were averaged.

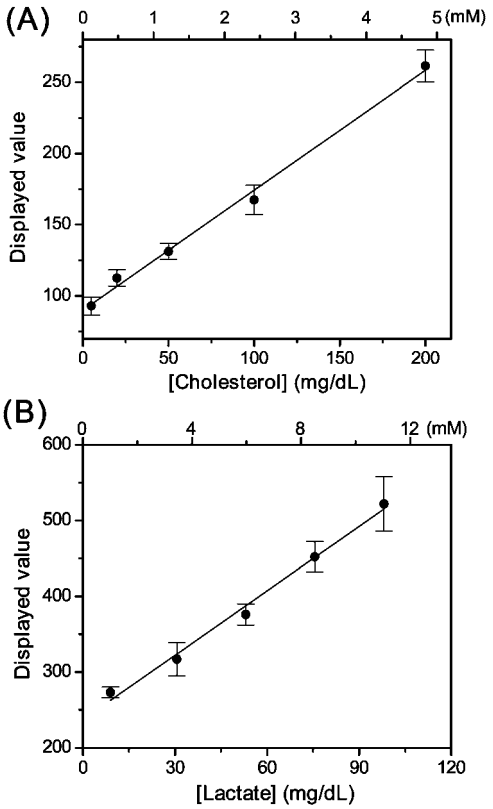

Fig. 3 Application of glucometers as electrochemical readers for measuring the concentrations of cholesterol and L-lactate in human plasma. Calibration plots for the analysis of cholesterol (A) and L-lactate (B) in EμPADs. The solid lines represent linear fits to experimental data with regression equations: (A) $y = 90.1 + 0.8x$ ($R^2 = 0.962$, $n = 7$) and (B) $y = 236.7 + 2.8x$ ($R^2 = 0.989$, $n = 7$).

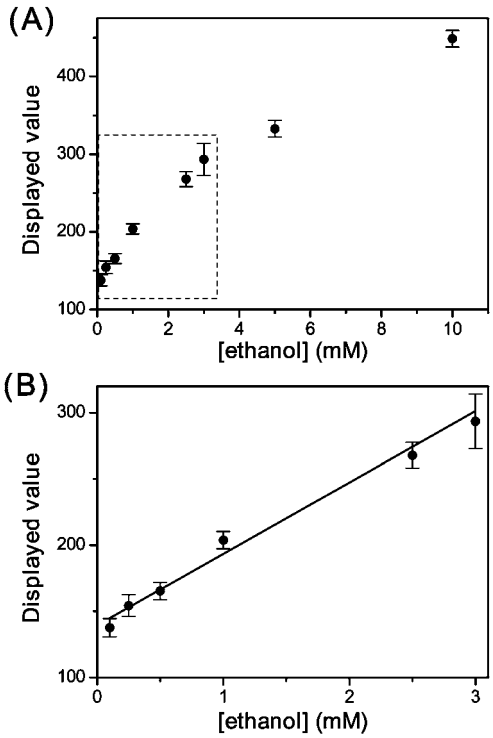

Fig. 4 Glucometers as electrochemical readers for the analysis of ethanol. (A) Calibration plot for the analysis of ethanol in aqueous solutions and (B) an enlarged graph in the dashed square in (A). The solid line in (B) represents a linear fit to experimental data with a regression equation: $y = 139.4 + 53.9x$ ($R^2 = 0.970$, $n = 7$).

have not done so for the cholesterol and L-lactate systems in the same way as we did for the glucose system. It would also be possible to use a chip to adjust for the response produced by our EμPADs, since different batches of commercial test strips are accompanied with individual calibration codes embedded in code chips.

We note that the glucometer displays a non-zero value in the analysis of sample solutions in the absence of analytes (Fig. 3). We attribute this value to background contributions due to the charging process of the electrical double layer, and to the redox reactions of ferrocyanide generated by the degradation of a small fraction of ferricyanide in solutions (even if the solution of electron-transfer mediators is freshly prepared).[35] Although this measured value could be calibrated to display an actual concentration of analytes.

Food quality control: analysis of alcohol in water

The electrochemical system has the potential to be useful in food quality control. We used EμPADs and glucometer to measure the concentration of ethanol. The calibration plot for the analysis of ethanol (Fig. 4A and B) showed a linear range from 0.1 to 3 mM ($R^2 = 0.970$) with a sensitivity of 54 units per mM. The limit of detection was 0.1 mM, and the coefficient of variation ranged from 3.2% to 10.1%.

Table 2 summarizes the performance of this electrochemical system for these analyses. The linear ranges of detection as well as the limit of detection achieved in EμPADs cover useful ranges, but leave substantial room for engineering improvement.

Conclusions

The EμPADs are compatible with commercially available glucometers. The use of glucometers as readers for EμPADs substantially increases the range of options for combining paper-based analytical devices and electrochemical detection for applications in resource-constrained environments. This electrochemical system has six potential advantages. (i) It is portable, reliable, and inexpensive. (ii) It takes advantage of the sophisticated engineering already embedded in commercially available, inexpensive glucometers. (iii) It can be adapted to analytes other than glucose. (iv) Electrochemistry—unlike colorimetry and spectrophotometry—is insensitive to local light conditions, and to certain types of contaminants (suspended solids, colored materials) present in samples. (v) It can be interfaced with a cell phone (either by human reporting of the data, by photography of the LCD display or, in principle, by a coded interface). It can also be used in home patient care with telephone or Internet communications.[13] (vi) It can also in principle be adapted to a range of different types of assays (amperometry, as here;

Table 2 Glucometers as electrochemical readers for amperometric detection in EμPADs

Analyte	Enzyme	Electron-transfer mediator	Dynamic linear range	Limit of detection	Notes
Glucose	Glucose oxidase	Ferricyanide	0–500 mg dL^{-1}	26 mg dL^{-1}	Pre-stored[a]
Ethanol	Alcohol dehydrogenase/β-NAD^+	Ferricyanide	0.1–3 mM	0.2 mM	Pre-stored
Cholesterol	Cholesterol oxidase	Ferricyanide	20–200 mg dL^{-1}	13 mg dL^{-1}	Pre-mixed[b]
L-Lactate	Lactate oxidase	Ferricyanide	1.1–11 mM	1.1 mM[c]	Pre-mixed

[a] Pre-stored: we stored chemical reagents needed for the assay on the EμPAD, and carried out the assay with the EμPAD in glucometer. [b] Pre-mixed: we mixed chemical reagents needed for the assay with a solution containing analytes, and allowed the reaction to proceed to completion off the EμPAD. The glucometer was used simply as an amperometer to read the result. [c] The commercially available human plasma itself contains 1.1 mM lactate before the addition of any lactate. In fact, we were able to detect 0.5 mM of lactate in PBS buffer solution (pH 7.0).

chronoamperometry, cyclic voltammetry, anodic stripping voltammetry, electrochemiluminescence and others).

The EμPAD has at least five useful characteristics for applications in resource-limited environments (no plastic strips have all of these characteristics). (i) It is well suited to mass-production at low cost using wax-printing and screen-printing technologies. It can, therefore, be manufactured almost everywhere, and easily adapted to local use. (ii) It can be used in analyses of complex fluids (*e.g.*, blood, urine, and saliva), even when they contain suspended solids and dirt. (iii) Its fundamental design is sufficiently simple that this design can be modified to generate test strips that fit into different types of glucometers, or that carry out different analytes. (iv) It is based on a system of paper-based microfluidic devices of rapidly increasing sophistication. The programming of flows of fluids in these devices makes it possible to carry out analysis requiring multiple steps, without using extra instruments such as pumps.[36] (v) It has sufficient flexibility to incorporate a variety of different functionalities—concentration of analytes by evaporative heating, and chromatographic separation of analytes from interference—while retaining the interface to the glucometer.

At this stage of development, the EμPADs that we have fabricated are slightly less accurate than commercial test strips, possibly due to the manual procedures we used in their fabrication; this accuracy will certainly improve with further engineering and attention to manufacturing detail. We are aware that detection in EμPADs might be sensitive to temperature and humidity due to temperature- and humidity-dependent evaporation rate of water from the solution of analytes in the open channels. A systematic study needs to be carried out to achieve a better understanding on this issue; this problem, however, can be fixed by improved engineering, such as sealing the detection zone with transparent tape.

Acknowledgements

This work was supported by the Bill and Melinda Gates Foundation (51308), and by the Micro/Nano Fluidics Fundamentals Focus (MF3) Center (Defense Advanced Research Projects Agency), the National Institutes of Environmental Health and Safety (016665), and postdoctoral fellowships from the Natural Science and Engineering Research Council of Canada (to Z.H.N. and X.Y.L.).

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