Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/watres

Tools for water quality monitoring and mapping using paper-based sensors and cell phones

Clémence Sicard [a,1], Chad Glen [b,1], Brandon Aubie [c], Dan Wallace [c], Sana Jahanshahi-Anbuhi [b], Kevin Pennings [b], Glen T. Daigger [d], Robert Pelton [b,c], John D. Brennan [a,c,*], Carlos D.M. Filipe [b,c,*]

[a] Biointerfaces Institute and Department of Chemistry & Chemical Biology, McMaster University, 1280 Main Street West, Hamilton, ON L8S 4L89, Canada

[b] Department of Chemical Engineering, McMaster University, 1280 Main Street West, Hamilton, ON L8S 4L7, Canada

[c] Biointerfaces Institute, McMaster University, 1280 Main Street West, Hamilton, ON L8S OA3, Canada

[d] CH2M HILL, Englewood, CO 80112, United States

ARTICLE INFO

Article history:
Received 4 April 2014
Received in revised form
27 November 2014
Accepted 3 December 2014
Available online 12 December 2014

Keywords:
Paper-based sensors
Water
Pesticide
Cell phones
Webpage
Low cost

ABSTRACT

In this paper we describe a combination of paper-based sensors and a novel smart-phone application for on-site quantification of colorimetric readouts as an ultra-low cost solution to monitoring water quality. The system utilizes a paper-based analytical device (μPAD) that produces a colorimetric signal that is dependent on the concentration of a specific target; a cell phone equipped with a camera for capturing images of two μPADs – one tested with a water sample and the other tested with clean water that is used as a control; and an on-site image processing app that uses a novel algorithm for quantifying color intensity and relating this to contaminant concentration. The cell phone app utilizes a pixel counting algorithm that performs with less bias and user subjectivity than the typically used lab-based software, *ImageJ*. The use of a test and control strip reduces bias from variations in ambient lighting, making it possible to acquire and process images on-site. The cell phone is also able to GPS tag the location of the test, and transmit results to a newly developed website, WaterMap.ca™, that displays the quantitative results from the water samples on a map. We demonstrate our approach using a previously developed μPAD that detects the presence of organophosphate pesticides based on the inhibition of immobilized acetylcholinesterase by these contaminants. The objective of this paper is to highlight the importance and potential of developing and integrated monitoring system consisting of μPADs, cell-phones and a centralized web portal for low-cost monitoring environmental contaminants at a large-scale.

* *Corresponding authors*. Biointerfaces Institute and Department of Chemistry & Chemical Biology, McMaster University, 1280 Main Street West, Hamilton, ON L8S 4L89, Canada.
E-mail addresses: brennanj@mcmaster.ca (J.D. Brennan), filipec@mcmaster.ca (C.D.M. Filipe).

[1] These authors contributed equally to this work.

http://dx.doi.org/10.1016/j.watres.2014.12.005

1. Introduction

Low-cost sensors are expected to play a key role in improving global public health, mainly as point-of-care (POC) diagnostic tools (Yager et al., 2006). Toward this goal, a number of microfluidic paper-based analytical devices (μPADs) (Martinez et al., 2009, 2007) have recently been developed for environmental and medical POC diagnostics. In the biomedical area, a number of portable, low-cost, low-volume, disposable, and simple analytical devices are now available to diagnose liver function (by detecting levels of two serum transaminase enzymes) (Pollock et al., 2012), blood type (by detecting red blood cell antigens) (Li et al., 2012), and to detect a wide range of biomedical analytes (*e.g.* malaria antigen, *mycobacterium tuberculosis*, HIV-1 antibodies, cancer and tumor markers, genotoxic activity, and more) (Yetisen et al., 2013), that will lead to powerful medical diagnostic tools.

Several paper-based environmental POC sensors have also been developed, primarily for testing of water-borne contaminants. More than 1.2 billion people do not have access to safe drinking water and 2.6 billion people, half of the population in the developing world, do not have access to basic sanitation (Shannon et al., 2008; Watkins, 2006). Some 4900 children die each day from diarrhea and water related illness with an additional loss of over 440 million school days due to illness (Watkins, 2006). Access to clean water is a critical step to improving global health. Therefore, developing a comprehensive water monitoring platform that uses μPADs to detect contaminants in water and on-site quantification and reporting to provide a rapid alerting system has enormous potential for improving the health of people around the world, a task which is not possible using the highly expensive and specialized current testing methods, which are normally based on liquid chromatography coupled to mass spectrometry.

To date, water monitor sensors have been developed for detecting organophosphate and carbamate pesticides (Hossain et al., 2009a), various metals (Hossain and Brennan, 2011; Apilux et al., 2010, 2012; Aragay et al., 2012; Nie et al., 2010; Ratnarathorn et al., 2012), coliform bacteria (Hossain et al., 2012) and phenolic compounds (Alkasir et al., 2012). However, one area where μPAD testing technology is lacking is the existence of simple, quantitative on-site analysis methods that can be performed at low cost by untrained personnel. Presently, quantitative results from μPADs are obtained by either a specialized handheld reader or by offline image analysis using a desktop scanner linked to a computer with image analysis software. To improve on these methods, we chose to leverage modern camera-equipped smart phones and the ability to produce simple software apps for on-board image analysis to maintain the portability of mobile scanners without the cost or training requirements of specialized equipment. According to a recent report from the World Bank (Bank and W, 2012), there are currently more than 6 billion cell phone subscriptions, with nearly 5 billion in the developing world, and more than 35 billion apps (App Store and Google Play-Android) have been downloaded. The global presence of powerful camera-equipped cell phones and the ease of downloading powerful apps gives rise to immense potential for revolutionary on-site medical diagnosis that could allow for the immediate initiation of appropriate treatments (Yager et al., 2006; Martinez et al., 2009, 2008). As an example, the Ozcan group, and others, have already developed small attachments to cell phones that turn simple camera phones into microscopes (Zhu et al., 2011a; Breslauer et al., 2009), flow cytometers (Zhu et al., 2011b), and fluorescence intensity readers (Zhu et al., 2012). In our approach, we turn a smartphone into a portable image acquisition and processing system to quantification of μPAD colorimetric outputs, based on an approach that has been previously reported for lateral flow immunoassays (You et al., 2013).

In addition to using the onboard hardware and software capabilities of smart phones, we also integrate the connective aspects of social media to our water quality monitoring system to make readings available to users worldwide, with data being geotagged using the GPS feature in smart phones and uploaded to a central website. A schematic of our proposed process is illustrated in Fig. 1. Briefly, a cell phone is used to capture an image of a test strip and a control strip to perform image analysis and produce a quantifiable measurement. The measured reading and the location are uploaded to a centralized web server where they are logged and made available for others to view on a map. Such an approach enables collaborative mapping capabilities that may be advantageous in a variety of situations such as decentralized wastewater treatment strategies, identification of water contamination hot spots and, most importantly, as an early detection tool for waterborne contaminants and diseases. This approach is also applicable in non-water related areas such as epidemiology (Mudanyali et al., 2012).

Fig. 1 – Paper-based sensors can change how water quality is tested and monitored globally. Cell phones can be used for data collection and to push data to a website where data is displayed on a map. Areas of contamination become easy to spot and can trigger additional monitoring to take place.