Quantitative drinking water arsenic concentrations in field environments using mobile phone photometry of field kits

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HIGHLIGHTS

- Mobile phone cameras can be used as an analytical device to determine the color and concentration of arsenic test-strips.
- We can quantitatively detect arsenic concentrations below 10 ppb in the lab, or 20 ppb under field conditions.
- In the field, we can use a single standard curve to predict arsenic concentrations from mobile phone pictures.

GRAPHICAL ABSTRACT
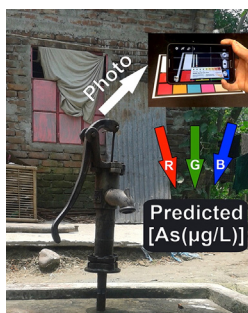
ABSTRACT

Arsenic (As) groundwater contamination is common yet spatially heterogeneous within most environments. It is therefore necessary to measure As concentrations to determine whether a water source is safe to drink. Measurement of As in the field involves using a test strip that changes color in the presence of As. These tests are relatively inexpensive, but results are subjective and provide binned categorical data rather than exact determinations of As concentration. The goal of this work was to determine if photos of field kit test strips taken on mobile phone cameras could be used to extract more precise, continuous As concentrations. As concentrations for 376 wells sampled from Araihazar, Bangladesh were analyzed using ICP-MS, field kit and the new mobile phone photo method. Results from the field and lab indicate that normalized RGB color data extracted from images were able to accurately predict As concentrations as measured by ICP-MS, achieving detection limits of 9.2 μg/L, and 21.9 μg/L for the lab and field respectively. Data analysis is most consistent in the laboratory, but can successfully be carried out offline following image analysis, or on the mobile phone using basic image analysis software. The accuracy of the field method was limited by variability in image saturation, and variation in the illumination spectrum (lighting) and camera response. This work indicates that mobile phone cameras can be used as an analytical tool for quantitative measures of As and could change how water samples are analyzed in the field more widely, and that modest improvements in the consistency of photographic image collection and processing could yield measurements that are both accurate and precise.

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1. Introduction

Arsenic (As) exposure in drinking water can cause cancers of the skin, bladder, and lung, and has been associated with other adverse health effects including skin lesions, reproductive effects, nonmalignant pulmonary disease, cardiovascular disease, and other illnesses(Ahsan et al., 2006a; Ahsan et al., 2006b; Argos et al., 2010; Smith et al., 2000; Wasserman et al., 2004). About 20 million to 45 million people are exposed to concentrations above the Bangladesh national standard of 50 µg/L and the World Health Organization's (WHO) guideline value of 10 µg/L, respectively (Flanagan et al., 2012). Within As impacted environments, As concentrations can vary in both location and depth. Thus, being able to accurately and quickly determine As concentrations in water is imperative in alleviating the burden of disease and for the protection of public health.

In Bangladesh, labeling wells with their As concentrations reduces exposures and promotes households with a high arsenic well to switch to a low arsenic well(Van Geen et al., 2002). The Multiple Cluster Indicator Survey in 2009 showed that in Bangladesh, 44% of well owners did not know the status of As in their wells (Pathey, 2009). Methods for determining As concentrations include laboratory and/or field-testing. Laboratory methods of analysis, such as inductively coupled plasma mass spectrometry (ICP-MS) and flow injection hydride generation atomic absorption spectroscopy (FI-HG-AAS), provide high precision measurements but can be costly, take place far from the water source, and require days to weeks for analysis, making it difficult to provide feedback to households, and for households to make informed decisions based on their results. Field methods often involve visually comparing the color of a test strip with a reference chart of colors that vary with As concentrations. These field methods are less expensive and allow for rapid, on-site sample analysis and immediate feedback to the households. Field kits can be effective at discriminating As above and below the Bangladesh drinking water standard of 50 µg/L when performed by trained technicians, but do not provide continuous or discrete As concentrations, and often are subject to bias (George et al., 2012; Steinmaus et al., 2006; Van Geen et al., 2005).

Improved analysis of test kit color changes could enable improved utilization of test results. The use of digital image processing has previously been shown to provide accurate determinations of field kit color changes that can be quantitatively transformed to concentrations in controlled laboratory settings (Carro Perez and Francisca, 2013; Jia et al., 2015; Kearns and Tyson, 2012; Paciornik et al., 2006; Salman et al., 2012). Digital sensors on current smartphone cameras have sufficient resolution and sensitivity to provide color values from various digital color spaces that are used to create, represent and visualize colors with a minimum number of channels. The most popular color space model is the RGB model, in which each sensor captures the intensity of the light in the red (R), green (G) or blue (B) portion of the spectrum. By extracting these colors, it is possible to digitally analyze the images to objectively quantify color, and thereby concentration in environmental samples.

Here, we present a novel method that transforms the information provided in existing As field test kits into quantitative data, and apply this method in the field to measure As levels in rural Bangladesh, where conditions can deviate considerably from ideal lab settings. Water samples were collected from private tube wells in Bangladesh and immediately analyzed by field kits. The test strip of the field kit was photographed next to a standard color chart using a cell phone. The photograph was analyzed to determine concentration and compared to laboratory measurements. This approach indicates that cell phone photometry can provide an accurate field method of quantitatively measuring groundwater As concentrations. It also identifies a number of sources of uncertainty in color measurements that affect both the accuracy and the detection limits of colorimetric analysis.

2. Methods

2.1. Field sampling

The field site is in the Araihazar upazilla located approximately 20 km east of Dhaka in Bangladesh. The study area is a 25 km^2 portion of Araihazar which consists of 61 villages. Over the past two decades, it has been the site of numerous health and geochemical studies (Ahsan et al., 2000; Argos et al., 2010; Dhar et al., 2011; Horneman et al., 2004). For this study, village health workers (VHW) sampled 376 tube wells that have been part of previous studies (Cheng et al., 2005; van Geen et al., 2014; Van Geen et al., 2002; Van Geen et al., 2007; Van Geen et al., 2003). The tube wells were sampled and analyzed by both field kits and ICP-MS during this study. During sampling, the VHWs collected the pH, Eh, and surveyed the head of household. From each well, groundwater was collected and stored in 20 mL scintillation vials for laboratory analysis. A separate sample of 50 mL was also collected for field analysis done on site using the EconoQuick test kit (Industrial Test Systems Inc. http://www.sensafe.com/) according to the manufactures protocol and previous studies (George et al., 2012; Rahman et al., 2002; Steinmaus et al., 2006; Van Geen et al., 2005) with the addition of a photograph taken of the strip at the end of the test.

2.2. Digital image capturing and processing

Field photos were taken with a Samsung S Duos-2 (Model no. GT-S7582 L) mobile phone, which has a resolution of 5 megapixels yielding photos of 1.3 megabyte JPEG files. Laboratory photos were taken with an iPhone 5S (Model no. ME308LL/A) mobile phone, which has a resolution of 8 megapixels yielding photos of 2.7 megabyte JPEG files. Written directions, translated into Bangla, provided to the VHWs asked that each photo be taken outdoors with indirect sunlight from approximately 60 cm at a 45° angle with the sample test strip, an unused test strip, the EQ arsenic test kit concentration color chart, and a color checker card (DGK Color Tools, http://www.dgkcolortools.com), (Figs. SI-3 to SI-8).

Digital image processing was conducted using Adobe Photoshop CS6 (Version 13.0 × 64, http://www.adobe.com/products/photoshop.html). Each photo was normalized using the Levels Adjustment tool. The goal of the normalization is to minimize the effect of lighting conditions and enable the determination of a consistent set of colors. The Levels tool was used to carry out black normalization for the photo, by defining the black spot on the color chart as black (0,0,0) in RGB space. White and gray normalizations were also evaluated and did not provide reliable results for concentrations below 100 µg/L due to overexposure of lighter colors, making it difficult to discriminate colors between the lower concentrations (data not shown). The Marquee tool was used to delineate the area of an image for color extraction, for example for the color sensitive portion of the test kit strip. The average RGB color value of the pixels in the center of the test strip, an undeveloped test strip, and the standards of the EQ standard concentration chart were extracted and recorded for regressions of color values and As concentrations.

Once successful image processing routines were developed in Photoshop, we performed parallel color extraction on photographs of test strips taken in Bangladesh during testing within the phone directly. This inline photographic analyses were performed on an Android phone with the ColorMeter app v3.1.0 (http://vistechprojects.blogspot.com/). Readings in the Blue and Green channel were recorded at two spots on each test strip: (a) the center of the color-sensitive pad at the end of strip, and (b) a white section of the strip next to the pad. As a simplified normalizing procedure, each reading for the reacting pad was multiplied by the ratio of 200, an arbitrary value comparable to the average, to the reading in the same channel for a nearby white section of the strip. Although this analysis was conducted after the field work, it could be applied in real-time in the field by calling the ColorMeter app