

Evaluation of Two New Arsenic Field Test Kits Capable of Detecting Arsenic Water Concentrations Close to 10 $\mu\text{g/L}$

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Millions of people worldwide are exposed to arsenic-contaminated drinking water. Arsenic field test kits may offer a cost-effective approach for measuring these exposures in the field, although the accuracy of some kits used in the past has been poor. In this study, arsenic concentrations were measured in 136 water sources in western Nevada using two relatively new arsenic test kits and compared to laboratory measurements using atomic fluorescence spectroscopy (AFS). Spearman's rank correlation coefficients comparing the Quick Arsenic and Hach EZ kits to laboratory measurements were 0.96 ($p < 0.001$) and 0.95 ($p < 0.001$), respectively. When analyzed in seven exposure categories (0–9, 10–19, 20–49, 50–99, 100–199, 200–499, and $\geq 500 \mu\text{g/L}$), test kit and AFS measurements were in the same category in 71% (Quick Arsenic) and 62% (Hach EZ) of samples, and within one category of each other in 99% (Quick Arsenic) and 97% (Hach EZ) of samples. Both kits identified all water samples with high arsenic concentrations ($> 15 \mu\text{g/L}$) as being above the United States Environmental Protection Agency's drinking water standard and the World Health Organization's guideline value for arsenic of $10 \mu\text{g/L}$. These results suggest that these easily portable kits can be used to identify water sources with high arsenic concentrations and may provide an important tool for arsenic surveillance and remediation programs.

Introduction

Inorganic arsenic (InAs) occurs naturally in the groundwater of many parts of the world, and millions of people worldwide are exposed (1). Ingesting InAs causes 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 (2, 3). Despite a lowering of the United States Environmental Protection Agency's (USEPA) regulatory

standard for drinking water arsenic from 50 to $10 \mu\text{g/L}$ and the World Health Organization's guideline value of $10 \mu\text{g/L}$, InAs ingestion continues to be an important public health problem worldwide. In developing areas with limited public health resources, such as Bangladesh or West Bengal, India where millions of people may be drinking water with arsenic concentrations well above $10 \mu\text{g/L}$ (1), the costs of identifying and replacing all contaminated water sources will be very high and will likely take many years. In the United States, 15% of the population receives their drinking water from small domestic private wells (4), which are not regulated under the USEPA drinking water arsenic standard (5). Although the proportion of private wells in the United States that contain high concentrations of arsenic is not known, a large number of private wells with arsenic levels above $10 \mu\text{g/L}$ have been reported in many states (6–9).

The severity of the health effects caused by arsenic, and the large number of people exposed, highlight the potential health benefits that might result from public health programs aimed at identifying and eliminating high arsenic exposures. A key element in these programs is the method used to measure arsenic water concentrations. The use of arsenic field test kits, which allow arsenic concentrations in water sources to be measured immediately at the water source, offer several advantages over more conventional laboratory analyses (10, 11). The first advantage may be cost, although there is some controversy on this issue (12). In the United States, traditional laboratory analyses typically cost around \$25–50 per sample (not including sample collection and shipping costs), but the cost may be less in other countries. The cost to purchase the field test kits evaluated in this study was approximately \$1–2 per sample, although training and other personnel costs involve additional expense. Perhaps the most important advantage of the field test kits is convenience. Traditional laboratory analyses involve collecting and shipping samples to specialized laboratories that may be hundreds or thousands of miles from the water source. With field test kits, measurements can be completed on site, and results can be provided to the water consumers almost immediately after sample collection. The ability to communicate findings and provide advice about drinking water sources soon after sample collection is of critical importance to community-based intervention programs in remote areas in less developed countries where long-distance communication and travel may be difficult.

Arsenic field test kits developed in the past have been inaccurate and the use of these kits in large surveillance programs has been criticized (13–15). Other disadvantages noted with the earlier field test kits were the release of toxic arsine gas and difficulties in training field personnel (11, 12, 16). Several more recent test kits seem to be more accurate but have undergone only limited testing in actual field situations. In this article, we report the results of a study assessing the accuracy of two relatively new field test kits, the Quick Arsenic test kit and the Hach EZ test kit. These kits were selected because, based on our experience, they were the most widely used and easily available commercial arsenic field test kits in our area. The accuracy of both of these test kits has been evaluated in previous studies (17, 18); however, these evaluations involved either a very small number of field water sources or presented limited or no data on the accuracy of exposures near the current USEPA standard and World Health Organization (WHO) recommended arsenic limit of $10 \mu\text{g/L}$. The present study involves either a larger number of individual water sources or a more extensive analysis than these previously published evaluations.

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Materials and Methods

Water Sources and Field Kit Measurements. The water sources used in this investigation were identified from records of private and public wells in western Nevada collected by the Nevada State Health Division (9). Wells were selected from these records, and the residents at the address listed were contacted by mail or phone regarding the study. At each residence that agreed to participate, three water samples were collected into unused sterile 50 mL polypropylene bottles. One bottle was transported overnight to the University of Washington for laboratory analysis. Samples from the two other bottles were analyzed using the Quick Arsenic test kit (catalog no. 481396) (19) and the Hach EZ test kit (catalog no. 28228-00) (20). These analyses were done immediately onsite by trained personnel. Both kits involve the addition of reagents that result in the production of arsine gas when arsenic is present (21). This gas is exposed to a test strip which changes color in a gradual spectrum from white (when no arsenic is present), to yellow and light brown (when moderate arsenic concentrations are present), to very dark brown (when arsenic levels are above 500 $\mu\text{g/L}$) based on the standard mercuric bromide method (11). The color strip is then compared to a colored reference card that indicates the arsenic concentration. For the Quick Arsenic kit, the color chart shows the colors associated with arsenic concentrations of 0, 5, 10, 20, 30, 40, 50, 60, 80, 100, 150, 200, 250, 300, 400, and 500 $\mu\text{g/L}$. For the Hach EZ kit, the color chart shows colors associated with arsenic concentrations of 0, 10, 25, 35, 50, 75, 100, 175, 250, 500, 1500, and 4000 $\mu\text{g/L}$. The field researchers recorded the arsenic level in the color chart that was nearest the color of the test strip. In addition, if the test strip color was between two colors in the color chart, an arsenic concentration was estimated by the field researchers based on the how close the test strip color was to each of its bordering two colors in the color chart.

For each kit, the manufacturer's instructions were followed, except that the reaction time for the Hach EZ kit was increased from 20 to 40 min. A 40-minute reaction time had been shown to increase accuracy in a previous study (17), although no difference in arsenic concentrations was noted by field personnel in our study between the two reaction times. Samples from each water source were tested with the field kits immediately after collection. Each source was tested using each of the two test kits with one field staff member using the Hach kit and a different field staff member simultaneously using the Quick kit. These personnel were blinded to the laboratory result and the result of the other test kit. The field personnel were supervised college students with several years of laboratory experience but no experience with water testing in the field. They received about 1 hour of instruction on the use of the kit and additional instruction on the research design, data recording, sample collection, and shipment and quality control. Field personnel reported that the instructions on both kits were well written, the color charts were easy to read, and the kits were relatively simple to use. Further information on the methods and technologies used in these test kits is provided elsewhere (17, 18).

Laboratory Analysis. For the laboratory analysis, 1 mL portions of each sample in amber crimp-top vials were spiked with 0.01 mL of concentrated hydrochloric acid and 0.01 mL of 30% aqueous hydrogen peroxide at least 1 h prior to treatment with KI and sodium borohydride. Standards were prepared similarly using NIST-traceable stock solutions. Samples with initial concentrations of $>200 \mu\text{g/L}$ were diluted as required and reanalyzed. The lower limit of quantitation was 10 $\mu\text{g/L}$. Instrumental analysis was performed by automated flow injection using borohydride reduction and continuous arsine detection by atomic fluorescence spectroscopy (AFS) (22). All laboratory tests were done within 2–3 weeks of collection, and samples were sealed in airtight

containers and maintained in a frozen state and under dark conditions for storage. Preservatives were not added to water samples sent to the laboratory. Preservatives are primarily used to prevent oxidation of arsenite (As(III)) to arsenate (As(V)) (13). Since As(V) is readily converted to As(III) in humans and both are important in human toxicity (2), total inorganic arsenic (III and V combined) was the focus of this study. All samples and standards were run in duplicate. The coefficient of variation in the duplicate samples was 3.6%. Quality control procedures also consisted of one blank and one calibrant per eight samples, and three analyses of SRM materials. The average InAs level in the 34 blank samples was $0.93 \pm$ (standard deviation) $2 \mu\text{g/L}$. The average InAs level in 42 aqueous calibration check samples spiked with 50 ppb InAs was $53.0 \pm 8.5 \mu\text{g/L}$ (average recovery = 105.9%). The average InAs level measured in six NIST Ultra-chek 100 ppb samples was $94.9 \pm 11.2 \mu\text{g/L}$ (average recovery = 94.9%). Recalibration occurred daily, about every 40–60 samples.

Statistical Analysis. The accuracy of the field test kits was evaluated by comparing the field test kit results to those of the laboratory AFS analysis. Graphs showing the results of both test kits and the laboratory analysis are presented later. The first graph shows results for all water samples where both the field test kit and laboratory arsenic levels were below 500 $\mu\text{g/L}$. A second graph is presented showing only those water sources with arsenic concentrations between 0 and 100 $\mu\text{g/L}$ since the results in this range are difficult to visualize in the first graph.

Correlations between field test kit and laboratory measurements were evaluated by classifying all measurements into one of seven exposure categories (0–9, 10–19, 20–49, 50–99, 100–199, 200–499, $\geq 500 \mu\text{g/L}$) and calculating the proportion of water sources in which the field test kit result and the laboratory result were in the same or adjacent exposure categories. Spearman's rank correlation coefficients were also calculated comparing AFS and test kit results both as categorical and continuous variables. In the analysis of arsenic concentration as a continuous variable, results below the quantitation limit were assigned a value of $1/2$ this limit, and field test kit results $>500 \mu\text{g/L}$ were excluded since this was the highest category on the Quick Arsenic test color chart. False negative and positive rates at cutoffs of 10 and 50 $\mu\text{g/L}$ were calculated for each test kit using the laboratory arsenic value to define "true" concentration (23). This study was approved by the human subjects committee at the University of California, Berkeley, and informed consent was collected from the residents of each water source. The researchers have no financial or other connection to the test kit manufacturers. Both test kits were purchased on-line without informing either manufacturer about their use for this study.

Results

In total, 136 individual water sources were included in this study. Arsenic concentrations ranged from below detection to 2362 $\mu\text{g/L}$ (median = 51 $\mu\text{g/L}$). A graphical display of the test kit and laboratory results for water sources with test kit and laboratory arsenic readings below 500 $\mu\text{g/L}$ is presented in Figure 1. Figure 2 shows these results for all water sources with laboratory arsenic concentrations measurements below 100 $\mu\text{g/L}$. The Spearman's rank correlation coefficient between arsenic concentrations measured using the Quick Arsenic test kit and those measured using AFS was 0.96 ($p < 0.001$). The corresponding correlation coefficient for the Hach EZ test kit was 0.95 ($p < 0.001$) (Table 1). Correlation coefficients were the same regardless of whether arsenic concentrations were analyzed as a continuous or categorical variable.

Tables 2 and 3 show further results of the analyses of arsenic concentrations divided into exposure categories. The Quick Arsenic and the Hach EZ field test kit results were in

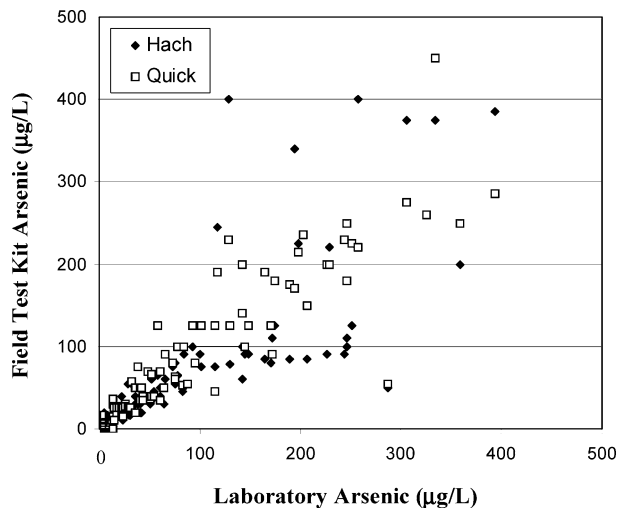


FIGURE 1. Arsenic measurements in all water samples with arsenic concentrations less than 500 µg/L ($n = 118$) measured in the laboratory by atomic fluorescence spectroscopy (AFS) and the Quick Arsenic and Hach EZ field test kits.

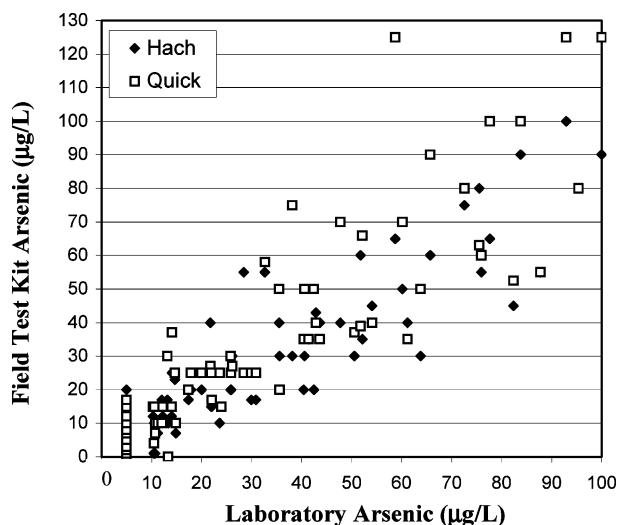


FIGURE 2. Quick Arsenic and Hach EZ field test kit and laboratory atomic fluorescence spectroscopy (AFS) arsenic measurements in the subgroup of 86 water samples with AFS arsenic levels at or below 100 µg/L. For some water sources with laboratory measurements ≤ 100 µg/L, the test kit measurements were above 100 µg/L.

TABLE 1. Spearman's Rank Correlation Coefficients (r) between Water Arsenic Concentrations Measured Using Atomic Fluorescence Spectroscopy (AFS) and Two Arsenic Field Test Kits

	arsenic concentration as a categorical variable ^a			arsenic concentration as a continuous variable ^b		
	<i>N</i>	<i>r</i>	<i>p</i> -value	<i>N</i>	<i>r</i>	<i>p</i> -value
Quick	136	0.96	<0.001	119	0.96	<0.001
Hach	136	0.95	<0.001	119	0.95	<0.001

^a Spearman's rank correlation coefficient between laboratory and field test kit results with arsenic levels categorized into seven exposure categories: 0–9, 10–19, 20–49, 50–99, 100–199, 200–499, ≥ 500 µg/L.

^b Spearman's rank correlation coefficient between laboratory and field test kit results with arsenic level as a continuous variable. Levels below the laboratory quantitation limit were set at $1/2$ the limit, and levels above 500 µg/L were excluded.

the same arsenic concentration category as the laboratory result in 71% ($n = 97$) and 62% ($n = 84$) of the water sources tested, respectively. Test kit and laboratory measurements

TABLE 2. Number of Water Samples Classified into Each Arsenic Exposure Category of Atomic Fluorescence Spectroscopy (AFS) and Field Test Kit Arsenic Concentration^a

AFS result (µg/L)	Quick Arsenic Test Kit Result (µg/L)							
	total	0–9	10–19	20–49	50–99	100–199	200–499	>500
0–9	27	23	4	0	0	0	0	0
10–19	17	3	8	6	0	0	0	0
20–49	23	0	2	15	6	0	0	0
50–99	18	0	0	4	10	4	0	0
100–199	19	0	0	1	1	13	4	0
200–499	15	0	0	0	1	2	12	0
≥ 500	17	0	0	0	0	0	1	16

AFS result (µg/L)	Hach EZ Test Kit Result (µg/L)							
	total	0–9	10–19	20–49	50–99	100–199	200–499	>500
0–9	27	25	2	0	0	0	0	0
10–19	17	5	8	4	0	0	0	0
20–49	23	0	6	15	2	0	0	0
50–99	18	0	0	6	11	1	0	0
100–199	19	0	0	0	11	3	5	0
200–499	15	0	0	0	4	3	7	1
≥ 500	17	0	0	0	0	0	2	15

^a The numbers in bold indicate the number of samples in which the arsenic concentrations measured using atomic fluorescence spectroscopy (AFS) and field test kit were in the same arsenic category. For example, in 23 samples, the arsenic concentration measured using AFS and the arsenic concentration measured using the Quick Arsenic test kit were both between 0 and 9 µg/L. In 4 samples, the AFS result was 0–9 µg/L and the Quick Arsenic test kit result was 10–19 µg/L.

TABLE 3. Proportion of Field Test Kit Arsenic Measurements Classified within the Same or Neighboring Categories as Concentrations Measured Using Atomic Fluorescence Spectroscopy (AFS)

	same category	one category below	one category above	total ^a
Quick	71%	10%	18%	99%
Hach	62%	24%	11%	97%

^a Proportion of samples in which the field test kit result was in the same category or within one category of the atomic fluorescence spectroscopy laboratory measurement.

were within one category of each other in 99% of samples ($n = 134$) for the Quick Arsenic kit and 97% of samples ($n = 132$) for the Hach EZ kit. Using 50 µg/L as the cutoff point, the false positive and false negative rates for the Quick Arsenic kit were 9.0% and 7.2%, respectively, and the false positive and false negative rates for the Hach EZ kit were 3.0% and 8.7%, respectively. Using 10 µg/L as the cutoff point, the false positive and false negative rates for the Quick Arsenic kit were 14.8% and 2.7%, respectively, and the false positive and false negative rates for the Hach EZ kit were 7.4% and 4.6%, respectively. For both kits, none of the water sources with arsenic concentrations greater than 15 µg/L as measured in the laboratory were classified as being below the USEPA and WHO values of 10 µg/L based on the test kit results.

Discussion

Overall, a good correlation was identified between the arsenic concentrations measured in the field using the Hach EZ and Quick Arsenic test kits and arsenic concentrations measured in the laboratory using AFS. In 266 of the 272 comparisons made (136 comparisons for each test kit), the results of the field test kit were in the same or an adjacent arsenic exposure category as the result of the laboratory analysis. Using the USEPA and WHO arsenic values of 10 µg/L as the cut off point, the false negative rate was low for both tests.

Importantly, all of the test kit false negatives had laboratory measured arsenic concentrations very near the 10 µg/L cutoff point. For example, the laboratory measured arsenic concentrations for the five Hach test false negatives were 10.4, 10.7, 10.7, 11.2, and 14.8 µg/L. The laboratory measured arsenic concentrations for the three Quick Arsenic test false negatives were 10.4, 10.7, and 13.4 µg/L. All water sources with arsenic concentrations above 15 µg/L (as measured in the laboratory) were classified as being above 10 µg/L using the test kits. Overall, these findings suggest that both kits can be used to reliably identify water sources with arsenic concentrations substantially above the current USEPA arsenic drinking water standard and the WHO guideline value. The low false negative rate for these kits is particularly important from a public health perspective since it means that in surveillance and remediation programs that use these kits, water sources with the greatest health risks are unlikely to be misclassified as safe.

Our results concerning the Hach EZ and Quick Arsenic field test kits are consistent with the limited information previously available. In a previous study performed by Battelle, in cooperative agreement with the USEPA, researchers reported correlation coefficients of 0.97 and higher between Quick Arsenic test kit measurements and measurements performed using inductively coupled plasma mass spectrometry (ICP-MS) (18). However, this investigation involved mostly water samples spiked with known amounts of arsenic. The number of different field water sources tested was six, of which only two had arsenic concentrations above 10 µg/L.

The accuracy of the Hach EZ kit has also been evaluated in a previous study (17). This study involved 799 wells in an arsenic-exposed region in Bangladesh. All wells had previously been tested by NGO workers using the Hach EZ kit and painted red if the kit result was above 50 µg/L, or green if the kit result was below 50 µg/L. At a later date, a different group of researchers collected water samples from these same 799 wells, analyzed them in the laboratory using ICP-MS, and compared the ICP-MS result to the color each well was painted. The researchers reported that based on the ICP-MS results, 700 of the 799 wells (88%) had been painted the correct color. The researchers also retested a subset of wells using the Hach EZ kit (and an extended reaction time of 40 min). In an analysis based on whether the Hach kit result was above or below 50 µg/L, the kit results agreed with the ICP-MS results in 101 (94%) of the 108 samples tested. These findings suggest that the Hach kit is quite good at distinguishing arsenic concentrations above and below 50 µg/L. Our results are similar for this water concentration. When we dichotomized all results as being either above or below 50 µg/L, the Hach EZ kit and AFS results were in agreement in 128 of the 136 (94%) water sources we tested.

Although the overall correlation between test kit and laboratory results was good in our study, we identified a few instances in which the laboratory result and test kit result were markedly different. The exact reason for these discrepancies is unknown, but could be related to the presence of other chemical substances in the water source. For example, in one water source, the arsenic concentration was 287 µg/L when measured in the laboratory and 50 µg/L when measured using the Hach EZ and Quick Arsenic test kits. In this source, our field technicians noted the smell of hydrogen sulfide. Hydrogen sulfide is known to interfere with the chemical reaction used in both test kits, and both kits provide instructions on additional steps that can help reduce this interference. However, in the few samples in which these steps were taken, our field researchers reported little change in the test kit results. These reports are anecdotal and a full formal analysis of the influence of hydrogen sulfide or other chemical contaminants on test kit accuracy was not per-

formed. Despite this, these findings do suggest that care must be taken when using the field test kits to measure water sources where other chemical contaminants may be present in high concentrations.

In summary, the findings of this study suggest that the Hach EZ and Quick Arsenic field test kits can be used to identify water sources with arsenic concentrations above the current USEPA standard and WHO guideline. While test kit results differed markedly from the results obtained from laboratory analysis in a few water sources, we found no instances in which water sources with arsenic concentrations above 15 µg/L would have been mislabeled as being below the USEPA drinking water standard of 10 µg/L when tested with either field test kit. Both kits were easily portable and described as relatively simple to use by our field researchers. As a whole, the results of this study suggest that the Quick Arsenic and Hach EZ test kits may provide reliable and convenient tools for public health arsenic surveillance and remediation programs.

Acknowledgments

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