Evaluation of a new water treatment for point-of-use household applications to remove microorganisms and arsenic from drinking water

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ABSTRACT

Contamination of drinking water by microorganisms and arsenic represents a major human health hazard in many parts of the world. An estimated 3.4 million deaths a year are attributable to waterborne diseases. Arsenic poisoning from contaminated water sources is causing a major health emergency in some countries such as Bangladesh where 35 to 77 million people are at risk.

The World Health Organization (WHO) has recently recognized point-of-use water treatment as an effective means of reducing illness in developing country households. A new point-of-use water treatment system that is based on flocculation, sedimentation and disinfection was evaluated for the removal of bacterial, viral and parasitic pathogens as well as arsenic from drinking water to estimate its potential for use in developing countries.

Tests were conducted with United States Environmental Protection Agency (EPA)-model and field- sample waters from developing countries. Samples were seeded with known numbers of organisms, treated with the combined flocculation/disinfection product, and assayed for survivors using standard assay techniques appropriate for the organism.

Results indicated that this treatment system reduced the levels from 10^8/l to undetectable (<1) of 14 types of representative waterborne bacterial pathogens including *Salmonella typhi* and *Vibrio cholerae*. No *Escherichia coli* were detected post-treatment in 320 field water samples collected from five developing countries. In addition, the water treatment system reduced polio and rotavirus titres by greater than 4-log values. *Cyrptosporidium parvum* and *Giardia lamblia* inocula were reduced by greater than 3-log values following use of this water treatment system. Arsenic, added to laboratory test waters, was reduced by 99.8%, and naturally occurring arsenic in field samples from highly contaminated Bangladeshi wells was reduced by 99.5% to mean levels of 1.2 μg/l.

This water treatment system has demonstrated the potential to provide improved drinking water to households in developing countries by removing microbial and arsenic contaminants.

Key words | arsenic, chlorine, developing country, disinfectant, drinking water, microorganisms, point-of-use

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INTRODUCTION

The World Health Organization (WHO) estimates that over one billion people are without access to safe and adequate drinking water sources. A significant number of illnesses and deaths are reported annually as a result of waterborne diseases. Diarrhoea-related illnesses alone are estimated to cause two to three million deaths per year; a

majority of the mortality occurs in children (Bern *et al.* 1992). A goal of the WHO is that 'all people, whatever their stage of development and their social and economic conditions, have the right to have access to an adequate supply of safe drinking water,' where 'safe' refers to a water supply that poses no significant health risk. To this end, the WHO established water quality guidelines for drinking water that included no detectable levels of *Escherichia coli* or coliform bacteria and arsenic levels at or less than 10 μg/l (WHO 1996/1998). In spite of this goal, improved water treatment has not been achieved, despite a concentrated effort to do so over the past decade (Bern *et al.* 1992; Makutsa *et al.* 2001; Riley *et al.* 2001).

A clear need for point-of-use (POU) water treatment has emerged (Mintz *et al.* 2001; Sobsey 2002). These recent reviews of a number of the systems available identify how POU treatment of drinking water can contribute to the reduction of diarrhoeal disease transmission. Chlorine and solar systems are among the options that have been reported. However, turbid waters often limit their effectiveness. These limitations may be overcome by a combined flocculant-disinfectant technology (Sobsey 2002). Additionally, arsenic poisoning from contaminated water sources is an increasing problem in a number of countries, including Bangladesh, Peru and the United States (Smith *et al.* 2000). The WHO estimates that 35 to 77 million people in Bangladesh alone are affected by arsenic toxicity (Smith *et al.* 2000).

This article describes a new POU water treatment system that has been developed. It utilizes an approach similar to that employed in conventional municipal water treatment facilities, namely flocculation, sedimentation and disinfection for the removal of microorganisms including bacteria, viruses, and protozoan cysts. Laboratory and field evaluations of the efficacy of this new water treatment process are reported both for microorganisms and for arsenic removal.

MATERIALS AND METHODS

Point-of-use water treatment and measurements

The POU water treatment product (Pur® Water Purifier, Procter & Gamble, Cincinnati, Ohio, USA) is composed of a coagulant, an alkaline agent, flocculation aids, a flocculent and a chlorine-based disinfectant. The product was supplied in individual sachets with a dose to treat 10 l of water. Test waters were treated in one of two ways:

1. In laboratory tests, the contents of the sachet were added to a bucket with 10 l of water and mixed vigorously in the water by continual agitation for 5 min. The floc was allowed to settle until the water appeared clear and the floc had grown in size. When the water was clear it was strained through a cloth filter into a 'safe' storage vessel. The water was allowed to stand for 20 min to complete the disinfection process.
2. For field samples, the contents of the sachet were added to 10 l of water in a mixing vessel and stirred vigorously for 30 sec. The water solution was then allowed to sit for 5 min to start the purification process. The solution was then stirred again for 30 sec and allowed to settle for another 5 min. A final stirring for 30 sec was followed by another 5 min of resting before straining through a cloth filter into a safe storage vessel. The filtered water was allowed to stand for 15 min.

Residual chlorine levels were assessed using the DPD method and reported in mg/l free chlorine. Measurements of water turbidity followed standard laboratory methods (APHA *et al.* 1998) and were reported in nephelometric turbidity units (NTU). For samples used for microbial measurements, water was first neutralized with sterile sodium thiosulphate and then processed to enumerate bacteria, viruses or protozoan oocysts using standard laboratory procedures.

Water sources

For laboratory tests, the types of water used included: deionised water, model surface water (EPA#1), model-stressed surface water (EPA#2), NSF International (NSF) model water, or city tap water. Model surface and model-stressed surface water types were selected from the United States Environmental Protection Agency (EPA) protocol on evaluation of microbiological water purifiers. Stressed

water conditions are indicative of highly contaminated waters and are the most stringent conditions for chlorine as a disinfectant. The compositions of EPA and NSF test waters are provided in Table 1 (US EPA 1998). For field tests, water was obtained from a variety of sources (tap, surface and well water) and countries (specific locations are listed in data summary tables).

Microbiological methods

Bacteria

Laboratory studies were conducted at the Freeman Hospital (Newcastle-upon-Tyne, UK). Representatives of waterborne bacteria commonly found in untreated water and sewage were added to deionised or EPA model waters at concentrations of 1×10^7 to 9.2×10^9 bacteria/litre. These contaminated waters were then treated with the POU water treatment system according to usage instructions described above and various contaminant bacteria were enumerated. Samples taken as controls were not treated with the water treatment system. Water obtained from springs, wells, lakes, rivers, rain caches and taps in five Asian, African and Latin American countries were also evaluated for coliforms and *E. coli* before and after use of the water treatment product. The standard membrane filtration method for microbiological analysis of water samples was used for these measurements (APHA *et al.* 1998). Briefly, the method involved filtration of 100 ml water samples through membranes with a rated nominal pore size of 0.2 millimicrons. The membrane was carefully transferred to an agar plate that contained medium and was then incubated at the appropriate temperature and for the time specified for the organisms being sought. After incubation, colonies of bacteria were counted.

Viruses

Efficacy of the water treatment system against viruses was measured using poliovirus type 1 (Attenuated) Strain CHAT ATCC VR-192 and simian rotavirus SA-11 (obtained from Dr Richard Ward, Children's Hospital Medical Center, Cincinnati, Ohio, USA) in EPA#1 and EPA#2 waters. Poliovirus type 1 was chosen as a representative enterovirus and because of the extensive historical information available from its use in disinfection studies. Rotavirus was selected as a second type of enteric virus that is a waterborne disease. Virus inocula were prepared in MA-104 cells, frozen and clarified by centrifugation at $820 \times g$ for 10 min. Stock virus suspensions were added to buckets containing 10 l of the test water and mixed to yield a concentration of approximately 10^7 PFU/l. Prior to treatment, a sample was taken to serve as an untreated control. The remaining samples were treated with the POU water treatment product following the usage instructions as described above. At the end of the treatment period, samples were neutralized with sodium thiosulphate. Samples were then inoculated directly onto MA-104 cell cultures for plaque assay using standard methods (APHA *et al.* 1998).

Parasites

Cryptosporidium parvum is an important waterborne pathogen that has known resistance to chlorine disinfection. Oocysts of *Cryptosporidium* were purchased from Moredun Scientific Limited (Moredun Scientific Limited, Penicuik, Midlothian, UK). These were added to the water samples under test to produce an estimated concentration of 10^5 oocysts per litre. Test waters were then treated with the POU water treatment product following recommended usage conditions. Post-treated water was filtered through cloth or simply decanted. A 500-ml sample was then processed for *Cryptosporidium* detection.

The staining methodology used to measure *Cryptosporidium* was based on standard methods (Environment Agency UK 1999). The method involved concentration of cysts by membrane filtration followed by staining of the cysts with FITC conjugated anti-*Cryptosporidium* monoclonal antibody Crypto-glo® (Waterborne Inc., New Orleans, Louisiana, USA). Each 500-ml sample was filtered through a 47-mm membrane filter (0.45-μm pore size) using a vacuum pump. Whenever necessary, the filters were replaced to allow rapid filtration. Each of these filters was carefully transferred to a sterile plastic universal bottle containing 10 ml of sterile distilled water. Each bottle was then vortexed at low speed

Table 1 | Composition of laboratory waters obtained from the US Environmental Protection Agency (EPA) and NSF International

Required attributes	Typical formulation
EPA #1: Model surface water	
• Free of chlorine or other disinfectant	• Deionised water
• pH range 6.5–8.5	• Sea salt 100 mg/l
• Total organic carbon 0.1–5 mg/l	• Humic acid 1.25–2.5 mg/l
• Turbidity 0.1–5 NTU	• Dust (0.3 μm) 0.5–1 mg/l
• Temperature 20 ± 5°C	
• Total dissolved solids 50–500 mg/l	
EPA #2: Stressed surface water	
• Free of chlorine or other disinfectant	• Deionised water
• pH 9.0 ± 0.2	• Sea salt 16,000 mg/l
• Total organic carbon > 10 mg/l	• Humic acid 30 mg/l
• Turbidity > 30 NTU	• Dust (0.3 μm) 24 mg/l
• Temperature 4 ± 1°C	• Sodium hydroxide to adjust pH
• Total dissolved solids 1500 mg/l	• Deionised ice
NSF Type 1	
• Free chlorine 0.5 ± 0.05 mg/l	• Sea salt 60 mg/l
• pH range 6.75 ± 0.25	• 0.77 mg/l calcium hypochlorite
• Total dissolved solids 50 ± 5 mg/l	• Sodium hydroxide to adjust pH
NSF Type 2	
• Total dissolved solids 200–500 mg/l	• Sea salt 500 mg/l
• Total organic carbon > 1.0 mg/l	• Humic acid 5 mg/l
• pH range 7.5 ± 0.5	• Sodium hydroxide to adjust pH
• Turbidity < 1 NTU	
• Temperature 20 ± 2.5°C	

NSF = NSF International.
NTU = nephelometric turbidity units.
Compositions have been taken from US EPA (1998) and NSF International (1999).

for a total of 5 min to remove the oocysts from the surface of the filters. Following centrifugation at 1500 × g for 10 min, the supernatant was carefully removed from the tube and the deposit was resuspended in 1 ml of sterile distilled water. Four 25-μl aliquots of this deposit were inoculated onto a multi-spot slide and allowed to air dry at 37°C. Once dry, each 'spot' was fixed by overlaying with acetone and then allowing the solvent to evaporate. Once fixed, each 'spot' was then stained with FITC conjugated anti-*Cryptosporidium* monoclonal antibody. Oocysts were then enumerated using fluorescence microscopy. *Giardia lamblia* cysts were obtained from Waterborne Inc., New Orleans, Louisiana, USA and were inoculated and assayed in an analogous manner. Cysts were enumerated by staining with FITC conjugated anti-*G. lamblia* monoclonal antibody Aqua-Glo™ (Waterborne Inc., New Orleans, Louisiana, USA).

Arsenic

Arsenic used in laboratory experiments was added as either arsenic (III) (in the form of arsenic trioxide; BDH/Merck Ltd, Lutterworth, UK) or arsenic (V) (in the form of sodium arsenate; Sigma-Aldrich, Poole, UK). Both the trivalent and pentavalent forms of arsenic occur naturally in waters, with the trivalent form typically being the harder to remove. Metal content was assessed before and after treatment with the POU water treatment product (Analytical & Environmental Services Ltd 2000), using hydride generation followed by atomic fluorescence detection. In other studies, arsenic levels were measured in arsenic-contaminated water from naturally occurring sources (i.e. municipal and well water). Samples from Bangladeshi wells were highly contaminated with arsenic, and water from Guatemala and the Philippines contained low-level arsenic contamination. Arsenic levels were assessed before and after use of the POU water treatment system in these field samples by the same method as described above.

RESULTS

Laboratory samples

Various controlled water sources were used for these experiments. The laboratory water sources contained increasing carbon load, solids and turbidity with the EPA#2 water source representing a stress model for chlorine disinfection.

Microbiology results

Fourteen representative types of waterborne disease-causing bacteria were tested, including *Salmonella typhi* and *Vibrio cholerae*. Additionally a mixture of faecal bacteria (*Escherichia coli* NCTC 10418, *Klebsiella pneumoniae* NCTC 10896, *Providencia rettgeri* NCTC 7475, *Enterobacter cloacae* NCTC 11936, *Serratia marcescens* NCTC 10211, *Salmonella typhimurium* NCTC 74, *Pseudomonas aeruginosa* NCTC 10662, *Enterococcus faecalis* NCTC 755, *Enterococcus faecium* NCTC 7171 and *Staphylococcus aureus* NCTC 6571) was added to the laboratory water sources to simulate a mixed-culture situation. Treatment of the test waters seeded with microbes with the POU water treatment system resulted in >7-log reduction in all cases (Table 2). No bacteria were detected (<1/litre) in any of the tests following use of the water treatment system. An 8-log reduction in initial titre was measured for the bacteria where the initial titres permitted. The EPA standard for water purification is a 6-log reduction in bacteria (US EPA 1998).

Both poliovirus and rotavirus assessed in the various laboratory water sources were substantially reduced by use of the water treatment system. A >4-log reduction was achieved for both viruses (Tables 3 and 4). EPA requirements for water purification specify that polio and rotaviruses should achieve a 4-log reduction (US EPA 1998).

Additionally, *Cryptosporidium* oocysts were effectively removed with >3-log reductions in EPA and deionised waters even at low temperatures of 3–5°C (Table 5). This 3-log reduction is consistent with the EPA performance standard for water purification. *Giardia* removal (log reduction) in EPA#1 and EPA#2 waters ranged from 3.23 to 4.19.

Arsenic contamination

The POU water treatment system effectively removed >99.7% of arsenic that was added at levels of 500 to

Table 2 | Efficacy of the POU water treatment system against bacteria in laboratory water sources

	Concentration (bacteria/l)				
Bacteria type	**Initial**	**After treatment**	**Log reduction**	**Number of experiments**	**Water types**
Aeromonas hydrophila (NCTC 8049)	1.6×10^8	< 1	> 8.20	4	EPA #2
Campylobacter coli (NCTC 11366)	2×10^7	< 1	> 7.30	4	EPA #2
	7.6×10^7	< 1	> 7.88	4	EPA #2
Campylobacter jejuni (NCTC 11351)	6.6×10^7	< 1	> 7.82	4	EPA #2
	2.02×10^8	< 1	> 8.31	4	EPA #2
Enterococcus hirae (ATCC 8043)	1.6×10^8	< 1	> 8.20	4	EPA #2
Enteropathogenic *Escherichia coli* (NCTC 8007)*	8.6×10^7	< 1	> 7.93	4	EPA #2
Enterotoxigenic *Escherichia coli* (NCTC 11602)**	1.28×10^8	< 1	> 8.10	4	EPA #2
Escherichia coli (NCTC 10418)	1.8×10^8	< 1	> 8.26	4	EPA #2
	2.4×10^8	< 1	> 8.38	5	EPA #2
	1.6×10^8	< 1	> 8.20	3	EPA #2
	1.6×10^8	< 1	> 8.20	3	EPA #1
	1.6×10^8	< 1	> 8.20	3	DI
	2.4×10^8	< 1	> 8.38	5	EPA #2
	2.4×10^8	< 1	> 8.38	2	EPA #1
	2.4×10^8	< 1	> 8.38	2	DI
Klebsiella terrigena (ATCC 33257)	2.8×10^8	< 1	> 8.45	5	EPA #2
	1.8×10^8	< 1	> 8.26	3	EPA #2
	1.8×10^8	< 1	> 8.26	3	EPA #1
	1.8×10^8	< 1	> 8.26	3	DI
P. aeruginosa (ATCC 15442)	1.8×10^8	< 1	> 8.26	5	EPA #2
	1.8×10^8	< 1	> 8.26	1	EPA #1
	1.8×10^8	< 1	> 8.26	1	DI
Plesiomonas shigelliodes (NCTC 10360)	1.42×10^8	< 1	> 8.15	4	EPA #2
S. aureus (ATCC 6538)	1.4×10^8	< 1	> 8.15	5	EPA #2

Table 2 | *Continued*

Bacteria type	Concentration (bacteria/l) Initial	After treatment	Log reduction	Number of experiments	Water types
Salmonella typhi (NCTC 51635)	1.6×10^8	<1	>8.20	4	EPA #2
	1×10^7	<1	>8.00	5	EPA #2
Shigella sonnei (NCTC 9776)	2.2×10^8	<1	>8.34	4	EPA #2
Vibrio cholerae (NCTC 8021)	1.12×10^8	<1	>8.05	4	EPA #2
	1.2×10^8	<1	>8.08	3	EPA #2
10 common faecal bacteria*	9.2×10^9	<1	>9.96	5	EPA #2
	9.2×10^9	<1	>9.96	4	EPA #1

ATCC=American Type Culture Collection (United States); DI=deionised water; EPA #1=model surface water; EPA #2=stressed surface water; NCTC=National Collection of Type Cultures (United Kingdom); POU=point-of-use.
*Mixture of *E. coli*, *K. pneumoniae*, *P. rettgeri*, *E. cloacae*, *S. marcescens*, *S. typhimurium*, *P. aeruginosa*, *E. faecalis*, *E. faecium*, *S. aureus* at approximately 10^9 bacteria/litre for each strain.

1000 μg/l to laboratory and municipal water sources (Tables 6 and 7). Final mean arsenic concentrations for As5+ and As3+ were 0.8 and 1.2 μg/l, respectively.

Field samples

To test the water treatment system under more realistic conditions, water from various developing countries was collected, treated and analysed for microbes and arsenic. Sources included lakes, rivers, rain caches, taps and wells that were used as drinking water sources.

Microbiology results

None of the 320 samples collected from Guatemala, Kenya, Pakistan, the Philippines and South Africa had detectable *E. coli* in the water following treatment with the test product (Table 8). Pretreatment *E. coli* counts ranged from 0 to 2.4×10^6 CFU/100 ml with a detection limit of 1 per 100 ml. Thus, each of the waters tested met the WHO safe drinking water criteria for absence of microbes.

Turbidities in the samples were reduced significantly, pre-treatment ranged from 0 to 1850 NTU (mean 19 NTU) and final values were generally less than 1 NTU (average 0.25 NTU). The highest final turbidity observed was 3.2 NTU for a water source whose starting turbidity had 1850 NTU (data not shown).

Arsenic levels

Successful arsenic removal of >99% was first demonstrated in a variety of laboratory waters as described above. To demonstrate the efficacy in natural waters contaminated with arsenic from a region where there are currently health problems due to arsenic poisoning, eight samples of water collected from drinking water sources from Bangladesh were treated and tested for arsenic reduction (Table 9). Mean pre-treatment arsenic levels were 229 μg/l and ranged from 49 to 430 μg/l. The mean post-treatment arsenic level in the eight samples was 1.2 μg/l (range 0.13 to 5.0 μg/l) representing a 99.5% removal. Three additional samples from other regions with low-level arsenic contamination also demonstrated

Table 3 | Efficacy of the POU water treatment system against poliovirus

Water treated	Initial viral count/ml (log_{10})	Log_{10} decrease (mean)
EPA #1	7.97	≥5.92
EPA #1	7.78	≥5.73
EPA #1	7.76	≥5.72
EPA #2	7.91	≥5.86
EPA #2	6.82	≥4.78
EPA #2	6.64	≥4.59

EPA #1=model surface water; EPA #2=stressed surface water; POU=point-of-use. Results are means from three separate trials.

Table 4 | Efficacy of the POU water treatment system against rotavirus

Water treated	Initial viral count/ml (log_{10})	Log_{10} decrease (mean)
EPA #1	8.10	> 6.06
EPA #1	8.00	> 5.96
EPA #1	7.89	> 5.84
EPA #2	8.04	> 5.99
EPA #2	7.92	> 5.88
EPA #2	7.85	> 5.81

EPA #1=model surface water; EPA #2=stressed surface water; POU=point-of-use. Results are means from three separate trials.

effective removal (Table 10). The mean level of arsenic before treatment was 13 μg/l and <0.3 μg/l after use of the POU water treatment system. The WHO health-based guideline value is 10 μg/l (WHO 1996/1998).

DISCUSSION

A number of point-of-use water purification systems have been used over the years, including those that contain iodine or chlorine or use solar radiation (Powers *et al.* 1994; Mintz *et al.* 2001; Sobsey 2002), and have been shown to reduce household diarrhoeal disease by 6 to 90%. Chlorine is the most widely used POU water treatment. However, it has limited effectiveness against parasites like *Cryptosporidium* and its effectiveness for disinfection is reduced in turbid waters (Powers *et al.* 1994). Many drinking-water sources in developing countries have significant levels of turbidity and other contaminants. Treatments that reduce turbidity and chlorine demand prior to the addition of chlorine may also reduce the formation of unwanted chlorination by-products (Sobsey 2002).

Table 5 | Efficacy of the POU water treatment system against protozoan oocysts

Cyst	Water	Untreated count/l	Log_{10} reduction
Cryptosporidium parvum	DI	1.87×10^6	4.32 ($n = 6$)
	EPA #1	1.76×10^6	3.98 ($n = 7$)
	EPA #2	1.76×10^6	4.01 ($n = 7$)
Giardia lamblia	EPA #1	1.76×10^6	3.61 ($n = 6$)
	EPA #2	1.84×10^6	3.55 ($n = 1$)

DI=deionized water; EPA #1=model surface water; EPA #2=stressed surface water; POU=point-of-use; n=number of replicate experiments.

A new product that contains materials similar to those used in conventional large-scale water treatment was evaluated for microbial efficacy. In numerous laboratory studies, samples artificially contaminated with model pathogens were effectively treated for bacteria, virus and parasite removal. Even under conditions known to stress chlorine disinfection (EPA#2 model water), the POU water treatment was effective. Water turbidity was reduced and free chlorine levels were measurable 30 min after the disinfecting process. The results of the laboratory studies demonstrated that the new treatment yielded water that met WHO guidelines for treated drinking water suggesting that the treatment would be effective in field testing.

Table 6 | Reduction of arsenic following the use of the POU water treatment product: removal of As5+

Water type	Spiked [As]/μg/l	After [As]/μg/l	% removal
Deionised	470	0.6	99.87
Deionised	500	0.4	99.92
Deionised	500	0.4	99.92
Deionised	520	0.9	99.83
Deionised	520	0	100.00
Deionised	520	0.6	99.88
Deionised	520	0.4	99.92
Deionised	530	0.5	99.91
EPA #2	500	0.7	99.86
EPA #2	500	0.5	99.90
EPA #2	500	8	98.40
EPA #2	510	0	100.00
EPA #2	540	0.8	99.85
EPA #2	540	0.3	99.94
LDN	490	0.3	99.94
LDN	500	1.5	99.70
LDN	500	0.8	99.84
LDN	500	0	100.00
LDN	520	0.9	99.83
LDN	530	0.8	99.85
LDN	530	0	100.00
LDN	530	1.3	99.75
NCL	500	0	100.00
NCL	500	0.4	99.92
NCL	510	0.45	99.91
NCL	520	0.5	99.90
NCL	520	0.7	99.87
NCL	530	0	100.00
NCL	540	0	100.00
NSF 1	1,000	2.6	99.74
NSF 2	500	0.5	99.90
NSF 2	1,000	1.4	99.86
Mean	543	0.8	99.9

EPA #2=model stressed surface water; LDN=London tap water; NCL=Newcastle tap water; NSF 1=model water; NSF 2=model water.

Table 7 | Reduction of arsenic following the use of the POU water treatment product: removal of As3+

Water type	Untreated [As]/μg/l	Treated [As]/μg/l	% removal
Deionised	500	0.6	99.88
Deionised	1,000	0.4	99.96
EPA #1	500	0.8	99.84
EPA #1	1,000	2.6	99.74
EPA #2	500	1.0	99.80
EPA #2	1,000	1.4	99.86
Hard municipal	500	0.9	99.82
Hard municipal	500	0.5	99.90
Hard municipal	1,000	1.4	99.86
Soft municipal	1,000	2.2	99.78
Mean	750	1.2	99.8

POU=point-of-use, EPA #1=model surface water; EPA #2=model stressed surface water.

Table 8 | Coliform and *E. coli* reduction in 320 water samples from five countries following POU water treatment

Country	No. of water samples* tested	Pre-treatment coliforms**	Pre-treatment *E. coli***	Post-treatment coliforms	Post-treatment *E. coli*
Guatemala	151	1 to 2.4×10^6	0 to 2.4×10^6	0	0
Kenya	14	38 to $> 10^5$	0 to 9,200	0	0
Pakistan	24	18 to > 200	0 to > 200	0	0
Philippines	123	1 to 7.1×10^5	0 to 7,915	0	0
South Africa	8	$> 1{,}100$	23 to $> 1{,}100$	0	0

*Water samples included spring, lake, river, well, rain and tap water.
**Counts/100 ml.
POU=point-of-use.

Field testing was carried out on drinking-water source samples collected and treated in five developing countries. Under real-world conditions, 320 drinking-water samples that initially contained *E. coli* were devoid of measurable *E. coli* and coliforms post-treatment, consistent with WHO drinking-water guidelines and suggesting that an effective treatment is possible under a wide variety of conditions.

Arsenic poisoning is reported to be a growing health concern due to drinking water contamination. An estimated 33 to 77 million people in Bangladesh alone are affected by the arsenic problem in drinking water (Smith *et al.* 2000). The POU water treatment system evaluated in these studies significantly reduced arsenic levels in deliberately contaminated laboratory water sources and in eight well-water samples from Bangladesh. These reductions were well below the 10-μg/l guideline

Table 9 | Levels of arsenic in highly contaminated well water: before and after use of the POU water treatment product

Water source	Before [As]/μg/l	After [As]/μg/l	Percent removal
Bangladeshi well	130	5.0	96.2
Bangladeshi well	180	0.9	99.5
Bangladeshi well	350	0.5	99.9
Bangladeshi well	400	1.2	99.7
Bangladeshi well	49	0.13	99.7
Bangladeshi well	130	1.0	99.2
Bangladeshi well	160	0.24	99.9
Bangladeshi well	430	1.3	99.7
Mean level	229	1.2	99.5

Table 10 | Low level arsenic contamination in well water: before and after use of the POU water treatment product

Water source	Before [As]/μg/l	After [As]/μg/l	Percent removal
Guatemalan municipal	12	< 0.3	> 97.5
Guatemalan municipal	11	< 0.3	> 97.3
Philippine well	16	< 0.3	> 98.1
Mean level	13	< 0.3	> 97.7

established by the WHO guidelines for arsenic in treated drinking water (WHO 1996/1998). The water treatment system was also effective in reducing arsenic content in water sources where the initial contamination level was lower. Thus, it appears that the new POU water treatment system may provide effective reduction against inorganic contaminants, such as arsenic, in addition to the removal of potential diarrhoea-causing microbial organisms.

As mentioned, other POU treatments are available (Sobsey 2002). However, the current test product versus chlorine alone would be expected to be more effective for disinfection in turbid waters and removal of *Cryptosporidium* oocysts while producing water with residual levels of chlorine that would help prevent re-contamination. Compared with solar disinfection, the test product removes turbidity and provides residual chlorine to protect the treated water in the absence of sunlight. Relative to both systems, the POU water treatment described here has the additional advantage of removing harmful chemical contaminants such as arsenic. A previous report using a product that contained a flocculent agent combined with chlorine isocyanurate as a disinfectant showed that bacteria were effectively removed, but the recommended log reduction of poliovirus to achieve microbiological purified status was not achieved (Powers *et al.* 1994). The POU water treatment system reported here has several potential advantages over the previously reported product including a form of chlorine with a safety profile that is better accepted, greater efficacy under conditions of water turbidity, more effective parasite removal, more effective turbidity reduction, and more consistent residual chlorine levels.

In both laboratory studies and field tests of water contaminated with microbial pathogens or arsenic, treatment with the test system effectively removed the contaminants in line with WHO guidelines and in doing so demonstrated the potential to provide improved drinking water to households in developing countries. Intervention studies with this new POU water treatment system and additional water quality studies are being conducted to demonstrate the utility under a variety of conditions that can be expected in areas without adequate access to safe drinking water.

CONCLUSIONS

1. The POU water treatment system studied here is expected to provide excellent disinfection (>7-log bacterial, >4-log viral and >3-log parasite reductions) across a variety of water types and under conditions that stress less effective purification products including solar or chlorine treatment alone.
2. No *E. coli* were detected post-treatment in any of 320 samples of drinking water sources collected in developing countries.
3. The POU treatment was also effective in removing arsenic from water artificially contaminated with arsenic and from water with naturally occurring arsenic contamination.
4. The POU treatment demonstrated the potential to provide improved drinking water to households in developing countries.

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