Microbiological effectiveness of locally produced ceramic filters for drinking water treatment in Cambodia

Joe Brown and Mark D. Sobsey

ABSTRACT

Low-cost options for the treatment of drinking water at the household level are being explored by the Cambodian government and non-governmental organizations (NGOs) working in Cambodia, where many lack access to improved drinking water sources and diarrhoeal diseases are the most prevalent cause of death in children under 5 years of age. The ceramic water purifier (CWP), a locally produced, low-cost ceramic filter, is now being implemented by several NGOs, and an estimated 100,000 + households in the country now use them for drinking water treatment. Two candidate filters were tested for the reduction of bacterial and viral surrogates for waterborne pathogens using representative Cambodian drinking water sources (rainwater and surface water) spiked with *Escherichia coli* and bacteriophage MS2. Results indicate that filters were capable of reducing key microbes in the laboratory with mean reductions of *E. coli* of approximately 99% and mean reduction of bacteriophages of 90–99% over >600 litres throughput. Increased effectiveness was not observed in filters with an $AgNO_3$ amendment. At under US$10 per filter, locally produced ceramic filters may be a promising option for drinking water treatment and safe storage at the household level.

Key words | Cambodia, ceramic water filtration, drinking water quality, point-of-use water treatment

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INTRODUCTION

Over 1 billion people worldwide lack access to improved drinking water sources, and many more lack access to safe water as defined by the WHO risk-based *Guidelines for Drinking-water Quality* (WHO 2004, 2006). Conventional piped water systems using effective treatment to deliver safe water to households may be decades away in much of the developing world, meaning that many of the poorest people must collect water outside the home and are responsible for managing (e.g. treating and storing) it themselves at the household level (Sobsey 2002). This gap in service is a serious public health issue and has been addressed in the Millennium Development Goals, which aim to halve, by 2015, the proportion of people without access to safe water in 2000 (United Nations 2000). Unsafe drinking water contributes to a staggering burden of water-related disease in developing countries, borne primarily by the poor (Prüss *et al.* 2002; Moszynski 2006). Particularly susceptible are children, the elderly and immuno-compromised individuals, who are most vulnerable to diarrhoeal and other water-borne infectious diseases (Lima & Guerrant 1992).

In response to the persistent problems associated with waterborne diseases worldwide, new strategies for safe water provision are gaining currency, including treating drinking water at the household level to reduce exposure to waterborne pathogenic microbes (Clasen *et al.* 2007). Taken together, devices that can be used to treat water and/or prevent contamination of stored water in the home are referred to as household water treatment (HWT) or point-of-use (POU) technologies (Sobsey 2002). These comprise a range of options that can enable individuals and

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communities to reduce microbial pathogens or chemical contaminants in collected water at the point of use, since contamination of stored water at the household level may occur even when source water may be safe to drink (Jensen *et al.* 2002; Wright *et al.* 2004). POU water quality interventions have the potential to fill the service gap where piped water systems are not possible or do not deliver safe water, potentially resulting in substantial positive health impacts in developing countries (Sobsey 2006). Systematic reviews of field trials have suggested that household-based water quality interventions such as appropriate treatment and safe storage are effective in reducing diarrhoeal disease (Fewtrell *et al.* 2005; Clasen *et al.* 2006, 2007).

Many technologies for POU water treatment exist and some are supported by extensive laboratory and field studies documenting effective reduction of waterborne pathogens and diarrhoeal disease in users. One promising technology is porous ceramic filtration. Studies of relatively expensive, commercially produced ceramic filtration devices have suggested that these filters can provide an effective barrier against microbial pathogen indicators in water and that interventions are associated with significant health gains in users versus non-users of the technologies (Clasen *et al.* 2004, 2005, 2006). Successful field trials of more expensive filters have suggested that low-cost, locally produced filters may also be promising technologies for increasing access to safe water at the household level. Locally produced filters have the advantages of lower cost, use of local materials, labour, and expertise, and possibly greater potential for local investment and entrepreneurship.

The evidence base for microbiological effectiveness of locally produced ceramic water filters in the laboratory and in field use remains limited, however, despite widespread and increasing use of these technologies worldwide. Oyanedel-Craver & Smith (2008) found that well-characterized filter disks constructed using the Potters for Peace-recommended methods reduced *Escherichia coli* by $\geq$97.8% under controlled laboratory conditions, with highest reductions achieved through application of colloidal silver. Unpublished studies have reported results that suggest some microbial reduction in similarly constructed filters (Lantagne 2001; Roberts 2004; Duke *et al.* 2006). Brown *et al.* (2007) reported a geometric mean 98% reduction in *E. coli* of local ceramic filters in Cambodia after 0–4 years in household use and a mean 46% reduction in diarrhoeal disease among users versus non-users. Van Halem (2006) reports a 3.0–6.8 $\log_{10}$ reduction of *E. coli* over six influent/effluent paired samples and a 3.3–4.9 $\log_{10}$ reduction of sulfite-reducing *Clostridium* spores (a protozoan surrogate) over 12 paired influent/effluent samples in a comparative study of Potters for Peace-style filters from Nicaragua, Ghana and Cambodia. Lantagne (2001) reports a 4.6 $\log_{10}$ reduction for *Giardia lamblia* and 4.3 $\log_{10}$ reduction of *Cryptosporidium parvum* in a single test ($n = 1$). These studies do provide some evidence that low-cost ceramic filters can reduce bacteria by 2 + $\log_{10}$ and protozoan parasites by 3 + $\log_{10}$ under controlled conditions, with generally lower reductions of bacteria observed in the field, although studies have been limited to small volumes and few matched pre- and post-treatment samples. Viruses have been reduced typically by less than 90% (1 $\log_{10}$). This is consistent with an effective pore size of the filters typically in the microporous range, therefore able to appreciably retain bacteria and protozoa but perhaps too large to retain viruses (20–100 nm in effective diameter). However, virus testing has been limited to few samples in unpublished studies (Van Halem 2006). The pore size distribution reported by Oyanedel-Craver & Smith (2008) and described by Fahlin (2003) indicates that significant potential variability in pore structure is possible in local ceramic filters, with the bulk of pore sizes in test samples being $\leq$20 μm. The pore size distribution in locally produced ceramic filters is likely to vary widely because of the various methods and materials used to manufacture filters at the local level.

The purpose of this study was to evaluate the performance of two Cambodian porous ceramic water filters (one treated with $AgNO_3$ to inhibit microbial growth, one without $AgNO_3$) against bacterial and viral pathogen surrogates in the laboratory under replicated household use conditions using actual drinking water sources. The laboratory testing reported here preceded a field-based intervention study and was intended to evaluate the extent to which filters could be effective against bacteria and viruses under extended household use and to assess whether a silver nitrate ($AgNO_3$) amendment had any impact on the microbial reduction efficiency of filters.

EXPERIMENTAL

Filters

ICAITI (Instituto Centroamericano de Investigación y Technología Industrial, a research institute based in Guatemala) developed a prototype, flower pot-shaped porous ceramic filter to be used for drinking water treatment in rural areas of Central America beginning in 1981. This basic filter design has been in development since then with the involvement of several NGOs in Latin America and around the world, with the NGO Potters for Peace (PfP) playing a key role in the diffusion of the technology from 1998. The PfP filter, called *Filtrón* in Latin America and the Ceramic Water Purifier (CWP) in Cambodia, is now produced in a number of countries. Programme success and implementation models vary widely between countries and there are no standardized production or quality control methods for the filters. PfP do have a set of recommended practices but these are not universally applied in the autonomous factories that have access to differing resources, materials and expertise. Broad-based efforts to standardize production and quality control of filters are under way.

Filters based on the PfP process have been made in Kandal Province, Cambodia, since 2002 (Figure 1) by the NGO Resource Development International (RDI) (Brown *et al.* 2007). At the RDI factory, locally sourced raw clay is dried, milled and mixed with finely ground (<1 mm diameter) rice husks and water; the wet clay mixture is then moulded in an hydraulic press and fired to cone 012 (870°C) in a masonry kiln to produce the porous ceramic filter element. Porosity in the filter is created as the rice husks combust and leave behind pore spaces. After flow testing (a quality control step) to ensure that the flow rate is in the proper range to indicate target pore size and structure based on empirical testing data ($1.5–3\,l\,h^{-1}$), the filter elements are painted with a 0.00215 molar reagent-grade (99.999%) $AgNO_3$ solution intended to inhibit microbial growth on the filter. Approximately 300 ml are applied to each filter: 200 ml on the inside (46 mg Ag) and 100 ml on the outside of the filter element (23 mg Ag). The Microdyn® (Mexico, Distrito Federal) silver-based disinfectant used in local ceramic filter applications (Lantagne 2001; Fahlin 2003; Van Halem 2006) and recommended by PfP is a solution of silver nitrate and copper nitrate according to US EPA records (EPA registration number 00485500004). Microdyn® is 3.2% $AgNO_3$ and 0.6% $Cu(NO_3)_2$ by mass. The food-grade plastic bucket receptacle shown in Figure 1 includes a tap and lid to provide safe storage for treated water, since post-treatment recontamination of water through improper handling practices (e.g. dipping soiled hands or utensils into stored treated water) may limit the effectiveness of filters in household use (Brown *et al.* 2007).

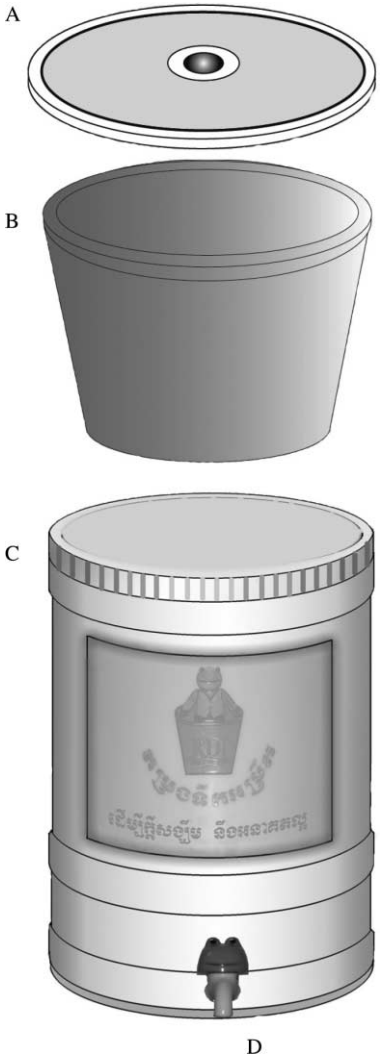

Figure 1 | Schematic of the ceramic water purifier (CWP) as produced by Resource Development International—Cambodia (courtesy of Mickey Sampson). The complete filter unit consists of a lid (A) covering the porous, 10 litre ceramic filter element (B) nested in the filter safe storage container (C). Treated stored water is collected via a tap at the base of the unit (D).

Challenge testing

Eight ceramic filters were tested in parallel: four CWPs with $AgNO_3$ treatment (CWP_{Ag}) and four CWPs without Ag amendment (CWP). All filters were produced at the RDI factory in Cambodia in two successive batches and passed all manufacturing quality control steps. Filters were flushed with 30 l of deionized, distilled water before testing. This volume is recommended by RDI as leaching of Ag has been observed to exceed the 0.1 mg l^{-1} EPA Primary Drinking Water Standard in the first 30 l and is therefore not recommended for consumption.

Filters were challenged with two test waters as representative drinking water sources in rural Cambodia. Both waters were in use as drinking water sources in the village where our laboratory is located, in Kandal Province, adjacent to the RDI filter factory. Challenge water A was harvested rainwater with low turbidity and organic matter and low levels of pre-spike *E. coli* (Table 1). Challenge water B was a surface water with mean turbidity 8.4 nephelometric turbidity units (NTU), organic matter content as ultraviolet (UV) absorbance at 254 nm of 0.05, and arithmetic mean pre-spike *E. coli* concentration of 145 colony-forming units (cfu) per 100 ml. Each testing day, water was collected from a rainwater catchment system and a surface water pond used for irrigation and household use.

After collection and initial characterization, each water was spiked with either *E. coli* CN13 or bacteriophage MS2 or both and mixed for 1 min. Each filter was then filled to the rim with spiked challenge water, approximately 10 l. Five hours later, filtrate (approximately 8 l) from each filter was collected, mixed manually with a sterile stirrer, and samples were taken of the post-treatment water for assay. Flow rates were approximately 2 l h^{-1} when filters were full (10 l), decreasing with declining head. Total filter throughput per sampling day was approximately 10 l. Pre-treatment (spiked) water was placed alongside the filter unit in a separate closed, opaque container for the duration of the test, with both pre- and post-treatment water samples taken for analysis at time = 5 h. Filter receptacles were completely drained but not disinfected between sampling days. Filters were cleaned once per week using methods recommended by RDI. During cleaning the filter and receptacle were scrubbed lightly with a brush, washed using boiled water and reassembled for use. No chemical disinfectant was used in cleaning. Residual silver in the post-treatment water was tested using Hach® Colorimetric Method 8120 (detection range: 0.005–0.7 mg l^{-1}) weekly. Silver in post-treatment water did not exceed 0.5 mg l^{-1} during testing in any filters.

Methods for testing the filter in the laboratory were intended to replicate household use conditions. An exception to this would be the volume filtered per day, which in household use could be more than 10 l (up to 30 l). The duration of testing, greater than 660 l throughput over more than 3 months, was intended to be representative of long-term use based on previous effectiveness data from a field-based study of CWPs (Brown *et al.* 2007).

Choice of test microbes

The non-pathogenic test microbes, *E. coli* CN13 (ATCC 700609) and bacteriophage MS2 (ATCC 15597-B1), were used as surrogates for bacterial and viral pathogens potentially present in drinking water sources, respectively. *E. coli* is a Gram-negative, rod-shaped bacterium

Table 1 | Challenge water characteristics; waters were currently used water sources in the village of Prek Thom, Kandal Province, Cambodia

Parameter	Challenge water A: rainwater (mean, range)*	Challenge water B: surface water (mean, range)†
pH	7.0 (6.8–7.5)	7.8 (7.0–8.3)
Turbidity (NTU)	1.1 (<0.05–8.1)	8.4 (0.63–21)
E. coli/100 ml before spike	<1 (<1–9.8)	145 (<1–540)
Temperature (°C)	29 (22–34)	30 (24–34)
UV absorbance, 254 nm	0.01 (<0.001–0.03)	0.05 (0.01–0.08)

*12.3% of total households and 13.6% of rural households use rainwater as a primary drinking water source, according to national data (NIS 2004).

†18.6% of total households and 21% of rural households use surface water as a primary drinking water source, according to national data (NIS 2004). Most of the remainder use dug wells as a source of drinking water. Access to well water is highly variable, however, and increasingly suspect as a source of drinking water in some areas because of arsenic contamination (Feldman *et al.* 2007).

originating in the gut of warm-blooded animals; cells are elongated, 1–2 μm in length and 0.1–0.5 μm in diameter. The well-characterized, non-pathogenic strain used was chosen because of its relative ease of production in the laboratory and its resistance to the antibiotic nalidixic acid, used to select for the bacterium in culture while excluding most other bacteria that might be present as interfering contaminants. Its size and morphology is characteristic of other pathogenic bacteria of concern in drinking water, such as pathogenic strains of *E. coli*, *Salmonella* spp., *Shigella* spp., *Campylobacter* spp. and *Vibrio* spp. Hence, *E. coli* CN13 was chosen as a model for the reduction of bacterial pathogens in water through the primarily physical separation process of ceramic filtration. *E. coli* CN13 is also not infected by the MS2 coliphage, making it suitable for concurrent use in filter testing with that virus as a test microbe in the same challenge water.

Bacteriophages such as MS2 are useful surrogates for modelling the behaviour of enteric viruses in water treatment processes (Grabow 2001) and have been used to model virus retention in other filtration processes (Sobsey *et al.* 1995; Van Voorthuizen *et al.* 2001). MS2, a male-specific (F+), single-stranded, non-enveloped coliphage, is an appropriate surrogate for human enteric viruses, owing to its similarity to poliovirus and hepatitis A virus in size (diameter = 24–25 nm), shape (icosahedral) and nucleic acid (RNA) (Dowd *et al.* 1998; Hassanizadeh & Schijven 2000). It is also useful in laboratory applications because of its ease of production, recovery and enumeration, its non-pathogenic nature and the ease of attaining high titres (Abbaszadegan *et al.* 1997).

Microbiological methods: *E. coli* testing

E. coli CN13 was inoculated in tryptic soy broth (TSB) medium (Difco™) and incubated overnight (16 h) at 37°C. The TSB medium was 3 g tryptic soy broth per 100 ml reagent water, which was sterilized and allowed to cool to 30°C or lower before use. Because *E. coli* CN13 is resistant to the antibiotic nalidixic acid, TSB for growing stocks was supplemented with 1% nalidixic acid (1 g of nalidixic acid sodium salt dissolved in 100 ml reagent water, filter sterilized via a 0.22 μm pore size membrane filter assembly) at 0.1 ml nalidixic acid to 10 ml TSB (final concentration 100 mg l^{-1}) (USEPA 2002). After overnight incubation, 1 ml of *E. coli* culture was transferred aseptically to 30 ml of fresh TSB medium (with nalidixic acid) in a shaker flask and incubated at 37°C for 3–4 h at 37°C, until absorbance was measured to be approximately 1.5 at 520 nm. Once cultures reached the stationary growth phase, 20 ml samples were taken and centrifuged at 4,800 × *g* for 20 min. The supernatant was discarded and the pellet of *E. coli* cells was washed three times and re-suspended in 20 ml of deionized (DI) water. A 1 ml aliquot of this mixture was added per 10 l of challenge water. The final concentration of *E. coli* CN13 was 10^4–10^7 cfu ml^{-1} in challenge waters.

E. coli in pre- and post-filter samples was enumerated by filtering undiluted and diluted samples through 47-mm diameter, 0.45 μm pore size cellulose ester filters in standard, sterile magnetic membrane filter funnels, and membranes were incubated on agar or broth media-soaked absorbent pads. Agar and broth media (Rapid HiColiform media, HiMedia, M1465/M1453) were used to detect total coliforms (TC) and *E. coli* (Manafi & Kneifel 1989; Manafi *et al.* 1991; Geissler *et al.* 2000). Plates were incubated for 20–24 h at 37°C. These methods conform to EPA Approved Method 1604 (USEPA 2002), except locally available HiMedia M1465 and M1453 were substituted for the more costly MI medium used in the EPA method. In preliminary studies in which samples were plated on both media, MI and M1465 or M1453, *E. coli* detection was comparable (data not shown). *E. coli* concentrations were expressed as cfu per unit volume of water.

Microbiological methods: MS2 testing

The F+ RNA coliphage MS2 (ATCC 15597-B1) was propagated to obtain high-titre stocks. Bacteriophages originally obtained from laboratory stocks were twice purified on *E. coli* C3000. High titre stocks were produced through confluent lysis on soft agar with phages, log-phase host (*E. coli* F-amp) and appropriate antibiotics and incubated at 37°C for 24 h. The lysate-agar mixture was subjected to chloroform extraction. Chloroform was added to the mixture in a 1:1 volume:volume ratio in 50 ml polypropylene centrifuge tubes, shaken vigorously by hand for 3 min, and centrifuged for 20 min at 4°C at 2,500 relative

centrifugal force (rcf). Following centrifugation, the supernatant was removed from individual centrifuge tubes and pooled. Sterile glycerol was added to the supernatant in a 1:4 volume:volume ratio. Finally, the stocks were aliquoted in 1 ml polypropylene microcentrifuge tubes and stored at −20°C and used within 2 weeks of production. Phage stocks were assayed to determine titre using standard plaque assay techniques (Adams 1959; USEPA 2001). Stocks of high titre bacteriophage were spiked into each challenge water to influent concentrations of 10^5–10^8 plaque-forming units (pfu) ml^{-1}.

MS2 bacteriophages in pre- and post-treatment water were enumerated on tryptic soy agars containing appropriate antibiotics (streptomycin/ampicillin) using the double agar layer (DAL) or spot titre pour plate plaque techniques (Adams 1959; Grabow & Coubrough 1986; USEPA 2001), with host *E. coli* F-amp (ATCC 700891; Debartolomeis & Cabelli 1991). The two methods were not significantly different in preliminary comparison tests (data not shown), although the spot titre method does not have as low a detection limit as the DAL method because of the small volumes assayed (Meschke 2001). Plaques were

Table 2 | Summary of laboratory effectiveness data for the CWP_{Ag} and CWP ceramic filters

Filter	Microbe	Challenge water	n^*	$V^\dagger$ (l)	Mean influent (log_{10} units)‡	Mean filtrate (log_{10} units)§	LRV mean‖	95% CI	LRV std dev	LRV variance
CWP_{Ag}	*E. coli*	Rainwater (A)	34	660	4.6	2.3	2.3	2.0–2.6	0.83	0.69
		Surface water (B)	34	660	5.1	2.7	2.4	2.1–2.6	0.72	0.51
	MS2	Rainwater (A)	17	660	6.9	5.6	1.3	0.47–2.1	1.6	2.6
		Surface water (B)	17	660	6.6	4.9	1.7	1.1–2.3	1.2	1.4
CWP_{Ag}	*E. coli*	Rainwater (A)	34	660	4.6	2.6	2.1	1.8–2.3	0.77	0.59
		Surface water (B)	34	660	5.1	2.9	2.2	1.9–2.5	0.79	0.62
	MS2	Rainwater (A)	17	660	6.9	5.4	1.4	0.73–2.0	1.3	1.6
		Surface water (B)	17	660	6.6	5.4	1.3	0.82–1.8	0.97	0.93
CWP_{Ag} (pooled)	*E. coli*	Rainwater (A)	68	1,340	4.6	2.5	2.2	2.0–2.4	0.80	0.64
		Surface water (B)	68	1,340	5.1	2.8	2.3	2.1–2.5	0.75	0.57
	MS2	Rainwater (A)	34	1,340	6.9	5.6	1.3	0.83–1.8	1.4	2.0
		Surface water (B)	34	1,340	6.6	5.1	1.5	1.1–1.9	1.1	1.2
CWP	*E. coli*	Rainwater (A)	34	660	4.6	2.8	1.8	1.4–2.3	1.1	1.3
		Surface water (B)	34	660	5.1	3.4	1.7	1.4–2.0	0.89	0.79
	MS2	Rainwater (A)	17	660	6.9	5.7	1.2	0.54–1.9	1.2	1.5
		Surface water (B)	17	660	6.6	5.4	1.3	0.69–2.0	1.3	1.7
CWP	*E. coli*	Rainwater (A)	34	660	4.6	2.3	2.3	2.1–2.6	0.69	0.47
		Surface water (B)	34	660	5.1	2.7	2.4	2.2–2.7	0.77	0.60
	MS2	Rainwater (A)	17	660	6.9	4.8	2.0	1.6–2.4	0.76	0.57
		Surface water (B)	17	660	6.6	4.9	2.0	1.6–2.4	0.83	0.69
CWP (pooled)	*E. coli*	Rainwater (A)	68	1,340	4.6	2.5	2.1	1.8–2.3	0.97	0.95
		Surface water (B)	68	1,340	5.1	2.9	2.1	1.9–2.3	0.90	0.81
	MS2	Rainwater (A)	34	1,340	6.9	5.3	1.6	1.2–2.0	1.1	1.2
		Surface water (B)	34	1,340	6.6	4.9	1.7	1.3–2.0	1.1	1.2

*Number of sample sets (matched influent effluent samples).
†Total spiked throughput (l).
‡Concentration (arithmetic mean) per 100 ml sample, log_{10} units.
§Concentration (arithmetic mean) per 100 ml sample, log_{10} units.
‖Arithmetic mean log reduction value (LRV) = log_{10} (influent/filtrate).

counted and bacteriophage concentrations are expressed as pfu per 100 ml.

Reported *E. coli* and MS2 concentrations in samples were calculated based on a minimum of two dilutions and three replicates according to *Standard Methods (1998)*. Log_{10} reductions for *E. coli* and MS2 were calculated for all filters' complete sample sets (both pre- and post-treatment concentrations). Descriptive statistics were used to characterize the water quality testing results from samples, including arithmetic mean (with 95% confidence intervals), standard deviation and variance of log_{10} reduction of *E. coli* and MS2. Parametric statistical tests were used to compare results. Comparisons were made using a two-sample mean comparison (t) test. Assumptions made in comparing log_{10} reduction data in parametric statistical testing were that data were normally distributed (verified using the Shapiro–Wilk test) and groups had equal variances (F-test). All statistics were interpreted using an a priori significance level of $\alpha = 0.05$. All statistical testing was performed in Stata version 8.1 (Stata Corporation, College Station, Texas).

RESULTS

Results of laboratory testing of filters for *E. coli* and MS2 reductions from spiked waters over time are summarized in Table 2. The results for repeated challenges indicate some variability in performance among filters in reducing both test microbes from both test waters, although no significant differences were detected in reductions of microbes (LRVs) between the filter types, among filter replicates of the same type, or between challenge waters. Reductions of *E. coli* were significantly higher than those of bacteriophage MS2 in all cases. The CWP_{Ag} reduced *E. coli* by a mean 2.2 log_{10} units (95% CI 2.0–2.4) and MS2 by a mean 1.3 log_{10} units (95% CI 0.83–1.8) in challenge water A (rainwater) and *E. coli* by a mean 2.3 log_{10} units (95% CI 2.1–2.5) and MS2 by a mean 1.5 log_{10} units (95% CI 1.1–1.9) in challenge water B (surface water). The CWP reduced *E. coli* by a mean 2.1 log_{10} units (95% CI 1.8–2.3) and MS2 by a mean 1.6 log_{10} units (95% CI 1.2–2.0) in rainwater and *E. coli* by a mean 2.1 log_{10} units (95% CI 1.9–2.3) and MS2 by a mean 1.7 log_{10} units (95% CI 1.3–2.0) in spiked surface water.

Log_{10} reductions of *E. coli* were not correlated with throughput over the total volume tested; linear regression using volume filtered as the independent variable did not yield evidence of association ($R^2 = 0.016$) in data pooled from filter types and challenge waters. Similarly, trending was not observed in MS2 reduction over the total volume tested ($R^2 = 0.17$). Greater reductions of both MS2 and *E. coli* were observed in initial testing of filters (within the first 100 l), however, in both challenge waters and in both filter types when comparing data up to the first 100 l with data from >100 l throughput. For *E. coli*, the mean log_{10} reduction was 2.9 log_{10} (95% CI 2.5–3.4) within the first 100 l of testing and 2.1 log_{10} (95% CI 2.0–2.2) thereafter ($p < 0.0001$). For MS2, the mean log_{10} reduction was 4.1 log_{10} (95% CI 3.5–4.8) within the first 100 l of testing and 1.2 log_{10} (95% CI 1.1–1.3) thereafter ($p < 0.0001$). The effect was consistent and significant in both challenge waters and in both filters tested for both *E. coli* and MS2.

DISCUSSION

E. coli reductions by all filters were near 99% under challenge conditions. MS2 reductions for all three filters were comparable, with mean reductions of 90–99%. Results indicate no effect of the $AgNO_3$ application on the performance of the filters against these indicators over extended laboratory testing, and performance was not significantly different over the limited range of water quality conditions represented by the challenge waters. These numbers are lower than other reported values for reduction of *E. coli* and higher than reported reduction values for MS2 from other laboratory studies over limited volumes using similar filters and different challenge waters in unpublished studies (Lantagne 2001; Van Halem 2006). One study has reported significantly greater microbial effectiveness via application of colloidal silver to ceramic filter disks, however (Oyanedel-Craver & Smith 2008).

More work is needed to further characterize the chemical composition and effectiveness of the various silver-based preparations used in ceramic filter manufacture in developing countries, since no standard exists and few data are available. Silver-based amendments used in filter manufacture have not been standardized and several different formulae are used in different locations; these are

commonly referred to as 'colloidal silver' although no published or unpublished studies have shown that the preparations used in filter manufacture contain colloidal suspensions of Ag versus other forms. Oyanedel-Craver & Smith (2008) used Argenol® (Zaragoza, Spain) in testing ceramic disks, also recommended by PfP, which is labelled as containing 7–8% colloidal silver and is sold in granular form; results indicated enhanced microbial reductions due to the silver additive. Silver nanoparticles (Sondi & Salopek-Sondi 2004; Kim *et al.* 2007), solutions of silver nitrate (Matsumura *et al.* 2003) and other silver preparations (e.g. Castellano *et al.* 2007) have been shown to be effective chemical disinfectants or microbial growth inhibitors, but other studies show no effect (e.g. Van Hasselt *et al.* 2004). No peer-reviewed studies of silver's effect on microbial reductions in actual water filters have been published, although unpublished studies have suggested that silver preparations may impact microbial reduction efficiencies in locally produced ceramic filters (Van Halem 2006). There are various means for applying silver preparations to filters, including painting or soaking filters in silver-containing solutions after firing or mixing silver preparations with clay before firing. No systematic studies of the forms of silver amendments, concentrations of silver, or methods of application to filters have been undertaken to determine the specific role of silver preparations in ceramic filters.

Results suggest that filter effectiveness against surrogate microbes was maintained over the volume tested. Since ceramic filters can be used for years in households, more data is needed to determine whether filters can remain effective for longer periods. The mean time in use of ceramic filters in a study from Cambodia was 2 years (Brown *et al.* 2007). The same study reported that the mean *E. coli* $\log_{10}$ reduction in filters in household use from 0 to 44 months was approximately 1.7 (95% CI 1.5–1.9, $n = 203$), over a wide range of water quality and use conditions in three provinces of Cambodia.

Filter challenge tests are sometimes carried out using relatively low volumes of challenge water. Results reported here suggest that initial performance of filters in challenge testing in low volumes (e.g. under 10 l) may overestimate performance over extended periods. Results from the first 10 l of challenge testing were significantly higher in all filter types, in both challenge waters, and for both microbes tested, in several cases more than one order of magnitude higher. Reduced retention of microbes over time may be due to short circuiting of the filter as preferential flow paths develop. No significant change in filter flow rate was noted over the testing period, however (data not shown).

In the United States and in some other countries, microbiological effectiveness standards based on reductions of pathogenic or indicator microbes apply to point-of-use water treatment devices. The United States Environmental Protection Agency and the National Sanitation Foundation (now NSF-International) require that water treatment devices intended to produce potable drinking water consistently meet a $6\log_{10}$ reduction of bacteria, $4\log_{10}$ reduction of viruses, and a $3\log_{10}$ reduction of protozoa (USEPA 1987; NSF 2003), using key surrogate microbes over a range of challenge water quality characteristics. The filters tested in this study would not meet this level of performance for bacteria or viruses. The risk-based approach for setting technology performance guidelines, however, now advocated by the World Health Organization (WHO 2006), recognizes the need for incremental improvement in water quality that can have real benefits where waterborne disease burdens are high. Because relatively modest improvements in water quality at the household level may result in substantial health gains in some settings, technologies not achieving the levels of microbial reduction required in rich countries should be studied further for potential health impacts in developing countries.

Because ceramic water filters are intended to improve health over long-term use by reducing exposure to pathogenic waterborne microbes, candidate technologies should be evaluated over extended periods under realistic use conditions. Moreover, results for these technologies may not be generalizable. Low-cost ceramic filtration for drinking water treatment in developing countries comprises a diverse range of technologies, varying by overall design, production method, clay and other materials, quality assurance and quality control (QA/QC) procedures, burnout material, firing temperatures and methods, chemical (e.g. so-called 'colloidal silver') amendments, and other characteristics, even those based on the common model as promoted by PfP (Lantagne 2001; Sobsey 2002; Dies 2003). Because the design and available materials and methods

vary widely from region to region, effectiveness data for one ceramic filter design may not be representative of other systems, or even in some cases of separate batches of filters made at the same factory where production methods are not consistent. Moreover, pot-style ceramic filtration technologies are changing as NGOs and others work to evaluate and improve the technologies to be more effective at improving water quality at the point of use. More work is needed to increase the evidence base of effectiveness for these promising interventions, including long-term health impact studies and field testing of filters under daily household use conditions in developing country settings.

CONCLUSIONS

Key findings from this study were that the CWP filters under investigation significantly reduced surrogates for waterborne bacterial and viral pathogens, with a mean of approximately 99% ($2\log_{10}$) reduction for *E. coli* bacteria and 90–99% ($1-2\log_{10}$) reduction for viruses; reductions of *E. coli* and MS2 were not significantly different between filters tested or challenge waters; the CWP with no application of silver was observed to be comparable in microbiological effectiveness to the CWP_{Ag} (with silver amendment). These results suggest that CWP technology, although not as effective as chlorination or boiling combined with safe storage, does reduce bacteria and viruses in water and may be suitable for treatment of moderately contaminated drinking water sources.

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