Assessment of a low-cost, point-of-use, ultraviolet water disinfection technology

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ABSTRACT

We describe a point-of-use (POU) ultraviolet (UV) disinfection technology, the UV Tube, which can be made with locally available resources around the world for under $50 US. Laboratory and field studies were conducted to characterize the UV Tube's performance when treating a flowrate of 5 L/min. Based on biological assays with MS2 coliphage, the UV Tube delivered an average fluence of 900 ± 80 J/m^2 (95% CI) in water with an absorption coefficient of 0.01 cm^{-1}. The residence time distribution in the UV Tube was characterized as plug flow with dispersion (Peclet Number = 19.7) and a mean hydraulic residence time of 36 s. Undesirable compounds were leached or produced from UV Tubes constructed with unlined ABS, PVC, or a galvanized steel liner. Lining the PVC pipe with stainless steel, however, prevented production of regulated halogenated organics. A small field study in two rural communities in Baja California Sur demonstrated that the UV Tube reduced *E. coli* concentrations to less than 1/100 ml in 65 out of 70 samples. Based on these results, we conclude that the UV Tube is a promising technology for treating household drinking water at the point of use.

Key words | drinking water treatment, low-cost, point-of-use, ultraviolet disinfection

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INTRODUCTION

Waterborne illnesses associated with contaminated water sources, inadequate sanitation, and poor hygiene are a leading cause of morbidity and mortality in the developing world, resulting in more than 1.7 million deaths annually (Ezzati *et al.* 2002; Pruss *et al.* 2002; WHO 2002). The burden of disease falls disproportionately on children, contributing significantly to high mortality rates for children under five years old, exacerbating malnutrition (Corteguera 1993), and stunting growth (Checkley *et al.* 2004).

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Waterborne illnesses are largely preventable through adequate hygiene, sanitation and safe drinking water; thus, one of the Millennium Development Goals (MDG) is to reduce the population without access to safe water and sanitation by 50% by the year 2015. Despite enormous progress over the past five years, 1.1 billion people still lack access to safe drinking water and an accelerated effort is required if the MDG is to be met (WHO & UNICEF 2006). In many regions, providing consistent, centralized water treat-

ment and safe distribution is prohibitively expensive or will take years to implement. One option that may overcome many of these problems is treating drinking water in the household at the point of use (POU) (Mintz *et al.* 2001; Sobsey 2002).

A variety of low-cost household POU water treatment methods have been shown to reduce the incidence of diarrheal illness in field studies in developing countries, including chlorination, flocculation plus chlorination, solar disinfection (SODIS), filtration with commercial ceramic filters, and boiling or heating to 70°C; several authors have reviewed these options (Sobsey 2002; Lantagne *et al.* 2006). In addition to provision of safe water, safe storage of water in the home, hygiene, and sanitation are also important interventions for reducing diarrheal illness (Wright *et al.* 2004; Fewtrell *et al.* 2005).

Factors that should be considered in choosing an appropriate POU option for water disinfection include effectiveness at eliminating potential pathogens, cost (initial, operation, and maintenance), availability of materials and parts, scale of treatment, mode of treatment (continuous vs. batch), and user preferences regarding time and effort required for operation and water odor and taste. Each of the POU water treatment methods mentioned above has distinct advantages and disadvantages. For example, chlorine is inexpensive but adds an undesirable taste to the water and is not effective against protozoan cysts. Boiling is effective at eliminating almost all microorganisms but is energy intensive and may contribute to deforestation if wood fuel is used. SODIS is very inexpensive but is dependent on adequate sunlight and has a long wait time. The varied nature of drinking water problems, availability of resources, and user preferences necessitate diverse and complementary treatment techniques (Mintz *et al.* 2001). Therefore, there is a need to continue to develop technologies to add to the POU water treatment toolbox.

Ultraviolet (UV) light is increasingly being applied instead of chlorination for the disinfection of both drinking water and wastewater in centralized treatment plants, because it is effective at inactivating protozoan cysts and does not produce disinfection byproducts (Masschelein 2002). Commercial UV disinfection units are currently available for household POU water treatment, but their cost is typically high (several hundred $US), and specialized replacement parts are expensive and may not be readily available in many parts of the world. If UV disinfection was affordable and available, however, it may have advantages for some households, including rapid and continuous treatment of water as it flows from the water source (e.g. household tap), little user effort required to produce relatively large volumes of treated water, no change in the taste of the water, and much lower energy requirements than boiling. A clear disadvantage for some households is the requirement for electricity; in addition, the lack of a residual disinfectant will not protect against recontamination after treatment.

In this paper we describe a point-of-use UV disinfection technology, the UV Tube, which can be made with locally available resources around the world for under $50 US. The UV Tube was developed and tested using an iterative design process that continuously incorporated feedback from potential users in rural Mexico. The objectives of the research reported herein were to: (1) measure the delivered fluence of the UV Tube at 5 L/min; (2) determine the residence time distribution in the UV Tube at 5 L/min; (3) develop a conservative model for estimating the fluence as a function of flow rates and absorption coefficient; (4) assess the safety of the materials used to build the UV Tube; and (5) evaluate the performance of the UV Tube under field conditions.

METHODS

The general design of the UV Tube and a protocol for its use are described below. Three types of tests (germicidal effectiveness, hydrodynamics, and materials degradation) were conducted in the laboratory to assess its performance. A simple irradiance model was also developed to provide rough estimates of the impact of flow rate and water absorbance on the germicidal effectiveness of the UV Tube. Following validation in the laboratory, a preliminary, short-term evaluation of field performance was conducted on UV Tubes installed in households in Baja California Sur, Mexico.

Description of UV tube

UV Tubes were constructed from a 65-cm long, 4-in diameter tube sealed with 4-in diameter Polyvinyl Chloride (PVC) end caps (Figure 1). A range of materials was evaluated, as described in Materials Degradation Testing section below. Based on these results, two different designs

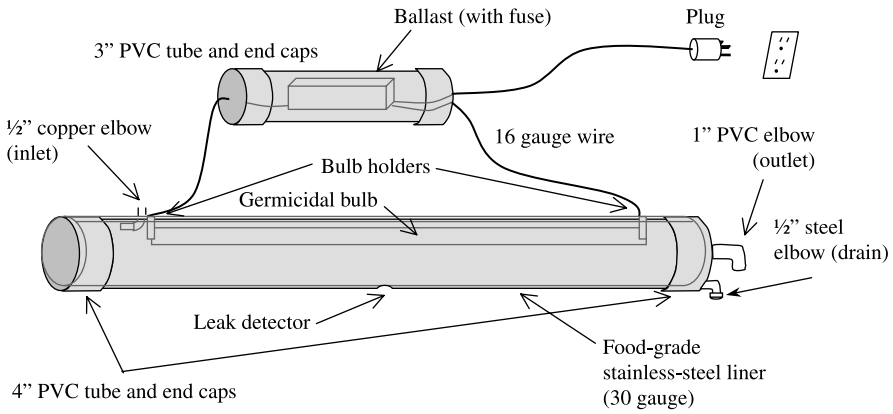

Figure 1 | Schematic of the PVC, stainless steel-lined, UV Tube water disinfection unit.

were used for the remaining research. In one design, the tube consisted of a PVC pipe lined three quarters of the way around with rolled, 26–28 gage, food-grade stainless steel sheet, with the remainder of the tube lined with aluminum foil to protect the PVC from UV exposure. To prevent water from flowing between the stainless steel liner and the PVC pipe, the edges were sealed with a silicone-based sealant; a hole was drilled in the bottom of the PVC pipe to serve as a leak detector. In the other design, the tube was formed by rolling 26 gauge, food-grade stainless steel sheet into a tube, which was secured at both ends with stainless steel hose clamps; the seam was located at the top of the tube. A General Electric germicidal G15T8 lamp was suspended from the top of the tube with lamp holders on the inside of the pipe. A small window was drilled at the top of the tube and covered with acrylic to enable the user to verify that the lamp is on before treating water. The ballast was mounted in a separate section of 3-in diameter PVC pipe with endcaps to protect it from moisture. Water entered through a 0.5-in copper elbow inlet inserted in the top of the tube, 7 cm from one end and exited through a 1-in PVC elbow outlet inserted in the center of the far end cap, which regulated the water height.

Germicidal effectiveness testing

Section 6.3 of the NSF/ANSI Standard 55 was used as a model for the biological assay of the UV Tube, but several modifications were made, as described below (NSF Joint Committee on Drinking Water Treatment Units 2002). All lamps had been used for at least 100 h prior to testing and were allowed to warm up for at least 30 min on the day of the test. Four bioassays were conducted on three separate dates.

MS2 coliphage (ATTC 15597-Bl) was propagated in antibiotic resistant *E. coli* (ATCC 700891) and stored at 4°C (APHA *et al.* 2005). On the day of each bioassay, about 10 ml of MS2 stock solution (approximately 10^{11} PFU/ml) was mixed with 250 L deionized water, achieving a concentration of about 10^{7} PFU/ml. The absorption coefficient (254 nm; 1-cm path length) was measured on a Lambda 14 UV/VIS spectrophotometer (Perkin Elmer, Freemont, CA) and ranged from 0.002 to 0.01 cm^{-1}. Challenge water was pumped from the mixing tank to a 50-L constant head tank from which it flowed by gravity through a flow meter to the inlet of the UV Tube. The UV Tube was operated at full power with a flowrate of 5 ± 0.05 L/min. For each bioassay, the UV Tube was flushed for five unit void volumes (about 3 min). Then, three 50-ml "outlet" samples were collected from the outlet at intervals of 1.5 residence times (about 45 s). Immediately after collecting the third sample, the UV bulb was turned off and the UV Tube was allowed to flush for five unit void volumes. Then, two 50-ml "inlet" samples were collected at intervals of 1.5 residence times from the outlet of the UV Tube (with the UV lamp off). The flowrate and operating volume were recorded. After the UV Tube was drained, another 50-ml "inlet" sample was taken from the tubing entering the inlet of the UV Tube.

On the same day as each bioassay, the fluence (dose) response for MS2 bacteriophage was measured. Triplicate

samples of challenge water were subjected to three to five UV fluences between 0 and 1200 J/m^2 using a bench-scale quasi-collimating beam (QCB) apparatus (Brownell & Nelson 2006). Using a pipette, 10-ml aliquots of challenge water from the bioassay inlet samples were placed in 60-mm Petri dishes, which were stirred magnetically during illumination. The incident irradiance at the center of the surface of each sample was measured before and after each exposure using a digital UV radiometer (IL1400A, International Light, Newburyport, MS). The average germicidal irradiance was estimated according to Bolton and Linden (Bolton & Linden 2003) using a modified version of the spreadsheet "Germicidal Fluence (UV Dose) Calculations for a Low Pressure UV Lamp" obtained from Bolton Photosciences Inc. (Edmonton, AB, Canada). Exposure time was controlled using a manual shutter and ranged from 0 to 29 min.

MS2 samples were serially diluted and plated in triplicate according to the double layer agar method (APHA *et al.* 2005). When cool, plates were inverted and incubated at 35 ± 1°C for 18 ± 2 h and enumerated. Only plates containing 25–250 PFU/ml were used to calculate the titer of the MS2 bacteriophage concentration for each sample.

Analysis of bioassay data

For each of four tests, fluence was calculated according to Section 6.3 of NSF/ANSI 55. In brief, the slope and intercept of the MS2 fluence response curve was used to calculate the average fluence in the UV Tube from the logarithm of the ratio of influent to effluent MS2 concentrations. The influent and effluent values for each test were calculated as the geometric means of the MS2 concentration of three different samples. Each sample concentration was calculated as the geometric mean of at least three replicates. Uncertainty for each fluence calculation was estimated by error propagation. The arithmetic mean of the fluences determined in each of the four tests was calculated to represent the overall average fluence delivered by the UV Tube. The corresponding prediction interval was calculated using the standard error and standard deviation of the four fluence estimates. To assess the sensitivity of the fluence values to different component variables, an individual fluence estimate was calculated for every possible combination of influent and effluent MS2 concentration measurements (1482 in total) and the average slope and intercept values from the fluence response curves.

Flow characterization

Three tracer studies were conducted to determine the residence time distribution and mean hydraulic detention time of the PVC-lined UV Tube at a constant flowrate of approximately 5 L/min. The flowrate was set with a flowmeter but measured for accuracy using a stopwatch and graduated cylinder. Approximately 2 ml of Rhodamine WT dye (Fisher Scientific) was injected just above the inlet to the UV Tube using a syringe. The exact amount of dye injected for each test was determined as the difference between the pre- and post-test weight of the syringe. 10-ml samples were collected from the outlet of the UV Tube at 3-s intervals for 3 min. The absorbance of each sample at 555 nm (1-cm path length) was determined and compared with a standard curve to establish the dye concentration of each sample (weight fraction). The operating volume was determined following the test by stopping the flow and immediately placing a beaker under the outlet. After the flowing water was collected, the UV Tube was tipped and the end caps were opened over the beaker to remove any remaining water for measurement by graduated cylinder.

Materials degradation testing

A range of materials was evaluated for constructing UV Tubes to determine if inorganic or organic compounds could be leached or produced in the water due to reactions with UV light under a range of operating conditions. Long-term exposure tests (>7 d) were conducted with acrylonitrile butadiene styrene (ABS) pipe, PVC pipe, PVC lined with galvanized steel, and PVC lined with stainless steel. During these tests the UV Tube contained stagnant water and the UV lamp was on; after the exposure period, water flow was turned on and the first outlet water was collected. Additional tests were conducted on the stainless-steel lined UV Tube using PVC pipe purchased in the U.S. (same as material used above) as well as PVC purchased in Mexico.

A flow-through test was conducted at a minimal flow rate of 0.24 L/min, and additional batch tests (lamp on with no flow) were conducted for exposure times of 1 h and 16 h (simulating overnight).

The inlet water for tests with PVC lined with stainless steel was Berkeley tap water augmented with humic acids (Sigma-Aldrich, Allentown, PA) to a concentration of 40 mg/L (20 mg/L dissolved organic carbon (DOC)). Humic acids have not been shown to produce by-products under UV radiation, but they are known precursors for halogenated disinfection by-products when using chlorine-based disinfectants. They were included in this study to determine if compounds produced from exposing PVC to UV radiation could interact with natural organic matter to produce chlorinated organics. The absorption coefficient of this test water ($\lambda = 254$ nm) was 0.20 cm^{-1}, resulting in about 90% attenuation of the UV light at the deepest part of the reactor. For the other tests distilled water was used.

The temperature and pH of all samples were measured in the laboratory and then samples were sent to Sequoia Analytical (Morgan Hill, CA) for analysis of 59 common volatile organic compounds (VOCs) according to the US EPA method 524.2. For the UV Tube with the galvanized steel liner, the sample was also analyzed for aluminum, iron, and zinc.

Mathematical modeling

A conservative irradiance model was developed by modifying the point source summation (PSS) method for a submerged lamp UV reactor (Blatchley 1997) to describe our suspended lamp design. Simplifications and assumptions in the model were designed to be conservative, i.e., to provide an underestimate of the fluence. For example, the light reflected from the inside surface back into the water was neglected in the model. The key variables used in the model are illustrated in Figure 2.

The following equation was used to calculate irradiance (modified from Blatchley 1997):

$$I_{i,j} = \frac{P_\lambda}{4n\pi\rho_{i,j}^2} \exp\left[-\left((\alpha \ln(10))(R - r_{\text{air}})\frac{\rho_{i,j}}{R}\right)\right] \quad (1)$$

where:

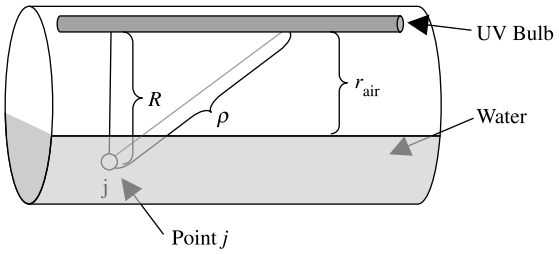

Figure 2 | Variables used in point source summation irradiance model.

$I_{i,j}$ = irradiance at point j due to site i in point source (mW/cm^2)
P_λ = lamp power at 254 nm (mW)
n = number of point sources
$\rho_{i,j}$ = distance separating site i in point source and site j in receptor (cm)
α = absorption coefficient of water at 254 nm (cm^{-1})
R = radial distance from lamp to receptor site (cm)
r_{air} = distance from lamp to surface of water (cm)

Additional calculations accounted for the operational flow-through height of the water (measured), the length of tube on each side of the lamp not directly below the light, the residence time, and the cumulative fluence (Cohn 2002). Calculations were performed using Engineering Equation Solver (EES, F-Chart Software, Middleton, WI). The individual irradiance distributions over multiple slices in the direction parallel to flow were summed to compute the average fluence. The hydraulics in the reactor were described assuming ideal plug flow, i.e. the irradiance for each section was multiplied by a fraction of the mean hydraulic detention time equivalent to its fractional volume. As discussed in the results section, the actual flow behavior deviated from plug flow, and the impact on the model is also discussed in the results section. The model was used to evaluate the effects of flow rate and absorption coefficient on the mean delivered fluence, using the following design values: radius = 5.08 cm; tube length = 65 cm; lamp output at 254 nm = 5,000 mW; weir height = 4 cm; distance from lamp to bottom of tube = 7.62 cm; distance between end of UV lamp and PVC endcap = 6.35 cm.

Field performance

During the summer of 2005, a small field trial was conducted in Baja California Sur, Mexico. The purpose of the field trial

was to gather information about the user-friendliness of the device, evaluate the performance of the UV Tube under field conditions (including water quality), and explore the feasibility of introducing the device in rural Mexico. Only the water quality component of the study is reported here; a full report of the field trial is reported elsewhere (Reygadas *et al.* 2007). UV Tubes were installed in the individual homes of 24 families in the communities of Los Espiritus (LE) and El Destino (ED); the communities' names have been changed to protect the anonymity of participants. Water sources included springs which were accessed in shallow hand-dug wells (LE) and deeper, concrete-lined wells (ED). Household members obtained water by pumping (gasoline or wind-powered), hand carrying, or transporting it in cars or trucks and stored water in an array of barrels (typically $\sim$200 L) around the house. The mean absorption coefficient for the water sources was 0.012 cm^{-1} $\pm$0.009 (s.d.). A support to hold the UV Tube was constructed from a plastic 20-L bucket; a second bucket installed above it provided a reservoir, from which water flowed through a small diameter tube to the UV Tube. The flow rate varied from 5 to 3 L/min as the reservoir emptied.

Each family was visited roughly five times during the field study. During each visit, four types of water samples were collected: water derived directly from springs and wells; source water which had been collected and stored in homes for drinking and other domestic purposes; source water which had been treated by the UV Tube; and source water which had been treated by the UV Tube and then stored in the home. To collect paired samples from before and after treatment, household members were asked to disinfect a batch of water in the presence of the researchers during a brief interview session; they obtained the water from their regular source and passed this water through the UV Tube. Small, sterile plastic bottles (Idexx WV120ST-20) were used to collect samples of the water before it was disinfected and as it exited the UV Tube. Samples were transported in the dark in an uninsulated vinyl bag to the local school building, where a small membrane filtration work area was devised. Samples not immediately analyzed were stored on ice for up to 24 h. Water samples were collected once a week for four consecutive weeks during July of 2005. An additional, fifth round of sampling was completed in September, approximately nine weeks after the fourth round.

E. coli were enumerated in 100 ml samples by membrane filtration with a 0.45 micron nitrocellulose membrane (Millipore). The stainless steel funnel and filter holder (Millipore) was sterilized between samples by spraying with 70% EtOH solution and flaming. The filter was then incubated with nutrient broth (mColiBlue24, Hach) at 35°C for 24 hours. Doors and windows were closed to prevent air movement, the work surface was sterilized with 70% EtOH, and a small flame was maintained in the center of the work area. The ambient temperature was often greater than 30°C, and sometimes greater than 35°C.

RESULTS AND DISCUSSION

Germicidal effectiveness

The bioassay data are summarized in Table 1. The fluence estimates for the four bioassays were 930 $\pm$ 70, 820 $\pm$ 60, 930 $\pm$ 60, 900 $\pm$ 210 (s.e.), resulting in a mean fluence of 900 $\pm$ 80 J/m^2 (95% CI). The prediction interval, or the range within which a new individual measurement of fluence would be expected to fall with 95% confidence, was $\pm$180 J/m^2, resulting in a range from 720 to 1080 J/m^2. The collimated beam data were consistent with published results summarized by Batch *et al.* (2004), and the regression line from the combined data falls close to the guidelines established by the National Water Research Institute (NWRI 2003).

The use of only three points in the fluence response curve did not significantly impact the final fluence calculations. When MS2 concentration measurements from collimated beam data collected during different tests were randomly combined with influent and effluent concentration measurements from different tests, variability in slope and intercept explained little of the variability in fluence. Regression analyses of fluences calculated from all possible combinations of individual influent and effluent MS2 concentration measurements showed that effluent number had a large and significant impact on fluence independent of test number but influent number did not. The larger impact of effluent concentration measurements on fluence reflects the fact that the relative variability in effluent MS2 concentration is several orders of magnitude greater than that in influent samples. Together, these data

Table 1 | MS2 inactivation data for three bioassay challenge tests of the UV Tube. Calculated values may not correspond directly to raw data due to rounding

	Inlet (PFU/ml)		Outlet (PFU/ml)				
Exp	**Sample (geomean of 3 replicates)**	**Geomean**	**Sample**	**Geomean**	**Log reduction**	**Fluence (J/m^2)**	**Standard error (J/m^2)**
1	3.5×10^8	3.6×10^8	9.0×10^3	1.2×10^4	4.5	930	70
	3.5×10^8		1.1×10^4				
	3.7×10^8		1.7×10^4				
2	3.9×10^7	3.7×10^8	3.6×10^3	2.6×10^3	4.1	820	60
	2.9×10^7		1.7×10^3				
	4.3×10^7		3.0×10^3				
3	4.3×10^7	3.9×10^7	1.6×10^3	8.8×10^2	4.6	930	60
	4.1×10^7		8.3×10^2				
	3.4×10^7		5.2×10^2				
4	2.3×10^7	1.5×10^7	4.2×10^2	6.4×10^2	4.4	900	210
	2.0×10^7		3.5×10^2				
	1.2×10^7		1.9×10^3				
Mean						900	80 (95% CI)

suggest that where resources are limited, the number of collimated beam and influent samples could be reduced without substantially harming data quality.

According to the Draft US EPA Ultraviolet Disinfection Guidance Manual (2003), UV fluences (doses) of 150 J/m^2 or more are sufficient to obtain 3-log reduction of the protozoa *Giardia lamblia* and *Cryptosporidium parvum*, and fluences greater than 1860 J/m^2 achieve 4-log inactivation of virus, thus meeting the criteria established in the Surface Water Treatment Rule (US EPA 2003). For certification of household-scale POU UV disinfection systems by the National Sanitation Foundation (NSF), a minimum delivered fluence of 400 J/m^2 is required (NSF Joint Committee on Drinking Water Treatment Units 2002). At 5 L/min, the mean fluence provided by the UV Tube was more than twice the NSF requirement. Based on the values given above, this fluence is expected to be sufficient to achieve several log inactivation of protozoan cysts and viruses. It should be kept in mind, however, that the absorbance of the water used for these bioassays was low (0.002 to 0.01 cm^{-1}), and a higher absorbance will significantly decrease the delivered UV dose.

Flow characterization

The results of the three tracer studies are summarized in Table 2. The flow rate was maintained at a constant value throughout each test, but varied between 4.96 and 5.22 L/min from test to test. The higher flow rates resulted in slightly higher liquid volumes in the UV Tube due to the higher water level over the outlet weir (pipe). The average theoretical HRT (θ), based on the measured volumes and flow rates, was calculated to be 35.8 s. The average experimental HRT (t_{bar}), based on analysis of the tracer curves, was found to be 35.4 s (Levenspiel 1999). The experimentally measured HRT was within 4% of the theoretical HRT in all three tracer tests. In one of the

Table 2 | Hydrodynamic characteristics of UV Tube based on three tracer studies

Parameter	Exp 1	Exp 2	Exp 3	Average	St. Dev.
Volume, L	2.91	3.15	3.12	3.06	0.14
Flowrate, L/min	4.96	5.18	5.22	5.12	0.13
Theoretical HRT (θ), s	35.2	36.5	35.8	35.8	0.64
Mean HRT (t_{bar}), s	36.2	35.5	34.5	35.4	0.83
σ^2, s^2	277	190	179	215	53
θ/t_{bar}	1.03	0.97	0.96	0.99	0.03
Dye recovery, %	100	108	101	103	5

tests, the mean HRT was slightly longer than the theoretical HRT, which may be explained by slight errors in the measurement of the time (starting the stopwatch as tracer was injected), flow rate, and/or operating volume of the UV Tube. The measured dye recovery ranged from 100 to 108%; values above 100% may have resulted from errors in the initial weight of dye, the spectrometer measurements, or in the numerical integration of the discrete data set. Overall, the agreement between the three different tracer tests and the high dye recovery are a validation of the experimental methods.

The flow pattern in the UV Tube was characterized by the differential residence time distribution curves (Figure 3). Both the tanks-in-series and plug flow with dispersion models were fit to the data. The model parameters were determined by minimizing the squares of the errors using all data points (Haas *et al.* 1997) by varying either N (tanks-in-series) or the Peclet (Pe) number (plug flow with dispersion); the HRT was fixed as the average value calculated from the tracer tests. The dispersion model, assuming closed boundaries and using the approximation suggested by Haas *et al.* (1997) provided the best fit, with Pe = 19.7, compared to N = 11.1 for the tanks-in-series (shown in Figure 3). Minimizing the errors provided a better fit than the method of moments (Levenspiel 1999). The first tracer exited the UV Tube between 3 and 6 s; visual observations of a clear PVC UV Tube (built for experimental purposes) revealed a somewhat radial velocity distribution, as expected due to shear forces, with faster-moving water at the top and center of the channel. Mixing also occurred as the inlet water plunged into the channel. No internal recirculation was observed visually, nor is evident as multiple peaks in the tracer curves. Finally, no dead spaces were observed, nor revealed by the tracer curves (evident when $t_{bar} < \theta$).

Materials degradation

Material degradation due to sunlight and/or UVA and UVB radiation is often studied, but little is known about the effect of 254-nm UVC radiation on the materials we investigated. The results from our tests are summarized in Table 3. For comparison, drinking water guidelines established by the World Health Organization (WHO 2006) and standards set by the US Environmental Protection Agency (US EPA 2003) are shown. In addition, when possible, a maximum acceptable concentration was determined based on the EPA Oral Reference Dose (US EPA 2006), which is an estimate of acceptable daily exposure. The reference dose, given in mg/kg-d, was converted to concentration (μg/L) by assuming a 50-kg person consumes 5 L of water per day.

At least one analyte was detected in all of the water samples tested. Benzene was detected in the ABS UV Tube at a concentration slightly lower than the EPA MCL. With the PVC UV Tube, several chlorinated organics were present at concentrations exceeding drinking water standards, and the pH was also unacceptably low. Lining the PVC UV Tube with galvanized steel produced high zinc levels, which cause a foul taste. Based on these results, we advise against the use of unlined ABS, PVC, or the use of galvanized steel as a liner.

UV Tubes made with PVC purchased in the U.S. and Mexico and lined with stainless steel produced similar results; thus, the data have been combined in Table 3. Lining the PVC UV Tube with stainless steel eliminated production of chlorinated organics and VOCs with the exception of bromomethane and butanone, which are unregulated (bromomethane was proposed and then removed from the US EPA's Contaminant Candidate List in 1998). Furthermore, these compounds were not detectable when the UV exposure time was 1 h or less. Interestingly, chloroform was the only detectable compound (at levels just above the detection limit) during the short-duration tests, and was also present at a similar concentration in the inlet sample that was tested.

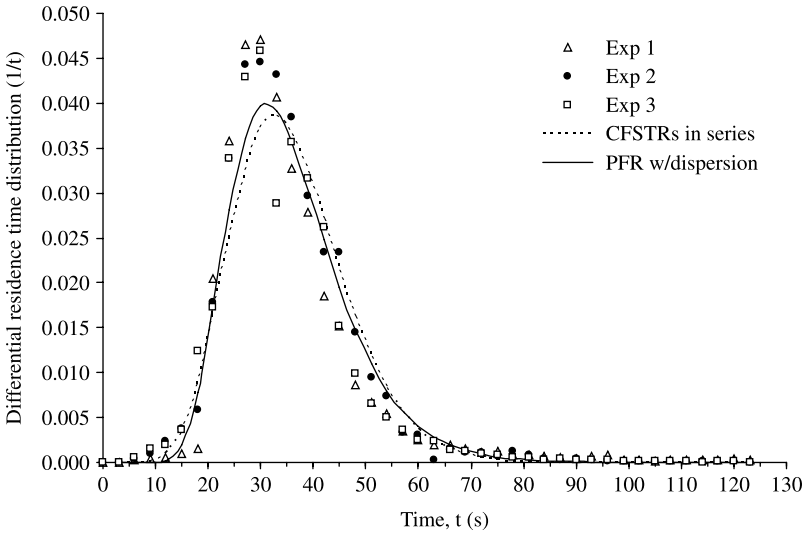

Figure 3 | Differential residence time distribution curves for three tracer studies and best fit curves for CFSTRs in series and PFR with dispersion models.

Thus, the likely source of chloroform was the tap water, which contains average annual concentrations of total trihalomethanes ranging from 27 to 51 μg/L (EBMUD 2006). Because chloroform is volatile, it may have been removed during the longer duration tests. The only compound which appeared at higher concentrations after longer exposure was acetone. Although we are unsure of its origin, possible sources of acetone include the silicone sealant or residue remaining from the stainless steel sheet manufacturing process; there is no evidence to indicate that these low levels represent a health risk.

Mathematical model

The average fluence delivered by the UV Tube was estimated using the point-source summation model for flow rates between 3 and 10 L/min and with absorption coefficients ranging from 0.01 to 0.16 cm^{-1} (Figure 4). At a flow rate of 5 L/min and absorption coefficient of 0.01, the model estimated a fluence of 812 J/m^2, compared to the experimentally determined fluence of 900 J/m^2, which is also shown in Figure 4. Thus, despite the assumption of plug flow hydraulics, the model provided a conservative estimate of the fluence. Although the model should not be used to estimate the exact delivered fluence, the results are useful for design purposes for understanding the quantitative impacts of flow and absorbance. For example, at a flow rate of 5 L/min, an absorbance higher than 0.13 cm^{-1} is likely to lead to fluences lower than the NSF minimum fluence of 400 J/m^2. These model results are roughly consistent with additional bioassay results which have been conducted in our lab using water with higher absorption coefficients (data not shown). One option for treating water with higher absorbance is to decrease the flow rate. Additional research is needed, however, to validate performance at other flowrates, because tracer experiments have indicated that the mixing regime at the UV Tube inlet changes significantly (data not shown).

Field performance

Ninety-four paired samples were collected of water entering and exiting UV Tubes during household use in Baja California, Sur. In 24 samples, no *E. coli* was detected in either the inlet or outlet samples; in the other 70 samples, the inlet concentration ranged from 1 to 243 with a geometric mean value of 15 CFU/100 ml. In 65 outlet samples, no *E. coli* was detected, and the counts in the remaining five samples were 1, 1, 1, 8, and 31 CFU/100 ml. The use of the UV Tube resulted in 20 out of the 24 families having access to water that conformed to the WHO guidelines (<1 *E. coli*/100 ml), whereas only one family would have had access to such water without the UV Tube.

Table 3 | Results from analysis of 59 volatile organic compounds and metals in water samples from the UV Tube following exposure to UV light. Compounds not shown in table were not detected in any sample[1]

	UV exposure time	Water type	Number of samples (independent experiments)	pH	Acetone (μg/L)	Benzene (μg/L)	Bromo methane (μg/L)	2-Butanone (μg/L)	Chloro ethane (μg/L)	Chloro form (μg/L)	Chloro methane (μg/L)	1,1-Dichloro ethane (μg/L)	1,2-Dichloro ethane (μg/L)	1,2-Dichloro propane (μg/L)	1,3-Dichloro propane (μg/L)	Dichloro methane (μg/L)	Zinc (mg/L)
Detection Limit					5.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.01
WHO (2006)				<8	NR	10	NR	NR	NR	300	NR	NR	30	40	NR	20	3
US EPA MCL (2003)				6.5–8.5	NR	5	NR	NR	NR	80[2]	NR	NR	5	5	NR	5	5
US EPA RfD[3]					1,000	40	14	6,000	NR	100	NR	NR	NR	NR	NR	600	NR
Inlet Water[4]	0	T + H	1	7.7	12	ND	ND	ND	ND	0.56	ND	ND	ND	ND	ND	ND	–
PVC w/stainless steel	8.6 min	T + H	2	7.8	15	ND	ND	ND	ND	0.61	ND	ND	ND	ND	ND	ND	–
〃	1 h	T + H	2	7.7	24	ND	ND	ND	ND	0.71	ND	ND	ND	ND	ND	ND	–
〃	16 h	T + H	2	7.7	230	ND	1.2	13	ND	ND	ND	ND	ND	ND	ND	ND	–
〃	>7 d	T + H	1	6.7	250	ND	1.4	7.7	ND	ND	ND	ND	ND	ND	ND	ND	–
PVC w/galvanized steel	>7 d	DI	1	–	ND	ND	ND	ND	ND	ND	3.2	ND	2.1	ND	1.1	4.1	43
PVC alone	>7 d	DI	1	1.8	ND	ND	ND	ND	50	1	115	2.5	28	8.4	13	41	–
ABS alone	>7 d	DI	1	–	ND	1.8	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	–

[1]ND, none detected; NR, compound is not regulated; "–", parameter was not tested; T + H, Berkeley tap water plus humic acids; DI, Distilled water.
[2]Regulated as total trihalomethanes.
[3]Oral Reference Dose (RfD) is an estimate of acceptable daily exposure made by the Integrated Risk Information System. The RfD is given as mg/kg-day, it was converted to μg/L by assuming a 50 kg person consumes 5 L of water per day (US EPA 2006).
[4]Inlet water (Berkeley tap water plus 40 mg/L humic acids) was measured on only one occasion. The characteristics of the inlet water may have been different on other days.

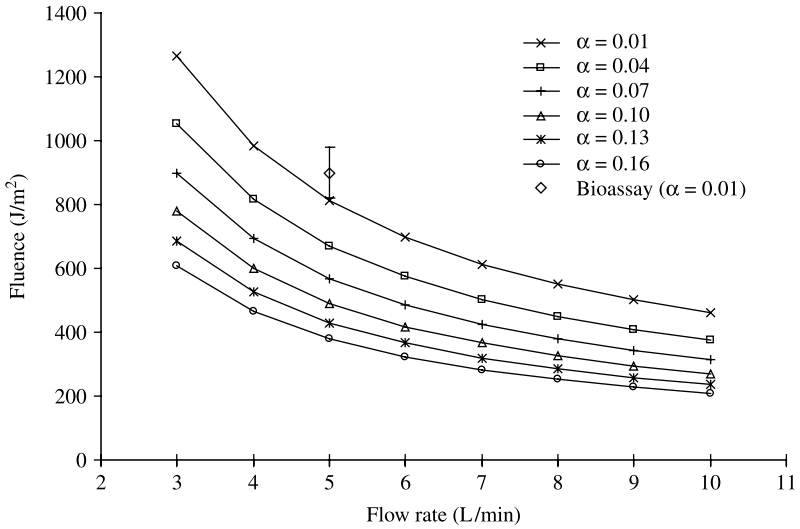

Figure 4 | UV Tube fluence predicted by the irradiance model as a function of flow rate and absorption coefficient (cm^{-1}) of water. The bioassay results at a flow rate of 5 L/min are also shown.

Thus, the UV Tube effectively lowered the level of bacterial contamination during actual use in the field. However, the presence of *E. coli* in the effluent of five samples suggests that additional research is needed to characterize and improve the performance of the UV Tube under field conditions. In addition, out of 83 samples collected from UV-treated water which had been stored in the home, 17 contained *E. coli*. Thus, there was evidence of recontamination or regrowth of *E. coli* during storage, probably due to the use of storage containers without effective seals and the use of a common cup for extracting water. These data illustrate that the lack of residual disinfectant in storage containers is a potential disadvantage of UV treatment compared to chlorination. However, safe storage in containers which do not allow contact with the treated water (e.g., spigot or hand pump) may be able to prevent recontamination.

CONCLUSIONS

Based on biological assays with MS2 coliphage, the UV Tube delivered an average fluence of 900 J/m^2 (95% prediction interval of 720 to 1080 J/m^2) at a flow rate of 5 L/min and an absorption coefficient of 0.01 cm^{-1}. Under the same conditions, the mathematical model predicted a fluence of 812 J/m^2. Thus, despite its simplicity, the model agreed fairly well with the experimentally determined fluence, and can be used to inform decisions about acceptable operating conditions (e.g., determining the maximum flow rate for water with higher absorbance). The residence time distribution at a flow rate of 5 L/min was characterized as plug flow with dispersion (Pe = 19.7) and a mean hydraulic residence time of 36 s. Based on the materials degradation testing, we advise against the use of unlined ABS, PVC, or the use of galvanized steel as a liner for UV Tubes. Lining the PVC pipe with stainless steel, however, prevented production of regulated halogenated organics. A small field study in two rural communities in Baja California Sur demonstrated that the UV Tube reduced *E. coli* concentrations to less than one per 100 ml in 65 out of 70 samples. Additional research is underway to expand the scope of our field studies to comprehensively address the factors that influence the disinfection performance as well as consistent and correct use of the UV Tube over longer time periods.

The laboratory and field studies reported here suggest that the UV Tube is a promising technology for treating household drinking water at the point of use. Because the UV Tube can be constructed using locally available resources, we believe it is a lower-cost (< $50 US) and a more sustainable option for POU UV treatment compared to commercially available UV disinfection units. Ultimately, by expanding the range of

technologies available for POU water disinfection, we hope that the UV Tube will contribute to long-term, sustainable global efforts which empower more households to gain access to safe water.

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