Assessing point-of-use ultraviolet disinfection for safe water in urban developing communities

Christina K. Barstow, Aaron D. Dotson and Karl G. Linden

ABSTRACT

Residents of urban developing communities often have a tap in their home providing treated and sometimes filtered water but its microbial quality cannot be guaranteed. Point-of-use (POU) disinfection systems can provide safe drinking water to the millions who lack access to clean water in urban communities. While many POU systems exist, there are several concerns that can lead to low user acceptability, including low flow rate, taste and odor issues, high cost, recontamination, and ineffectiveness at treating common pathogens. An ultraviolet (UV) POU system was constructed utilizing developing community-appropriate materials and simple construction techniques based around an inexpensive low-wattage, low pressure UV bulb. The system was tested at the bench scale to characterize its hydrodynamic properties and microbial disinfection efficacy. Hydraulically the system most closely resembled a plug flow reactor with minor short-circuiting. The system was challenge tested and validated for a UV fluence of 50 mJ/cm^2 and greater, over varying flow rates and UV transmittances, corresponding to a greater than 4 log reduction of most pathogenic bacteria, viruses, and protozoa of public health concern. This study presents the designed system and testing results to demonstrate the potential architecture of a low-cost, open-source UV system for further prototyping and field-testing.

Key words | developing communities, drinking water, point-of-use, ultraviolet disinfection

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INTRODUCTION

In developing communities there is a daily struggle to consume safe drinking water. While recent estimates by the World Health Organization (WHO) show progress towards the reduction of those at risk – from 1.1 billion people in 2006 to the current estimate of 768 million people – a large problem still exists (WHO 2013). The problem threatens to become worse with an ever growing population and displacement of entire communities owing to climate change-induced weather patterns (Dawson & Spannagle 2009; World Bank 2013).

Point-of-use (POU) water treatment

The term ‘improved source’ is used by the Joint Monitoring Program for Water Supply and Sanitation to determine if one is at risk from drinking water contamination. Improved sources include household connections, public standpipes, boreholes, protected dug wells, protected springs, and rainwater collection systems (WHO 2010). However, a source being improved alone does not guarantee safe water quality at the time of consumption. Many community-level improved sources such as a protected spring or boreholes may be already contaminated or can be re-contaminated after water collection (Wright *et al.* 2004; Onda *et al.* 2012). This highlights the need for POU treatment directly prior to consumption. Additionally, several studies have found higher effectiveness in preventing diarrhea through POU treatment options over community treatment options (Clasen *et al.* 2009).

Many POU water treatment technologies have been implemented worldwide in an effort to curb the incidence of diarrheal disease. Common POU technologies

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include but are not limited to: boiling, chlorination, bio-sand filtration, ceramic filtration, and solar disinfection (SODIS). However, many of these technologies have drawbacks such as environmental degradation (e.g., loss of natural resources or reduction of indoor air quality) with boiling (Sobsey 2002), the user's dislike of the taste of the water with chlorine (Mintz *et al.* 2001; Sobsey 2002) and long treatment times with ceramic filters or SODIS (Sobsey 2002; Sobsey *et al.* 2008).

Like users in many industrial countries, a safe, on-demand, drinking water source is most ideal because it provides high quality drinking water consistently and conveniently. Many urban developing communities may be specifically well suited for in-line POU technologies because they are more likely to have taps in their home. This water often has been subjected to some level of water treatment including filtration but may not be consistently safe to drink or esthetically suitable for consumption.

Ultraviolet (UV) disinfection in developing communities

Over the past decade, several UV disinfection systems have been developed, tested, and deployed in developing communities. These systems are reviewed in Table 1. While these systems have demonstrated the feasibility of UV-based technologies in a developing world context, lessons learned from the development and testing of these systems can be integrated into an improved design. UV Waterworks and the Bring Your Own Water (BYOW) processes are both community-scale systems, and as such are subject to the same downfalls as other community-scale systems such as recontamination of water after it has been collected. Additionally, the BYOW system recognized the need for cost optimization through locally available or manufactured materials (Gold *et al.* 2007). The POU UV system, the UV tube, reported recontamination of water after treatment, most likely from improper storage (Brownell *et al.* 2008). Another POU UV system, the UVeta or UV bucket also reported similar problems of recontamination when the storage bucket was not cleaned well enough or

Table 1 | Evaluation of existing UV systems for developing communities

UV system	Treatment point	Description
UV Waterworks (Gadgil *et al.* 2002)	Community	40 watt low pressure UV bulb
		Housed in aluminum and stainless steel
		Lamp suspended above the water
		Weighs approximately 15 pounds
		Implemented in India, South Africa, Bangladesh, Mexico and the Philippines
Bring Your Own Water System (Gold *et al.* 2007)	Community	Designed to provide 5,000 liters per day
		Placed at a central location within a community
		Collected water in bucket
		17 or 25 watt UV low pressure mercury vapor bulb
		Includes pretreatment through a roughing filter and sand filter
		Powered by photovoltaic cells
UV Tube (Brownell *et al.* 2008)	POU	8 watt low pressure UV bulb
		Sits above the water
		Chamber is a 4-inch PVC pipe covered in stainless steel
UVeta (UV Bucket) (Niparaja 2007)	POU	3 chambers, made out of plastic buckets, stacked
		Water moves from first chamber to the second chamber
		Second chamber houses UV bulb and a baffling scheme
		Water moves to third chamber for storage

when water was transferred to another container (Niparaja Organization 2007). The recontamination issue illustrates the tangible benefits of an in-line system, where water is available on-demand and thus can be treated on-demand and then consumed immediately.

From examining these past systems, a set of design requirements was established. POU UV systems must be made primarily of local materials and constructible with skills that are locally available. To minimize costs, the system must be optimized yet provide an appropriate factor of safety. Key properties of optimization include reactor hydraulics, UV bulb power and output, and maintenance requirements. Ideally, water should be available on-demand to eliminate the need for storage, and thus prevent recontamination. Therefore a reasonable flow rate is needed to meet on-demand use patterns.

For this research a POU UV system was designed, constructed, and efficacy tested under conditions relevant to an urban developing community's tap water. The objectives were to provide an example of construction under constraints of locally available materials, at a low cost. The testing demonstrates a method for validating UV systems for safe operation in developing countries including evaluation of hydraulic properties under a range of water quality using coliphage as a challenge organism.

MATERIALS AND METHODS

Description of reactor

Design considerations for the POU UV reactor included the use of materials that are commonly available and easy to work with in an urban developing country setting. Additionally, the design targeted a simple-to-construct process with minimal engineering skill required.

Figure 1 is a three-dimensional model of the POU UV reactor design, a photo of the UV bulb, and a photo of the reactor. This final design follows four iterations (not shown) of design, construction, testing, and redesign. The outer housing is a 1/4 inch-thick aluminum square tube. The interior of the reactor consists of three 1/4 inch-thick square aluminum baffles with 1/8 inch-thick aluminum spacers. A 2 inch diameter UV transmitting quartz tube runs through the middle of the reactor, and the entire system is sealed with gaskets and clamped shut. Water exits and enters the reactor through two fittings (1/8 inch hose barbs 1/4 inch-thick male pipe thread). The total volume of the reactor was 770 mL. The UV bulb installed was a 9 watt, 60 volt, 0.17 amp low-pressure mercury lamp developed by Philips (PL-S9W/TUV). The system was designed so the bulb slides into and out of the quartz tube without dismantling the reactor so bulbs can be replaced easily.

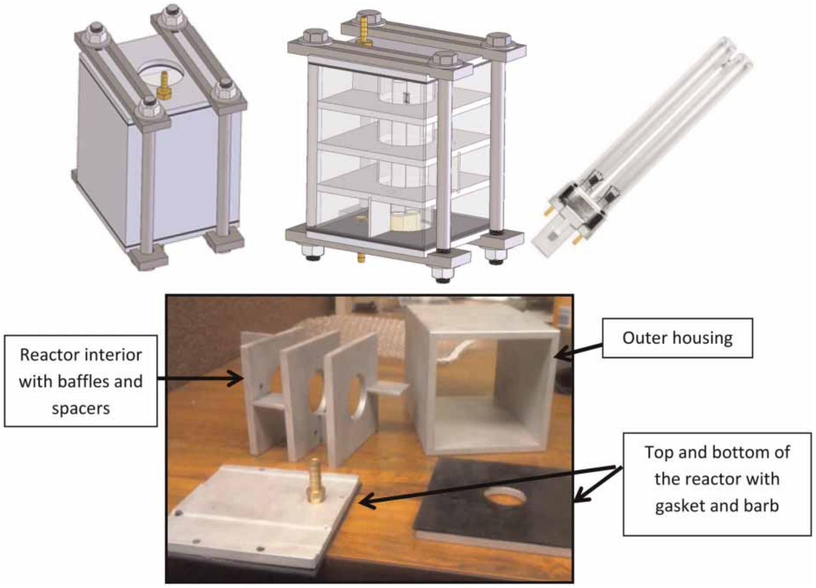

Figure 1 | Three-dimensional model, photo of the UV bulb (Phillips PL-S9W/TUV), and photo of the disassembled UV POU reactor.

Flow through testing

The reservoir for the flow through setup was a 5 gallon Pyrex carboy. Tygon tubing (1/2 inch diameter) conveyed water from the reservoir with a magnetic drive pump (Little Giant 1-MD, Franklin Electric, Bluffton, IN) to the POU UV reactor. A ball valve was fitted downstream of the reactor to adjust flow rate.

Hydraulics: tracer study

A step-input tracer study was conducted to determine hydraulic properties of the reactor. Lignin sulfonic acid (LSA) was used as a conservative tracer using the absorbance at 254 nm as the tracer monitor. Approximately 1 mL of LSA was spiked into the reservoir and mixed completely. The reactor was initially filled with deionized water and then switched to the LSA reservoir to start the test. The UV light was off during the entirety of the tracer study experiment, thus no photolytic degradation of the organic tracer would occur. A 5 mL sample was collected in borosilicate tubes every 5 seconds at a flow rate of about 1.0 L/min. The absorbance at 254 nm was then measured using a UV/Vis spectrophotometer (Cary 100 Bio, Varian Corp., Houston, TX).

Microbial challenge testing

MS2 coliphage was used as the challenge microorganism. The culture media used for the MS2 assay was 1.5% tryptic soy agar (Difco # 236950) with the addition of the antibiotics ampicillin sodium salt (Sigma A9518) and streptomycin sulfate (Sigma S6501). Growth of *Escherichia coli* F_{amp} (ATCC # 700891) was achieved through inoculation of 1 mL of stock bacteria into 50 mL of tryptic soy broth (Difco # 211825) containing the ampicillin and streptomycin antibiotics. The *E. coli* was allowed to grow in a shaker incubator at 36 °C for 12–18 hours to establish an overnight host bacteria stock culture. 0.5 mL of the overnight stock was inoculated into 50 mL of tryptic soy broth with antibiotics and incubated at 36 °C for approximately 2 hours to achieve a log-phase culture.

MS2 testing was achieved by spiking the stock MS2 coliphage into sterile phosphate-buffered saline (PBS) water to achieve a starting concentration of approximately 10^6 plaque forming units per mL. Sample concentration was determined using the double agar layer method (EPA Method 1601) where 0.1 mL of the sample is added to 5 mL of 0.7% tryptic soy agar and 0.1 mL of the *E. coli* F_{amp} host. Plates were incubated overnight at 36 °C and plaques counted.

Testing was performed at three different UV transmittance (UVT) levels (87.7, 94.4, and 99.7%), with three different flow rates (between 0.5 and 1.2 L/min) at each UVT. UVT was varied through the addition of LSA. The log reduction at each test point was then calculated as the log of the ratio of the influent concentration to the treated effluent concentration collected after passing through the reactor.

Collimated beam testing

Bench scale collimated beam testing was performed to produce a standard UV fluence (also termed 'UV dose') response curve for the MS2 coliphage. Collimated beam testing followed protocols presented in Bolton & Linden (2003). Stirred samples of 20 mL MS2-spiked PBS water (1 cm sample depth) were irradiated in Petri dishes at fluences of 15, 30, 45, and 60 mJ/cm^2. A low pressure mercury vapor lamp was used to irradiate samples for the UV exposures. Irradiance was measured at the water surface by an IL-1700 radiometer equipped with a SED 240 detector and W-diffuser (International Light, Peabody, MA) calibrated at 254 nm using methods traceable to the National Institute of Standards and Technology. Average UV fluences were determined as described in Bolton & Linden (2003). The collimated beam generated standard fluence–response curve fell within the NWRI guidelines for MS2 UV inactivation (NWRI 2003).

Challenge testing data analysis

The log reductions measured during challenge testing were converted to UV fluence using the reduction equivalent fluence concept via biodosimetry testing as described in the *Ultraviolet Disinfection Guidance Manual* (USEPA 2006) (termed reduction equivalent dose in the EPA guidance). The fluence per log reduced was obtained from the collimated beam testing of the 254 nm low pressure system. A fluence was then prescribed to each flow rate and UVT combination in the UV reactor system.

RESULTS

Reactor design

The reactor met requirements of being made of common materials that can be easily found although the cost of the system was higher than desired at $63 USD for the unit. Cost reductions could be found through use of a thinner aluminum which was chosen for convenience although this design aspect could be modified based on a local provider's available materials. Leaking from the system was a common issue and a few iterations of fitting the gaskets were necessary to solve this issue. Clamping of the reactor shut proved to be a key feature in ease of maintenance as the system can be easily taken apart whereby it can be cleaned and the bulb can be replaced easily.

Hydraulic: tracer study

Tracer studies were performed on previous reactor iterations and were used to optimize the design and identify any major hydraulic problems with the reactor flow. The exit age distribution of the final prototype at 1.0 L/min is shown in Figure 2. The theoretical hydraulic residence time (HRT) was 44.4 seconds. Using the tracer data, the mean HRT was calculated as 37.3 s (Crittenden *et al.* 2012), slightly lower than the theoretical HRT revealing minor short-circuiting through the reactor.

The tracer data indicated the reactor behaved like 2.1 continuous flow stirred tank reactors in series (Crittenden *et al.* 2012). The plug flow reactor (PFR) model dispersion number was calculated as 0.36 for the closed boundary case and 0.27 for the open boundary case.

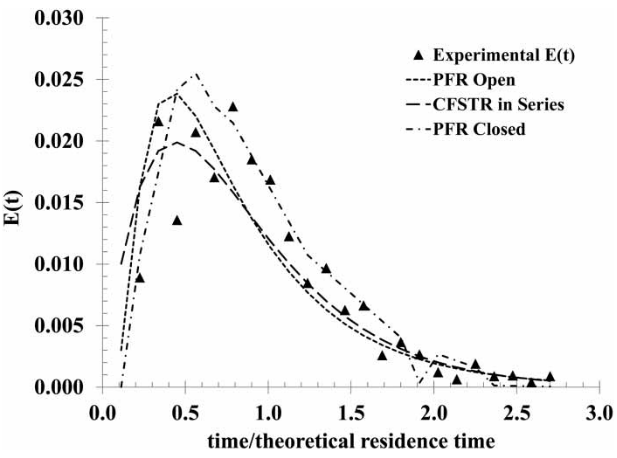

Figure 2 | The exit age distribution of the UV POU prototype at a flow rate of 1.0 L/min.

Challenge testing results

Figure 3 and Table 2 show the MS2 bioassay results for the UV reactor. UV fluence through the reactor ranged from 50 to 100 mJ/cm^2. As expected, the high UVT water (99.7%) yielded the highest fluence with an average fluence of 85 mJ/cm^2 at 1.2 L/min. Lower flow rates of 1.0 and 0.72 L/min yielded a fluence greater than 99 mJ/cm^2 (inactivation was greater than detection limit). At 94% UVT the low flow rate (0.62 L/min) also yielded inactivation greater than the detection limit resulting in fluence >91 mJ/cm^2. Higher flow rates of 0.92 and 1.1 L/min yielded an average fluence of 76 and 63 mJ/cm^2, respectively. At the lowest UVT of 87.7% the average fluence was 55, 64, and 90 mJ/cm^2 at flow rates of 1.1, 0.87, and 0.60 L/min, respectively.

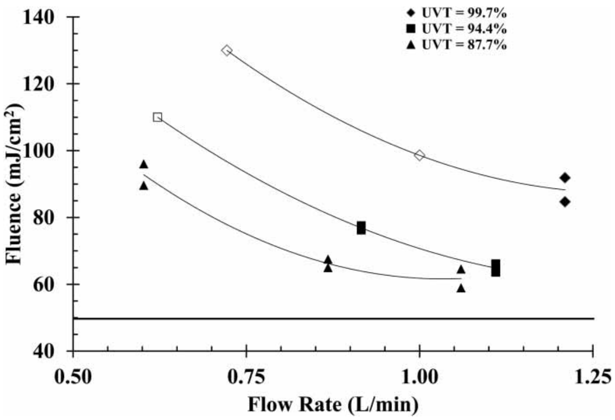

Figure 3 | Biodosimetry results for the UV POU reactor. Arrows indicate the detection limit of the test was reached and those points should be read as equal to or greater than the fluence shown on the figure.

Table 2 | Biodosimetry results for the UV POU reactor

UVT (%)	Flow rate (L/min)	Fluence (mJ/cm^2)
99.7	1.2	85
	1.0	>99
	0.72	>99
94.4	1.1	64
	0.92	76
	0.62	91
87.7	1.1	55
	0.87	64
	0.60	90

DISCUSSION

Reactor hydraulics

An ideal UV reactor would exhibit hydraulics closely related to a perfect PFR; however, the tracer study revealed some short-circuiting. Short-circuiting likely occurred owing to spaces nearest to the quartz tube and the wall of the reactor as the baffles do not have water-tight seals. Short-circuiting occurring close to the quartz tube is not of concern as those parcels of water will receive a higher level of UV irradiation compared to those parcels of water short-circuiting near the outer reactor walls that will receive a lower UV fluence. Parcels of water short-circuiting along the outer reactor walls is a design concern as these parcels may not receive adequate UV exposure.

An additional source of non-uniformity is the general shape of the reactor. Using a cylindrical reactor compared to the square tube shape used in the design would likely have yielded a more uniform hydraulic flow pattern. However, as the reactor is intended for use in developing urban communities, shape, material selection, and fabrication of the reactor have to be considered. Rounded metal is often difficult to work with and expensive to fabricate and thus would be a difficult material to work with in a developing region.

Reactor microbial efficiency

The UV reactor delivered significantly high fluences to provide protection against most microorganisms of public health concern. Fluences higher than 50 mJ/cm^2 were achieved at all test points. At these fluences, at least 4 log inactivation of most pathogenic bacteria, protozoa, and viruses would be achieved (Hijnen *et al.* 2006). Given the high degree of inactivation observed, it may be possible to use a lower power UV bulb to save energy and material costs. However, any new bulb would require microbial challenge testing to ensure adequate inactivation of pathogenic organisms. Use of more sophisticated hydraulic analysis, such as computational fluid dynamics, may also assist in optimizing the fluid flow in the reactor system, improving efficiency. As a comparison, common household UV systems currently available can range anywhere from $99 USD to several hundred dollars depending on the flow rate and UV dose needed, compared to a cost of about $63 for this unit.

CONCLUSION

An ultraviolet POU reactor specifically designed for use in urban developing communities was designed and tested to determine its hydraulic characteristics and disinfection efficacy under varying water quality. The study concluded the following:

- The system evaluated was designed and tested with the understanding of locally available materials and operation in an urban developing community. The system was able to provide disinfected water for an on-demand scenario, thereby reducing the possibility of recontamination during storage.
- Key features were realized in the design of the system including ease of maintenance, cleaning, and removal and change of the bulb.
- While materials were chosen to fit into an urban developing world context, local alternatives for metallic housing are likely suitable. For example, steel may be a better option than aluminum due to availability and welding requirements.
- Hydraulically the reactor closely resembled a PFR. However, the reactor showed several signs of short-circuiting. This is likely caused by spaces between the baffles and walls as well as the baffles and quartz tube.
- At all experimental flow rates and UVTs the reactor achieved fluences greater than 50 mJ/cm^2. At these fluences, greater than 4 log inactivation of most pathogenic bacteria, viruses, and protozoa is guaranteed. Achieving sufficient inactivation at greater than 1 L/min at the lower UVT (87.7%), indicates that the reactor has met the design goal of providing an on-demand flow rate, providing conservatively safe water at 1 L/min.
- As the reactor provided sufficient microbial inactivation, further development of fluence curves at increased flow rates and lower UVTs will provide insight into operational thresholds for use of the system. Additional guidelines such as maximum influent turbidity could be developed to assess the threshold under which additional POU pretreatment for particle removal might be warranted. General guidelines set by the USEPA for UV disinfection require a turbidity of under 5 nephelometric turbidity units (NTU) for unfiltered systems and under 1 NTU for filtered systems.

- The material cost of the experimental reactor was approximately $63 USD, which would need to be reduced for affordability in a developing community's setting. However, the cost of many parts, when sourced within a local context, can be brought down with the use of recycled metal and alternative materials. An additional cost not accounted for is powering the unit which would vary country to country.
- Additional design elements also need to be considered before field implementation. Owing to warm-up time, the UV lamp would need to either be on all the time or be turned on before water flow occurred. Therefore a switch with a lamp on/lamp ready indicator light would be needed. This switch could also indicate the lifetime of the bulb. Any additional components and safeguards need to be assessed carefully as they will likely increase the cost and complexity of the system.

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