Laboratory Assessment of a Gravity-Fed Ultrafiltration Water Treatment Device Designed for Household Use in Low-Income Settings

Thomas Clasen,*† Jaime Naranjo, Daniel Frauchiger, and Charles Gerba

Abstract. Interventions to improve water quality, particularly when deployed at the household level, are an effective means of preventing endemic diarrheal disease, a leading cause of mortality and morbidity in the developing world. We assessed the microbiologic performance of a novel water treatment device designed for household use in low-income settings. The device employs a backwashable hollow fiber ultrafiltration cartridge and is designed to mechanically remove enteric pathogenic bacteria, viruses, and protozoan cysts from drinking water without water pressure or electric power. In laboratory testing through 20,000 L (~110% of design life) at moderate turbidity (15 nephelometric turbidity unit [NTU]), the device achieved log₉₉₉₁₀ reduction values of 6.9 for Escherichia coli, 4.7 for MS2 coliphage (proxy for enteric pathogenic viruses), and 3.6 for Cryptosporidium oocysts, thus exceeding levels established for microbiological water purifiers. With periodic cleaning and backwashing, the device produced treated water at an average rate of 143 mL/min (8.6 L/hour) (range 293 to 80 mL/min) over the course of the evaluation. If these results are validated in field trials, the deployment of the unit on a wide scale among vulnerable populations may make an important contribution to public health efforts to control intractable waterborne diseases.

INTRODUCTION

Unsafe drinking water is a leading cause of preventable disease, particularly among young children in developing countries. Waterborne pathogens, including a variety of viral, bacterial, and protozoan agents, account for much of the estimated 4 billion cases and 1.8 million deaths from endemic diarrheal disease each year. Among children <5 years of age in developing countries, diarrheal disease accounts for 17% of all deaths. Microbiologically contaminated water also contributes to the heavy burden of disease associated with cholera, typhoid, paratyphoid, hepatitis, poliomyelitis, and gastroenteritis. Low-income populations are particularly at risk of such diseases because of the unavailability of safe water and sanitation.

Interventions to improve water quality, particularly when deployed at the household level, are an effective means of preventing endemic diarrheal disease, a leading cause of mortality and morbidity in the developing world. We assessed the microbiologic performance of a novel water treatment device designed for household use in low-income settings. The device employs a backwashable hollow fiber ultrafiltration cartridge and is designed to mechanically remove enteric pathogenic bacteria, viruses, and protozoan cysts from drinking water without water pressure or electric power. In laboratory testing through 20,000 L (~110% of design life) at moderate turbidity (15 nephelometric turbidity unit [NTU]), the device achieved log₉₉₉₁₀ reduction values of 6.9 for Escherichia coli, 4.7 for MS2 coliphage (proxy for enteric pathogenic viruses), and 3.6 for Cryptosporidium oocysts, thus exceeding levels established for microbiological water purifiers. With periodic cleaning and backwashing, the device produced treated water at an average rate of 143 mL/min (8.6 L/hour) (range 293 to 80 mL/min) over the course of the evaluation. If these results are validated in field trials, the deployment of the unit on a wide scale among vulnerable populations may make an important contribution to public health efforts to control intractable waterborne diseases.

THE WATER TREATMENT SYSTEM

The LifeStraw Family is a fully-integrated, gravity-fed, point-of-use microbial water treatment system intended for routine use in low-income settings. To meet the needs of the most vulnerable populations, it was designed to operate without electricity or other power and without a piped-in water supply. The unit was also designed to treat water of unknown microbiologic quality, and thus meet internationally recognized levels for microbiological water purifiers. It was also designed to operate under heavier levels of turbidity that may characterize water in such settings, especially during rainy seasons.

The microbiologic barrier consists of a 26-cm-long × 3-cm-diameter plastic cylindrical cartridge containing a number of hollow fibers with a 20-nm pore size. Although the cartridge is
potentially suitable for tabletop and other configurations, we tested a configuration designed for mass distribution and use in settings that do not necessarily have surfaces for tabletop units (Figure 1). Source water is introduced into the system by dipping the 2.5 L receptacle into an open vessel or pouring water into it if hanging or mounted on a wall. The water passes through a cleanable 27-µm textile prefilter mounted inside a removal plastic basket inside the receptacle and then through a 1 m length of 12-mm-diameter plastic tubing filling the cartridge. A slow-eluting solid chlorine tablet can be installed in a halogen chamber at the receptacle to help prevent biofilm, but was not included in this assessment to avoid any biocidal action that might be attributable to the disinfectant. When the side tap is opened, water passes through the walls of the hollow fiber membrane bundle and out the tap, mechanically removing microbes and other suspended solids greater than 20 nm in size.

The prefilter is cleaned by removing the prefilter basket from the receptacle and rinsing it in water. The microbial cartridge must also be cleaned from time to time by backwashing it. This is done by closing off the side tap, squeezing the hand pump located on the lower part of the cartridge three times, and opening the cock at the bottom of the cartridge for a few seconds to allow the backwash to flow to waste. The bottom cock is then closed and the unit is ready for use.

The unit is designed to produce ~150 mL of product water/minute (9 L/hour) and to last for at least 18,000 L. As it relies on mechanical filtration and not disinfection or adsorption, there is no need for a means of measuring volume of water treated or end of useful life; as long as the device remains intact, water from the tap will be effectively treated. When the flow from the unit cannot be restored to an acceptable rate by prefilter cleaning and cartridge backwashing, the entire unit is intended to be replaced. Assuming a household of five persons, the unit would provide 2 L of drinking water/person/day for almost 5 years without any replacement parts. In larger quantities, the manufacturer sells this configuration for about US$20.00. Using the foregoing assumptions, this works out to less than US$1/person/year. The cost per liter treated would be US$0.001/L.

METHODS AND MATERIALS

Setup and test waters. Test methods were based generally on EPA Protocol and Guide Standard for Testing Microbiological Water Purifiers (the “EPA Protocol”). Three production units of the LifeStraw Family provided by the manufacturer were conditioned in accordance with the manufacturer’s instructions with unspiked test water and installed on the bench for testing using apparatus conforming to EPA Protocol (Figure 1). Aging was performed using water based on EPA general test water #1, except that the turbidity level was increased from 0.1 to 5.0 NTU prescribed by the Protocol to 15 nephelometric turbidity unit (NTU), and the organic carbon level was increased from 0.1–5.0 mg/L prescribed under the Protocol to 5 mg/L. These harsher conditions were intended to challenge the longevity and flow rate of the device. Microbial challenges were performed using water based on EPA challenge test water #3, except that the water was maintained at room temperature and not chilled to 4°C as prescribed by Protocol. The performance of occlusion devices, such as the LifeStraw Family, is not expected to be impacted by low temperatures, which are known to affect halogen disinfection. The parameters for the test water, including the materials used for adjusting the parameter, are set forth in Table 1.

Test organisms. The test organisms consisted of microbes shown to simulate the range of waterborne pathogens commonly found in untreated water. The bacteria group was represented by *Escherichia coli* (ATCC # 25922) spiked into the input water at concentrations of 10⁷ to 10⁸ colony forming units (CFU)/100 mL. The viral group was represented by male-specific coliphage MS2 (ATCC #15597-B-1) spiked into the input water at concentrations of 5 × 10⁵ plaque forming units (PFU)/100 mL and inoculated into *E. coli* (ATCC # 15597) for assay. The MS2 coliphage has been recognized as a suitable surrogate for enteric viruses for water treatment processes and point-of-use device testing. The protozoan cyst group was represented by *Cryptosporidium parvum* oocysts spiked into the input water at concentrations of 5 × 10⁷/L.

Microbiologic methods. *Escherichia coli* was grown overnight in Trypticase Soy broth (Difco, Detroit, MI) at 37°C to obtain the organisms in the stationary growth phase. The bacterial cells were pelleted by centrifugation and resuspended in phosphate buffered saline (PBS). This procedure was repeated three times to remove organic matter present in the broth. Bacterial assays were conducted by the membrane filtration method on m-Endo Agar LES (Becton Dickinson, Cockeysville, MD). Appropriate dilutions of influent samples were made in sterile 0.025 M PBS at pH 7.0. A 100 mL sample of undiluted unit effluent was also assayed. All assays were in triplicate according to Standard Methods. The MS-2 virus
stated that to meet the requirements of a microbiological water purifier under the EPA Protocol, the geometric mean of all LRVs must be at least 6 for bacteria, 4 for viruses, and 3 for cysts. Moreover, not more than 10% of the influent/effluent sample pairs may deviate from the required LRV by one order of magnitude in the case of bacteria and viruses, and one-half order of magnitude in the case of cysts.

RESULTS

Microbiologic assessment. Table 2 sets forth the log reduction values at each sampling point for each of the three treatment units for the bacterial, viral, and protozoan cyst test organisms. The mean log$_{10}$ reduction for all sample pairs over the life of the three treatment units for the bacterial, viral, and protozoan cyst test organisms. The mean log$_{10}$ reduction for all sample pairs over the life of the three treatment units for the bacterial, viral, and protozoan cyst test organisms. The mean log$_{10}$ reduction for all sample pairs over the life of the three treatment units for the bacterial, viral, and protozoan cyst test organisms. The mean log$_{10}$ reduction for all sample pairs over the life of the three treatment units for the bacterial, viral, and protozoan cyst test organisms. The mean log$_{10}$ reduction for all sample pairs over the life of the three treatment units for the bacterial, viral, and protozoan cyst test organisms. The mean log$_{10}$ reduction for all sample pairs over the life of the three treatment units for the bacterial, viral, and protozoan cyst test organisms. The mean log$_{10}$ reduction for all sample pairs over the life of the three treatment units for the bacterial, viral, and protozoan cyst test organisms. The mean log$_{10}$ reduction for all sample pairs over the life of the three treatment units for the bacterial, viral, and protozoan cyst test organisms. The mean log$_{10}$ reduction for all sample pairs over the life of the three treatment units for the bacterial, viral, and protozoan cyst test organisms. The mean log$_{10}$ reduction for all sample pairs over the life of the three treatment units for the bacterial, viral, and protozoan cyst test organisms. The mean log$_{10}$ reduction for all sample pairs over the life of the three treatment units for the bacterial, viral, and protozoan cyst test organisms. The mean log$_{10}$ reduction for all sample pairs over the life of the three treatment units for the bacterial, viral, and protozoan cyst test organisms. The mean log$_{10}$ reduction for all sample pairs over the life of the three treatment units for the bacterial, viral, and protozoan cyst test organisms. The mean log$_{10}$ reduction for all sample pairs over the life of the three treatment units for the bacterial, viral, and protozoan cyst test organisms.

Flow rate and cleaning. Figure 2 shows the effluent flow rate of mL/minute for each unit tested over 20,000 L (111% of the 18,000 L design life). Although the initial flow rates ranged from 200–293 mL/minute, the rate fell to 129–143 mL/minute by 25% of life (3,750 L), and to 100–130 mL/minute by 100% of life (18,000 L). Thereafter, flow rates diminished to 60–110 L/minute. Over the 18,000 L design life, the mean flow rates ranged from 132 mL/minute to 159 mL/minute, with an overall mean of 146 mL/minute (8.8 L/hour). The average required interval for cleaning to restore flow rate was 11 hours of operation for the filter cartridge and 30 hours for the prefilter.

Filter life. In accordance with the terms of the study protocol, the device was tested through 20,000 L, representing 111% of its design life. Although flow rates showed some evidence of diminishing over filter life, all three units continued to produce at least 100 mL/min through the 18,000 L design life. There was no evidence of impaired microbiologic performance through 20,000 L of operation.

DISCUSSION

Results from this assessment indicate that the treatment unit is effective under controlled circumstances in removing a range of microbial indicators of fecal contamination for up to 20,000 L, or roughly 110% of its design capacity. The average log$_{10}$ reductions exceeded 6 logs (99.9999%) of the test organism for bacteria, 4 (99.9%) of the test organism for virus, and 3 logs (99.9%) of the test organism for protozoan cysts.
These LRVs would meet the requirements for a microbial water purifier prescribed by the EPA Protocol.

The treatment unit continued to produce 100–130 mL of water/minute through 18,000 L, despite increasing the turbidity of the aging water to 15 NTU (15 times the minimum level prescribed by the EPA Protocol) and increasing the total organic carbon level to 5.0 mg/L (50 times the minimum). This is less than the 150 mL/minute design rate, but significantly greater than the flow rate from ceramic filters, which are also used in low-income settings. Cleaning was required, but at frequencies that probably would not exceed once per week under real world conditions.

In accordance with the study protocol, testing of the units was terminated after 20,000 L, representing 111% of design life. At this point, there was no evidence of any failure or diminution of microbiologic performance or flow rate. As the device relies solely on mechanical filtration to remove microbial pathogens from the water, its microbiologic performance should not be impaired by continued use past such levels unless there is a fracture or other failure in the seal that holds the hollow fibers in place. Further testing in the field will help determine the actual longevity of the device and the need for a halogen to control biofilm, which may build up on the hollow fibers over long-term use.

This device is one of the few point-of-use water treatment options designed for routine use in low-income populations that meets the 6–4–3 standard for microbiologic water purifiers. Hybrid filters that combine filtration/adsorption with disinfection have been shown to meet the 6–4–3 standard, but these are not fully serviceable in the field and require replacement of consumable components. Sachets combining a floculant and a disinfectant also have been shown to meet the 6–4–3 standard, but requires batch treatment of a consumable product. Other common point-of-use water treatment products meet this international standard for bacteria, viruses, or cysts, but not all three.

Our results must be interpreted in the context of certain limitations. First, this assessment was undertaken under controlled laboratory conditions, not in the field and not as the unit may actually be used by householders. Second, this evaluation was undertaken using a single aging and challenge water. Although these waters were specifically designed to reflect the key parameters that would challenge filtration devices (and actually exceeded the EPA guidelines for turbidity and TOC), the performance and life of water treatment units can be affected by various chemical and physical conditions that may not be encompassed by these tests. Finally, the 20,000 L evaluation reported here was conducted over just 10 months, less than a quarter of the time a householder might actually be expected to use the device in the field. It is possible that use of the device over longer periods in the tropics could accelerate the growth of biofilm on the hollow fiber membranes and thus impair flow rate or cause premature choking. The manufacturer reports that it has developed a slow-eluting chlorine donor that can be permanently deployed in the unit under the prefilter if field testing shows evidence of adverse impacts because of biofilm. However, this chlorine donor was not incorporated into the units we tested.

We note that as the treatment unit has no residual disinfection, the treated water is immediately susceptible to recontamination, a particular problem in the low-income settings for which it was designed. Although the manufacturer has designed an alternative configuration that includes a collapsible or rigid container to improve the safe storage of treated water, this will add to the cost. Field testing is underway to investigate the extent to which such recontamination actually occurs when the devices are used by a target population.

Notwithstanding these limitations, this study does establish the basis for further testing in the field. Such testing is necessary to confirm the durability of the system and to identify any potential gaps in performance under actual field conditions.

---

**Table 2**

<table>
<thead>
<tr>
<th>Test point</th>
<th>Percentage of design life of unit</th>
<th>0%</th>
<th>25%</th>
<th>45%</th>
<th>50%</th>
<th>60%</th>
<th>80%</th>
<th>100%</th>
<th>110%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Volume passed (L)</td>
<td>10</td>
<td>3,750</td>
<td>7,500</td>
<td>9,000</td>
<td>11,250</td>
<td>15,000</td>
<td>18,000</td>
<td>20,000</td>
</tr>
<tr>
<td><strong>Unit 1</strong></td>
<td><em>Escherichia coli</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 7.1*</td>
<td>&gt; 8.3</td>
<td>&gt; 6.9</td>
<td>&gt; 6.9</td>
<td>4.8</td>
<td>&gt; 7.5</td>
<td>&gt; 7.3</td>
<td>&gt; 7.6</td>
</tr>
<tr>
<td></td>
<td>MS2</td>
<td>3.8</td>
<td>5.7</td>
<td>4.2</td>
<td>3.8</td>
<td>3.6</td>
<td>4.7</td>
<td>&gt; 6.0</td>
<td>&gt; 6.8</td>
</tr>
<tr>
<td></td>
<td><em>Cryptosporidium</em> oocysts</td>
<td>&gt; 3.1</td>
<td>3.8</td>
<td>3.4</td>
<td>3.7</td>
<td>3.9</td>
<td>&gt; 3.7</td>
<td>&gt; 3.8</td>
<td>&gt; 3.8</td>
</tr>
<tr>
<td><strong>Unit 2</strong></td>
<td><em>E. coli</em></td>
<td>6.6</td>
<td>6.3</td>
<td>&gt; 6.9</td>
<td>5.8</td>
<td>6.1</td>
<td>&gt; 7.5</td>
<td>&gt; 7.3</td>
<td>&gt; 7.6</td>
</tr>
<tr>
<td></td>
<td>MS2</td>
<td>3.6</td>
<td>3.8</td>
<td>3.5</td>
<td>4.4</td>
<td>4.8</td>
<td>4.7</td>
<td>&gt; 6.0</td>
<td>&gt; 6.8</td>
</tr>
<tr>
<td></td>
<td><em>Cryptosporidium</em> oocysts</td>
<td>&gt; 3.1</td>
<td>&gt; 3.6</td>
<td>3.4</td>
<td>3.4</td>
<td>3.5</td>
<td>&gt; 3.7</td>
<td>&gt; 3.8</td>
<td>&gt; 3.8</td>
</tr>
<tr>
<td><strong>Unit 3</strong></td>
<td><em>E. coli</em></td>
<td>&gt; 7.1</td>
<td>6.8</td>
<td>&gt; 6.9</td>
<td>5.4</td>
<td>7.0</td>
<td>&gt; 7.5</td>
<td>&gt; 7.3</td>
<td>&gt; 7.6</td>
</tr>
<tr>
<td></td>
<td>MS2</td>
<td>3.6</td>
<td>3.7</td>
<td>3.6</td>
<td>4.4</td>
<td>4.3</td>
<td>5.0</td>
<td>&gt; 6.0</td>
<td>&gt; 6.8</td>
</tr>
<tr>
<td></td>
<td><em>Cryptosporidium</em> oocysts</td>
<td>&gt; 3.1</td>
<td>&gt; 3.6</td>
<td>3.6</td>
<td>3.2</td>
<td>3.9</td>
<td>&gt; 3.7</td>
<td>&gt; 3.8</td>
<td>&gt; 3.8</td>
</tr>
</tbody>
</table>

*Log_{10} reduction. Figures in italics are individual sampling points where the LRV was below the 6–4–3 average for bacteria, viruses, and cysts, respectively, under the EPA Guide Standard.

---

**Figure 2.** Flow rate (mL/minute) of tested units over 20,000 L.
It is also important to assess the performance and life of the treatment unit under a wider variety of water conditions and when subjected to less than optimal maintenance.

The ultimate objective of water treatment units such as this, however, is not only to improve water quality but to improve human health. The increasing body of evidence suggesting the potential for household water treatment to dramatically reduce diarrheal morbidity provides good reason to believe that the device can also prevent disease. If this turns out to be the case, then a company that has demonstrated success in the widespread distribution of environmental health products to low-income populations should be encouraged to scale up the intervention on an affordable and sustainable basis.

REFERENCES


