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Field efficacy evaluation and post-treatment contamination risk assessment of an ultraviolet disinfection and safe storage system

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ABSTRACT

Inconsistent use of household water treatment and safe storage (HWTS) systems reduces their potential health benefits. Ultraviolet (UV) disinfection is more convenient than some existing HWTS systems, but it does not provide post-treatment residual disinfectant, which could leave drinking water vulnerable to recontamination. In this paper, using as-treated analyses, we report on the field efficacy of a UV disinfection system at improving household drinking water quality in rural Mexico. We further assess the risk of post-treatment contamination from the UV system, and develop a process-based model to better understand household risk factors for recontamination. This study was part of a larger cluster-randomized stepped wedge trial, and the results complement previously published population-level results of the intervention on diarrheal prevalence and water quality. Based on the presence of *Escherichia coli* (proportion of households with ≥1 *E. coli*/100 mL), we estimated a risk difference of −28.0% (95% confidence interval (CI): −33.9%, −22.1%) when comparing intervention to control households; −38.6% (CI: −48.9%, −28.2%) when comparing post- and pre-intervention results; and −37.1% (CI: −45.2%, −28.9%) when comparing UV disinfected water to alternatives within the household. We found substantial increases in post-treatment *E. coli* contamination when comparing samples from the UV system effluent (5.0%) to samples taken from the storage container (21.1%) and drinking glasses (26.0%). We found that improved household infrastructure, additional extractions from the storage container, additional time from when the storage container was filled, and increased experience of the UV system operator were associated with reductions in post-treatment contamination. Our results suggest that the UV system is efficacious at improving household water quality when used as intended. Promoting safe storage habits is essential for an effective UV system dissemination. The drinking glass appears to represent a small but significant source of recontamination that is likely to impact all HWTS systems.

1. Introduction

Household water treatment and safe storage (HWTS) is an important option for people whose drinking water sources do not meet microbiological water quality guidelines (Mintz et al., 1995; Rosa and Clasen, 2010). Several studies have found that HWTS can reduce self-reported diarrhea outcomes (Arnold and Colford Jr, 2007; Clasen et al., 2009; Fewtrell et al., 2005; Sobsey, 2002). However, it remains a major challenge for HWTS programs to achieve higher rates of adoption and consistent use (Brown and Clasen, 2012; Clasen, 2008; WHO and UNICEF, 2012a). Consistent use of existing HWTS systems has been limited by the perceived negative taste of chlorine; the dependence on the constant acquisition of chlorine and coagulation products; and the relatively long wait times for treatment via solar disinfection, boiling, and certain filtration systems (Sobsey et al., 2008). From the user's perspective, ultraviolet (UV) disinfection, where technologically feasible, may be

Abbreviations: CI, Confidence interval; EC, *E. coli* (*Escherichia coli*); HH, Household; HWTS, Household water treatment and safe storage; MPN, Most probable number; MXN, Mexican Peso; N, Number of units in sample; OR, Odds ratio; USD, United States Dollar; UV, Ultraviolet.

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an attractive option because it is a fast process that does not require consumables and does not negatively impact the aesthetic characteristics of water.

Although UV disinfection is an established technology and has been effective both for centralized and point-of-use systems (Abbaszadegan et al., 1997; Colford et al., 2009; EPA, 2006; Hijnen et al., 2006), there have been only a few evaluations of its effectiveness in developing country households (Brownell et al., 2008; Gruber et al., 2014a, 2013; Reygadas et al., 2007). Water quality can degrade during household storage (Kumpel and Nelson, 2013; Levy et al., 2008; Wright et al., 2004), and thus assessing the risk and potential determinants of post-treatment contamination is particularly important for UV systems because they do not produce a residual disinfectant.

We conducted a cluster-randomized trial to evaluate an HWTS program based on a UV disinfection and safe storage system. The research objectives were to: (i) measure the field efficacy of the system in improving water quality (*Escherichia coli* levels), (ii) assess the risk of post-treatment contamination, and (iii) develop a process-based model to better understand household risk factors that drive recontamination. As part of this trial, we also measured the health and water quality impacts and the levels of adoption and consistent use achieved by the program. We have elsewhere reported the population level impacts on drinking water quality and diarrheal prevalence (Gruber et al., 2013, 2014a), and the results on adoption and consistent use (Reygadas, 2014).

2. Background

2.1. Study site

We conducted our field trial in 24 rural communities in Baja California Sur, Mexico. Participating communities ranged from 8 to 31 households, and had limited access to urban centers and basic services. Only 14% of households were connected to the electricity grid, and 81% had solar panels. The main economic activities were livestock ranching, small-scale farming, and fishing. Most households relied on springs and shallow wells for their drinking water; 20% of the study population regularly bought *garrafon*-bottled water (reusable 20-L narrow-necked containers, filled with treated water) from urban vendors. Locally-sourced water was commonly stored in wide-mouth containers (e.g., 200 L barrels, buckets, plastic water coolers, and *tinajas* – traditional clay or rock containers) (Gruber et al., 2013). Except for *garrafones*, and to some extent water coolers, water was typically extracted by dipping a cup into the storage container.

2.2. Description of the intervention

The Mesita Azul ("little blue table" in Spanish) safe water program was developed through a collaboration between the University of California, Berkeley and Fundación Cántaro Azul, a non-profit organization based in Mexico (Reygadas et al., 2009). The program consisted of an ultraviolet disinfection system (Mesita Azul), a 20-L narrow-necked container (*garrafon*) for storing treated water, and outreach activities intended to increase access to and consumption of safe water in rural households.

The Mesita Azul was designed as an easy-to-use and attractive water treatment system for low-income settings (Fig. 1). It uses a low-pressure UV lamp (254 nm) to inactivate bacteria, viruses, and protozoa, without affecting the physicochemical characteristics of water (including temperature and taste). The system operates at flow rates of up to 5 L/min, allowing households to treat their daily drinking water in less than five minutes. While in operation, the system consumes 20 W of electricity, equivalent to a small compact fluorescent lamp. For Mexico, the Mesita Azul program was coupled with a *garrafon* because it is ubiquitous and is widely perceived as a safe drinking water storage container.

The Mesita Azul was developed based on the UV Tube design principles (Brownell et al., 2008). Under standard conditions it delivers a germicidal fluence of 1224 ± 66 J/m^2 (95% confidence interval), determined from biological assays using MS2 coliphage, and following Section 6.3 of the NSF/ANSI Standard 55 as a microbiological performance test model (NSF, 2002). This dose meets the WHO's "highly protective" microbial performance target for household water treatment (WHO, 2011a) and exceeds by three times most other UV disinfection standards (DVGW, 2006; NSF, 2002; ÖNORM, 2001). The high design dose allows the system to maintain its germicidal effectiveness throughout the lamp's lifetime and for water with absorbance up to 0.1 cm^{-1}.

The Mesita Azul program, implemented by Cántaro Azul, included a needs assessment, a community presentation on safe water, enrollment of program participants, household installation of UV systems, training of household members to operate and provide basic maintenance on the UV system, training of several technicians in each community to carry out system repairs, and a follow-up visit to support technicians and households that reported any problems using the system. During the needs assessment, Cántaro Azul staff tested the water in each community for absorbance (at 254 nm), arsenic, nitrates, and total dissolved solids. The program was rolled out in communities whose drinking water was at risk of microbiological contamination and met the system's operation guidelines (absorbance at 254 nm < 0.1 cm^{-1}; most low turbidity sources meet this criterion, except when iron or manganese are present), but did not contain other tested contaminants that could not be addressed by UV treatment. To enroll in the program, households had to make a one-time payment of USD$20 (MXN$250) or commit to paying $24 (MXN$300) in installments over a six-month period. The cost of the UV system for this initial production round was approximately USD$80 (MXN$1,000).

3. Materials and methods

3.1. Study design

Our research team conducted a cluster-randomized stepped wedge trial to evaluate the Mesita Azul as it was rolled out to 444 households in the study communities (Gruber et al., 2013). The trial lasted 18 months. Cántaro Azul agreed to randomize the sequence of program rollout at the community level; this balanced covariates between control and intervention periods (Brown and Lilford, 2006; Hussey and Hughes, 2007) and created two comparable groups (Gruber et al., 2013). All communities started in the control group, and at each "step" households in four new communities crossed-over to the intervention group (Fig. 2). Cántaro Azul staff carried out key program activities (community meetings and UV system installations) during the step in which clusters crossed-over to the intervention group. Our evaluation team visited all communities to measure outcomes at baseline and during each subsequent step. By the end of step six, Cántaro Azul had rolled out the program to all 24 communities and the evaluation team had visited each cluster at least seven times.

We registered this study at ClinicalTrials.gov (NCT01637389); the Office for the Protection of Human Subjects at the University of California, Berkeley approved all research protocols (CPHS 2009-1-47); and all participating households provided informed consent.

3.2. General data and sample collection procedures

In each survey visit, we collected data on the demographics,