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Risk reduction assessment of waterborne *Salmonella* and *Vibrio* by a chlorine contact disinfectant point-of-use device

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ABSTRACT

Unsafe drinking water continues to burden developing countries despite improvements in clean water delivery and sanitation, in response to Millennium Development Goal 7. *Salmonella* serotype Typhi and *Vibrio cholerae* bacteria can contaminate drinking water, causing waterborne typhoid fever and cholera, respectively. Household water treatment (HWT) systems are widely promoted to consumers in developing countries but it is difficult to establish their benefits to the population for specific disease reduction. This research uses a laboratory assessment of halogenated chlorine beads treating contaminated water to inform a quantitative microbial risk assessment (QMRA) of *S.* Typhi and *V. cholerae* disease in a developing country community of 1000 people. Laboratory challenges using seeded well water resulted in $\log_{10}$ reductions of 5.44 (±0.98 standard error (SE)) and 6.07 (±0.09 SE) for *Salmonella* serotype Typhimurium and *V. cholerae*, respectively. In well water with 10% sewage and seeded bacteria, the $\log_{10}$ reductions were 6.06 (±0.62 SE) and 7.78 (±0.11 SE) for *S.* Typhimurium and *V. cholerae*, respectively. When one infected individual was contributing to the water contamination through fecal material leaking into the water source, the risk of disease associated with drinking untreated water was high according to a Monte Carlo analysis: a median of 0.20 (interquartile range [IQR] 0.017–0.54) for typhoid fever and a median of 0.11 (IQR 0.039–0.20) for cholera. If water was treated, risk greatly decreased, to a median of 4.1×10^{-7} (IQR 1.6×10^{-8} to 1.1×10^{-5}) for typhoid fever and a median of 3.5×10^{-9} (IQR 8.0×10^{-10} to 1.3×10^{-8}) for cholera. Insights on risk management policies and strategies for public health workers were gained using a simple QMRA scenario informed by laboratory assessment of HWT.

Introduction

The combination of inadequate sanitation, poor hygiene, and unsafe drinking water is responsible for an estimated annual burden of 2 million diarrheal deaths (Boschi-Pinto et al., 2008). The Millennium Development Goal 7, Target 7.C was to "halve, by 2015, the proportion of the population without sustainable access to safe drinking water and basic sanitation" (United Nations, 2010). While the goal has been met for access to improved sources of drinking water, the most recent estimates report there remain 780 million people worldwide without access to improved water sources and 2.5 billion people without access to improved sanitation (World Health Organization, 2012). In addition, improved water sources are not necessarily safe water sources (World Health Organization, 2012). Water, poor sanitation and hygiene are associated with 1.6 million deaths in low-income countries ($825/person/year or less; World Health Organization, 2009).

Lower quality source waters, such as surface water or shallow wells, are often used for drinking water and can harbor a number of contaminants and pathogens. Two important examples are *Salmonella* serovar Typhi and *Vibrio cholerae*, which cause typhoid fever and cholera, respectively. The global burden of typhoid fever has been approximated at 10–100 cases per 100,000 people per year in Asia, Africa, and Latin America, while south-central Asia and south-east Asia experience greater than 100 cases per 100,000 people per year (Crump et al., 2004). Over 200,000 deaths were caused by typhoid fever in 2000 (Crump et al., 2004). For cholera, the WHO estimates that there are 3–5 million cholera cases resulting in 100,000 deaths annually worldwide (World Health Organization, 2011a). African countries accounted for nearly all reported cholera cases from 2000 to 2009, and reported 217,333 cases in 2009 alone (World Health Organization, 2010). In regions affected by cholera and typhoid fever without the financial or technical capabilities for widespread water treatment, household water treatment (HWT) could be used to inactivate or remove these bacterial pathogens.

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Household water treatment (HWT) empowers the individual to control the quality of their drinking water and is effective in reducing diarrheal illness when used correctly (Wright et al., 2004; Clasen and Bastable, 2003; Mintz et al., 1995). Studies on HWT have reported a greater than 4 $\log_{10}$ reduction in 30 min for *V. cholerae* with an electrochemical oxidant (brine and free chlorine; Venczel et al., 2004), a greater than 6 $\log_{10}$ reduction using a combination of activated carbon and ultraviolet light for *V. cholerae* and *Salmonella serotype Typhi* (Abbaszadegan et al., 1997), and a greater than 7 $\log_{10}$ reduction using Pur® water purifier for *V. cholerae* and *S.* Typhi (Souter et al., 2003). The latter two approaches meet the target of 99.999% reduction of bacteria recommended by the United States EPA (USEPA, 1987). However, these systems required a high level of technical ability and resource replenishment. Costs and availability of the materials, water volume produced, and treatment time all influence sustainability of HWT (Sobsey et al., 2008). A comparison of filtration technologies (biosand filter (BSF), bucket filter (BF), ceramic candle filter (CCF), and silver-impregnated porous pot (SIPP) filter) also reported on reductions of *V. cholerae* and *S.* Typhi (Mwabi et al., 2011). Spiked water samples (sterile DI) resulted in approximately 2 $\log_{10}$ reductions by the BSF, BF, and CCF for both microbes, while the SIPP filter produced 5 and 3 $\log_{10}$ reductions on *V. cholerae* and *S.* Typhi, respectively (Mwabi et al., 2011). However, when using natural surface water less than 1 $\log_{10}$ reduction for all filters for both groups of pathogens was observed, except for the SIPP filter in regards to *S.* Typhi which was reduced by 2.89 $\log_{10}$. While ceramic and biosand filters may have an advantage in sustainability over other technologies due to improved appearance of water and lower recurring costs, they still require proper maintenance (e.g., cleaning the filter), replacement of broken parts (Sobsey et al., 2008), and there is no disinfection capacity. A device that is simple to operate, requires no electricity, and can provide chemical disinfection without having the user to purchase, measure, and mix chemicals to produce safe water over weeks or months, depending on the quality of water, is a likely candidate for sustainable HWT.

The HaloPure® halogenated N-halamine bead technology provides contact disinfection using chlorine or bromine (Chen et al., 2003, 2004). The halogenated beads are the active component of the AquaSure™ water purifier, a gravity fed system in which water is poured into an upper tank, passes through a cartridge containing HaloPure® media. The treated water is collected in a lower storage tank from which the water is dispensed though a spigot. Disinfectant is released from the beads as water flows through the canister, at a rate dependent on halogen demand, such that microorganisms are inactivated but only a small amount of halogen residual remains in the treated water. The precise mechanism of halogen release in response to demand in the HaloPure® beads is unclear; however, water with more particulates and organic matter, including microorganisms, would have a higher halogen demand and would consequently receive a higher dose of halogen. The HaloPure® technology has been previously tested using both chlorinated and brominated beads challenged with viruses and microcystin toxin (Coulliette et al., 2010). The chlorine and bromine beads achieved 2.98 ± 0.26 and 5.02 ± 0.19 mean $\log_{10}$ reduction ($\pm$ SE) against MS2 bacteriophage and a 27.5% and 88.5% reduction of microcystin toxin, respectively (Coulliette et al., 2010). In addition, the halogenated bead technology was equally or more effective than other chlorine disinfectant HWT technologies (sodium dichloroisocyanurate [NaDCC] tablets and flocculant-disinfectant powder) in inactivating six naturally occurring microbial indicators (total coliforms, heterotrophic bacteria, *Escherichia coli*, *Enterococcus*, *Clostridium*, and coliphage) in studies on sewage-contaminated water with removals of a low of 0.9 $\log_{10}$ for coliphage to a high of >6.6 $\log_{10}$ for fecal indicator bacteria (McLennan et al., 2009).

Although it is relatively straight forward to determine the effectiveness of a HWT device in the laboratory, evaluating its effectiveness against diarrheal illness in actual communities is laborious and expensive. The World Health Organization (WHO) Guidelines for Drinking Water Quality (World Health Organization, 2011b) includes Quantitative Microbial Risk Assessment (QMRA) as a viable approach to determine disease burden for developing regions, accepting that it may not be feasible to regularly monitor disease burden. The QMRA paradigm requires two key computational steps to characterize population risks from a pathogen. First, the exposure route and concentration of the pathogen are evaluated and used to estimate the average dose ingested by the population. Second, a pathogen specific mathematical dose–response relationship is used for assessment of the probability of infection or illness posed to the exposed population (Haas et al., 1999; Center for Advancing Microbial Risk Assessment, 2011).

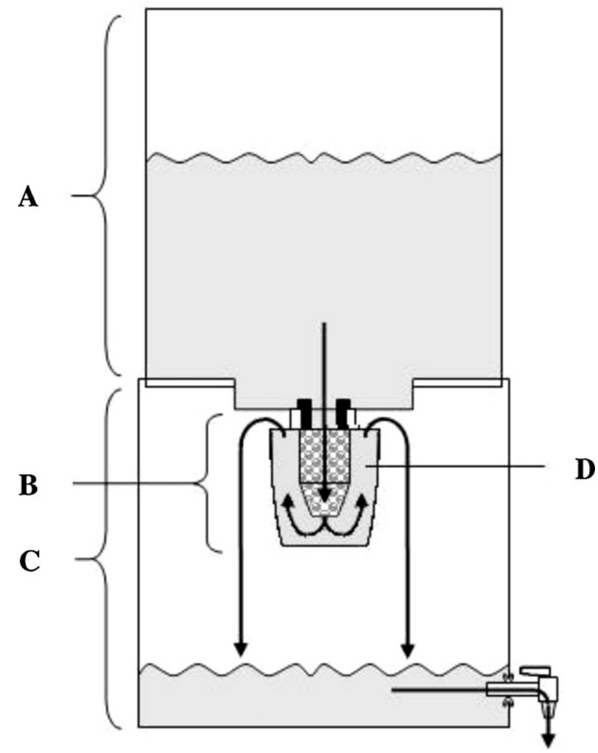

Fig. 1. A schematic of the AquaSure system used for this study. The arrows represent the flow of water in the system and the sections are designated as the upper reservoir (A), HaloPure canister (B) within the lower reservoir (C), and halogenated beads (D).

The goals of this study were to (1) evaluate the chlorinated HaloPure® beads for the reduction of bacterial pathogens with concurrent sewage contamination and (2) use a QMRA scenario to estimate risk reduction of waterborne typhoid fever and cholera within a hypothetical community of 1000 people treating their water with the chlorinated HaloPure® beads. Laboratory assessments of the inactivation of *Salmonella* serovar Typhimurium (proxy for *S.* Typhi) and *V. cholerae* by a modified AquaSure™ device in sewage impacted water were combined with published information in an exposure scenario to examine the risk reduction attributable to the HaloPure® beads.

Materials and methods

Evaluation of the HaloPure® beads

The functionality of the chlorinated HaloPure® canisters (HaloSource, Bothell, WA, USA) housed in AquaSure™ Purifier Units (Forbes Aquatech Ltd., Bangalore, India; Fig. 1), is described in detail in Coulliette et al. (2010) and the bead chemistry is described