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Household Water Treatment and Safe Storage to Prevent Diarrheal Disease in Developing Countries

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Abstract Household water treatment and safe storage (HWTS), such as boiling, filtering, or chlorinating water at home, have been shown to be effective in improving the microbiological quality of drinking water. However, estimates of their protective effect against diarrhea, a major killer, have varied widely. While results may be exaggerated because of reporting bias, this heterogeneity is consistent with other environmental interventions that are implemented with varying levels of coverage and uptake in settings where the source of exposure represents one of many transmission pathways. Evidence suggests that the effectiveness of HWTS can be optimized by ensuring that the method is microbiologically effective; (2) making it accessible to an exposed population; and (3) securing their consistent and long-term use.

Keywords Water treatment · Water storage · Point-of-use · Household · Drinking water · Diarrhea

Introduction

An estimated 748 million people lack access to improved water supplies [1]. Up to 1.1 billion more rely on sources that qualify as improved under international monitoring criteria (protected wells and springs, public taps, household connections, rainwater harvesting) but are nevertheless contaminated [2].

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Unsafe drinking water is estimated to cause 502,000 deaths from diarrhea annually, mainly among young children [3]. Diarrheal disease also contributes to decreased food intake and nutrient absorption, leading to malnutrition, reduced resistance to infection, and impaired physical growth and cognitive development [4]. Repeated exposure to fecal pathogens is also associated with subclinical infections, leading to environmental enteropathy [5]. Unsafe drinking water also contributes to more than 25 million cases and 250,000 deaths annually from enteric fevers (typhoid and paratyphoid) [6], as well as too much of the disease burden from cholera, poliomyelitis, and hepatitis A and E in the world.

Providing safe, reliable, piped-in water to every household is an essential goal, yielding optimal health gains while contributing to the international targets for poverty reduction, nutrition, childhood survival, school attendance, gender equity, and environmental sustainability. While being committed strongly to this goal, and to incremental improvements in water supplies wherever possible, the World Health Organization (WHO), the United Nations Children's Fund (UNICEF), and others have called for targeted, interim approaches that will accelerate the heath gains associated with safe drinking water for those whose water supplies are unsafe [7].

One such alternative is household water treatment and safe storage (HWTS) using methods such as boiling, filtration, or chemical disinfection. In many settings, both rural and urban, populations have access to sufficient quantities of water, but that water is unsafe for consumption as a result of microbial or chemical contamination. Depending on the method, treatment at the household level can remove, kill, or inactivate most microbial pathogens [8]. Moreover, by focusing on the point of use rather than the point of delivery, HWTS can minimize the risk of recontamination that even improved water supplies can present [9].

Although HWTS is not new, its promotion as a focused public health intervention strategy has grown significantly over the past two decades [10]. This was due in part to a proliferation of randomized, controlled trials summarized in systematic reviews, which showed a consistent, albeit highly heterogeneous, protective effect against diarrhea [11–14, 15•]. Despite concerns about exaggerated estimates of effect, due to reporting bias and to limited duration and external validity of research-driven efficacy trials [12–14, 15•, 16, 17], the United Nations (UN) and other organizations have endorsed the intervention and continue to promote its implementation [18, 19].

This paper summarizes the evidence on the effectiveness of HWTS interventions to prevent diarrheal diseases. It also describes research that has evaluated the circumstances and conditions of use under which the impact of HWTS may be optimized.

Estimating Effectiveness

Several systematic reviews have assessed evidence on the effectiveness of HWTS in preventing diarrheal diseases (Table 1). In 2005, a systematic review [11] first identified the protective effect of HWTS interventions against diarrhea and their apparent advantage over interventions at the source or at other points of distribution, such as community wells and tap stands. A subsequent Cochrane review of water quality interventions also found HWTS to be protective against diarrhea but noted that the effect was mostly observed in open-design trials, while blinded trials consistently reported no effect on diarrhea [12]. It also found considerable heterogeneity in the results, only some of which could be explained by subgrouping on the basis of intervention type, compliance, and ambient conditions associated with exposure. A subsequent review also reported similar results [14]. While more than a dozen additional trials of HWTS interventions have been conducted since those initial reviews, three new blinded trials conducted in low-income settings all reported no protective effect against diarrhea [22–24•].

In view of this uncertainty about the contribution of water quality interventions to prevent diarrhea, the Institute for Health Metrics and Evaluation (IHME) commissioned its own systematic review of water, sanitation, and hygiene interventions as part of the 2012 Global Burden of Disease study. On the basis of the blinded trials of HWTS interventions, the review concluded that there was no additional benefit from improved water quality over improvements in water supply [25]. This led to another systematic review, led by the WHO, which included HWTS interventions [15•]. Rather than dismissing the open trials, Wolf and colleagues elected to discount the pooled estimates of all HWTS interventions by about 30 % on the basis of studies suggesting that this was the exaggerated effect from open trial designs of non-objective outcomes [26]. The review then concluded that filters were protective against diarrhea for those relying on unimproved water supplies, even after such adjustment for non-blinding. The pooled estimate of effect was a reduction in risk of 33 % (95 % confidence interval [CI] 8–53 %) or 45 % when combined with safe storage (95 % CI 19–62 %). Other estimates for chlorine, solar disinfection, and combined disinfection–flocculation were not effective after adjustment for non-blinding.

A large-scale trial is underway in Bangladesh and Kenya, which includes objective outcomes and may shed additional light on the effectiveness of HWTS [27•]. In the end, however, the effectiveness of HWTS to prevent diarrhea is likely to depend largely on the prevailing conditions—a conclusion that is consistent with the heterogeneity observed in pooled estimates [12]. A single, generalizable estimate of effect is unlikely to emerge, given important differences in pathogens circulating in the population, transmission dynamics, seasons,

Table 1 Summary of systematic reviews reporting risk ratios of water quality interventions to prevent diarrheal diseases

Intervention (improvement)	Risk ratio (95 % confidence interval) [no. of studies]			
	Fewtrell et al., 2005[11]	Clasen et al., 2006[12]	Waddington et al., 2009[14]	Wolf et al., 2014[15•][1]
Source (point of distribution)	0.89 (0.42–1.90) [3]	0.73 (0.53–1.01) [6]	0.79 (0.62—1.02) [3]	0.89 (0.78–1.01)
Household (point of use)	0.65 (0.48–0.88) [12]	0.53 (0.39–0.73) [20]	0.56 (0.45—0.65) [21•]	
Chlorination		0.63 (0.52–0.75) [16]		0.63 (0.55–0.72) *0.84 (0.61–1.16)*
Filtration		0.37 (0.28–0.49) [6]		0.41 (0.33–0.50) *0.55 (0.38–0.81)*
Solar disinfection		0.69 (0.63–0.74) [2]		0.63 (0.55–0.72) *0.84 (0.61–1.16)*
Flocculation disinfection		0.69 (0.58–0.82) [6]		

[1] Pooled estimates of effect in settings with unimproved water supply, prior to adjustment for non-blinding. For household interventions, estimates are for studies that combine treatment with safe storage. Figures in *italics* are estimates after adjustment for non-blinding

compliance, and other factors [21•]. At the same time, research suggests that the impact of the intervention can be optimized when the intervention (1) is microbiologically effective; (2) is made accessible to a population at risk; and (3) is used correctly, consistently, and over the long term.

Microbiological Performance

In 2002, the WHO commissioned a report to assess the most promising HWTS candidates on the basis of selected technical characteristics and performance criteria, including effectiveness in improving and maintaining microbial water quality, health impact, technical difficulty or simplicity, accessibility, cost, acceptability, sustainability, and potential for dissemination [8]. After evaluating at least 37 different technologies for improving water quality at the point of use, the report concluded that five were the most promising: filtration with ceramic filters; chlorination with storage in an improved vessel; solar disinfection in clear bottles; thermal disinfection (pasteurization) in solar cookers or reflectors; and combination systems employing chemical flocculation and chlorination.

In the ensuing years, scores of studies have assessed the microbiological performance of variants of these and emerging technologies in the laboratory, often using different techniques. In an effort to standardize methods and establish performance criteria for HWTS technologies, the WHO has adopted recommendations on evaluating household water treatment options [28]. These recommendations specify three performance levels based on the log reduction values (LRV) that the technology was able to achieve. In order to qualify as "most protective", interventions must demonstrate a 4-log reduction against bacteria, a 5-log reduction against viruses, and a 4-log reduction against protozoan cysts. The corresponding LRV values for "protective" level performance are 2 logs for bacteria, 3 logs for viruses, and 2 logs for cysts. An "interim" designation requires the technology to achieve "protective" targets for two classes of pathogens and be supported by some epidemiological evidence suggesting health gains. The WHO has also established the International Scheme to Evaluate Household Water Treatment Technologies in order to promote and coordinate independent and consistent testing and evaluation of HWT products on the basis of WHO-recommended criteria (http://www.who.int/household_water/scheme/en/).

While the WHO recommendations and testing scheme have been helpful in making laboratory validation more uniform, the establishment of three performance levels may result in continuing uncertainty among policymakers and implementers about the level of microbiological performance necessary to provide protection. A recent large-scale study that identified *Cryptosporidium* as a leading cause of severe to moderate diarrhea among young children in low-income countries has raised questions about the suitability of promoting chlorine-based HWTS solutions even though they meet the "interim" criteria [29•]. Moreover, there is evidence that the benefits from increasing LRVs strongly depend on compliance [30].

Reaching an Exposed Population

Certain subpopulations have been the target of HWTS interventions because they are perceived to be especially at risk. The most obvious target should be populations relying on unsafe water sources. However, current methods for monitoring water safety rely on proxies, such as the service level, rather than actually testing water quality, providing a poor tool for identifying an exposed population [20]. Young children, especially after weaning, account for much of the mortality associated with diarrhea [31]; they are also particularly at risk because of stunting and the serious and irreversible sequelae associated therewith [4]. Nevertheless, evidence suggests that such children regularly drink untreated water, even in households that report treating their water at home [23, 32]. Programs including HWTS have also targeted schools and healthcare facilities [33]. The WHO recommends that HWTS be considered in caring for people living with HIV/AIDS [34], and a recent systematic review suggested that the intervention is effective in such populations, both in preventing diarrhea and in extending the time for progression from HIV infection to disease [35]. HWTS is also widely recommended in outbreaks of waterborne diseases, such as cholera, though there is mixed evidence of its contribution in other emergencies, such as flooding, earthquakes, and conflicts [36, 37].

Part of the challenge is reaching these populations with scalable and sustainable strategies. Commercial approaches have been widely employed, though it is unclear whether these can reach the very base of the economic pyramid both because of cost and because of the need to establish supply chains. Social marketing, which normally involves some subsidy, has had some success [38], and microfinance, which provides credit for higher upfront items such as filters, is being employed in South Asia and Africa [39]. There is ongoing debate about the effectiveness of cost-recovery approaches versus free distribution, but, unlike insecticide-treated bed nets for malaria (which was the subject of the same debate a decade earlier), no government has yet distributed free HWTS products on a large scale outside of emergencies or outbreaks. Nevertheless, UNICEF, non-governmental organizations (NGOs), and others have provided HWTS products such chlorine, biosand, and ceramic filters; bottles for solar water disinfection; and sachets of flocculant/disinfectant. Researchers have investigated other distribution strategies, including chlorine dispensers at water collection points [40], free distribution financed by carbon credits [41], and the use of HWTS products as incentives for participation in voluntary counseling and testing for HIV/AIDS [42].

Securing Consistent and Sustained Use

Research has also shown that the potential impact of HWTS interventions is conditioned on consistent use. Analyses based on quantitative microbial risk assessment (QMRA) suggest that for those relying on water with moderate to high levels of fecal contamination, potential health gains from water quality interventions are reduced sharply even with occasional consumption of untreated drinking water [30, 43•]. A decline in adherence from 100 % to 90 % reduces predicted health gains by up to 96 %, with the largest declines occurring when pretreatment water quality is of higher risk. This is consistent with prior research showing that the overall risk attributable to drinking water is controlled by those periods of higher exposure risk from interruptions in water treatment [44].

Poor compliance may explain the lack of a protective effect of HWTS interventions in several recent studies. In a 12-month blinded trial in the Democratic Republic of Congo, a gravity filter showed no significant impact on diarrhea [23]. While 68 % of intervention households met the study's definition of current users, 73 % of adults and 95 % of children also reported drinking untreated water on the day prior to the enumerator visit. A blinded trial of chlorine tablets also reported no protective effect in a 12-month study, although only a third of household members participating in the trial were confirmed users of chlorine tablets, despite extensive promotional efforts [24•].

In addition to these intervention studies, two assessments of programs by NGOs to introduce HWTS among vulnerable populations demonstrate the challenges of achieving uptake and the corresponding lack of any measurable health impact. Arnold and colleagues [45] assessed the uptake and health impact of a 3-year program by NGOs in Guatemala to promote HWTS (boiling, solar disinfection, and chlorination) and hand washing with soap. The 6-month study used propensity scoring to match and compare 600 households in 30 villages (15 intervention/15 control). They found very low levels of confirmed household water treatment by any method among both intervention and control households for HWTS (9 % versus 3 %, respectively; $p=0.053$) or hand washing. Consistent with the low sustained behavior adoption, the investigators found no difference between intervention and control villages in terms of child diarrhea, respiratory infections, or growth. Mausezahl and colleagues [46] used a cluster-randomized, controlled trial design in 22 rural communities in Bolivia to evaluate the effect of solar disinfection (SODIS) in reducing diarrhea among children under the age of 5 years. A local NGO conducted a standardized interactive SODIS-promotion campaign in 11 villages, targeting households, communities, and primary schools. Mothers completed a daily child health diary for 1 year. Despite this extensive promotion campaign, investigators found only 32 % compliance with the intervention and no strong evidence of a substantive reduction in diarrhea among children [risk ratio (RR)0.81 (95 % CI 0.59–1.12)].

Researchers have increasingly focused on the consistency of effective HWTS use and the factors associated therewith [47]. Field studies by Rosa and colleagues in India, Zambia, and Peru suggest that even among householders that report usually treating their water at home before drinking it, the consistency of the practices is exaggerated and the microbiological effectiveness is suboptimal [32]. Numerous studies have reported on consumer preferences for and satisfaction with various HWTS solutions [48–50]. It is not clear, however, whether these are useful proxies for actual consistent use. The WHO has recently led an effort to develop and validate metrics for monitoring and evaluating HWTS programs, which include measures for assessing correct and consistent use [51].

In addition to initial uptake, HWTS interventions will be effective only if they are sustained. There is evidence that the health impact of some HWTS interventions diminishes over time—an indication of unsustained uptake but also a possible methodological artefact from study subject fatigue [13, 14]. There are also issues concerning the sustainability of common HWTS options themselves, due to affordability and the need to establish and maintain a supply chain of consumables and replacement filters. Researchers have begun to follow promotion strategies and document the factors associated with sustained uptake [47].

Conclusions

The classic F-diagram first depicted more than a half century ago reminds us that fecal–oral diseases, such as diarrhea, are not just waterborne but are transmitted through multiple pathways [52]. More recently, epidemiological modeling has pointed to the interdependency of these pathways and the need to adopt systems-based approaches in order to understand and control enteric pathogens to reduce the burden of diarrheal disease [21•].

In the end, the actual protective effect accorded by HWTS or any water quality intervention against major killers such as diarrheal disease is likely to depend on multiple factors, including the circulating pathogens, other sources of exposure, and population density and susceptibility. While investigators continue to explore these factors, research should continue on measures that optimize the intervention by offering solutions that are microbiologically effective, accessible to targeted populations, and used consistently and sustainably. Under these conditions, HWTS has a role to play in providing vulnerable people with a tool to improve their own water safety while they continue to wait for reliable water supplies—which much of the world has enjoyed for more than a century.

Compliance with Ethics Guidelines

Conflict of Interest Thomas Clasen conducts research for UN organizations, NGOs, governments, and private sector companies on household water treatment products and interventions. The private sector companies include DelAgua Health, Vestergaard-Frandsen, Unilever, and Medentech.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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