Microbiological Effectiveness and Cost of Boiling to Disinfect Drinking Water in Rural Vietnam

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Despite certain shortcomings, boiling is still the most common means of treating water in the home and the benchmark against which alternative household-based disinfection and filtration methods must be measured. We assessed the microbiological effectiveness and cost of boiling among a vulnerable population relying on unimproved water sources and commonly practicing boiling as a means of disinfecting water. In a 12 week study among 50 households from a rural community in Vietnam, boiling was associated with a 97% reduction in geometric mean thermotolerant coliforms (TTCs) ($p <$ 0.001). Despite high levels of faecal contamination in source water, 37% of stored water samples from self-reported boilers met the WHO standard for safe drinking water (0 TTC/100 mL), and 38.3% fell within the low risk category (1–10 TTC/100 mL). Nevertheless, 60.5% of stored drinking water samples were positive for TTC, with 22.2% falling into the medium risk category (11–100 TTC/100 mL). The estimated cost of wood used to boil water was US$ 0.272 per month for wood collectors and US$ 1.68 per month for wood purchasers, representing approximately 0.48% to 1.04%, respectively, of the average monthly income of participating households.

Introduction

Unsafe drinking water, along with poor sanitation and hygiene, are the main contributors to an estimated 4 billion cases of diarrheal disease annually, causing 1.8 million deaths, mostly among children under 5 years of age (*1*). By inhibiting normal consumption of foods and adsorption of nutrients, diarrheal diseases are an important cause of malnutrition, which leads to impaired physical growth (*2*), reduced resistance to infection (*3*), and potentially long-term gastrointestinal disorders (*4*). Contaminated water is an important contributor to other potentially waterborne diseases, including typhoid, hepatitis A and E, and poliomyelitis.

An estimated 1.1 billion people lack access to improved water supplies; many more rely on piped or other improved supplies that are nevertheless microbiologically unsafe (*5*). Evidence has shown that treating water at the household level is effective in improving the microbiological quality of drinking water and in preventing diarrheal disease (*6, 7*). A variety of filtration, disinfection and other methods have emerged for treating water at the point of use (*8*), and the World Health Organization now endorses effective household water treatment as a means of achieving the health gains associated with safe drinking water to those not yet served by reliable piped-in water (*9*).

Boiling or heating with fuel is perhaps the oldest means of disinfecting water at the household level (*8*). It is also the most widely used means of treating water in the home, with perhaps hundreds of millions of practitioners (*10*). If practiced correctly, boiling is also one of the most effective, killing or deactivating all classes of waterborne pathogens, including protozoan cysts that have shown resistance to chemical disinfection and viruses that are too small to be mechanically removed by microfiltration (*11*). Heating water to even 55 °C has been shown to kill or inactivate most pathogenic bacteria, viruses, heminths, and protozoa that are commonly waterborne (*12*). Moreover, while chemical disinfectants and filters can be challenged by excess turbidity and certain dissolved organics, boiling can be used effectively across a wide range of physical and chemical characteristics. In rural Kenya, pasteurization of water using a simple wax indicator to show household members when water reached 70 °C increased the number of households whose drinking water was free of coliforms from 10.7 to 43.1% and significantly reduced the incidence of severe diarrhea compared to a control group (OR 0.55, $p = 0.0016$) (*13*).

Governments, NGOs, and others have promoted the practice, both in developing countries where water is routinely of uncertain microbial quality and in developed countries when conventional water treatment fails or water supplies are interrupted due to disasters or other emergencies. Sources vary in the time recommended for bringing water to a boil for necessary disinfection, from 1 min (*14*) to 10 min (*15*), 20 min (*16*), and even 25 min (*17*). These longer times may have evolved from recommendations for sterilizing medical devices rather than the water itself. The WHO Guidelines for Drinking Water Quality simply recommend bringing water to a rolling boil as an indication that a disinfection temperature has been achieved (*18*).

Despite its long history, however, boiling water presents certain disadvantages that may limit its scalability as a means of routinely treating drinking water. First, boiling is more costly than some other alternatives for treating water in the home (*19*), and in some cases prohibitively expensive (*20*). Second, more than half of the world's population relies chiefly on wood, charcoal and other biomass for their energy supplies (*21*). The procurement of these fuels represents a substantial commitment of time and energy, primarily for women and girls, and may detract from other productive and potentially health-promoting activities (*22*). Third, boiling can be an important cause of other health hazards, including respiratory infections associated with poor indoor air quality (*23*) and burns, especially among young children (*24 ,25*). Fourth, depending on the fuel used, boiling may be environmentally unsustainable and contribute to greenhouse gases. Finally, there is an increasing body of evidence suggesting that as actually practiced in the home, boiling and storing water often does not yield microbiologically safe drinking water. Once the water begins to cool, it is immediately vulnerable to recontamination from hands and utensils since it contains no residual disinfectant and is often stored in open vessels without a tap (*26 ,27*). Recent studies have shown that the stored drinking water in the homes of families who report

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boiling show it often contains high levels of faecal contamination (*28, 29*).

Alternative means of treating water in the home, including chlorination, filtration, solar disinfection, and combined flocculation/disinfection, may not present some of the potential disadvantages associated with boiling. However, before household members are encouraged, as a matter of public policy or commercial marketing, to use such alternatives, it is useful to assess the effectiveness and cost of boiling as it is actually practiced in the home so that it can be compared with such alternatives.

This paper reports on our assessment of boiling practices in rural Vietnam, a country in which boiling is believed to be the most common method for disinfecting drinking water at the household level (*30*). In addition to documenting certain demographic characteristics of self-reported boilers and quantitative information regarding their boiling practices, we assessed the extent to which boiling improves the microbiological quality of their drinking water and the cost and affordability of boiling to allow for comparisons with alternative methods for treating water in the home.

Materials and Methods

Study Setting. The study was conducted over a period of 12 weeks (November 2006 to January 2007) in Boc Bo commune, an agricultural community of approximately 3000 people in 15 small villages. The commune is situated in Pac Nam, a remote and mountainous district of Bac Kan province where the practice of boiling to treat drinking water is common and where householder members rely primarily on unprotected sources (rivers, streams, or open wells) for their water supplies. Houses are mainly constructed of wood, with living quarters above on stilts and animals (cattle, pigs, poultry) below. Water is typically stored below in open vessels. Though a few households have pour-flush toilets, the main type of sanitation facilities in the community is a simple pit latrine. The average annual income per capita is equivalent to 409 kg of rice (around $150 per year).

Sample Size Calculation and Enrolment of Participating Households. Based on previous work in India in which boiling was compared with a water treatment device, we anticipated that 30% of paired (source/treated) samples from participating households would show a difference of at least 10 thermotolerant coliforms (TTC). Assuming a study designed with 80% power to demonstrate this difference at the 95% confidence level yields a sample size of 32 households, which we adjusted to 50 to account for loss to follow up. The number of households recruited in each village was proportional to the size of that village. Participants were first selected from a list of all households using systematic random sampling and were assessed for eligibility. Households were eligible for enrollment in the study if the female head of the household reported that (i) the water that the household uses for drinking is from an untreated surface source (river, pond, irrigation ditch) or unprotected groundwater sources (open well or unprotected spring), and (ii) in that household, they "always" or "almost always" boil their water before drinking it.

Household Surveys and Boiling Demonstrations. During the initial visit, the female head of each participating household provided information to a Vietnamese-speaking investigator who filled in a prepiloted structured survey. Information included household demographics; water collection, treatment, and storage practices; hygiene practices; and sanitation facilities. Once during the 12 week study period, the person at the household normally responsible for boiling water for drinking was asked to provide information on the manner in which such water treatment was actually practiced in the home (definition of boiling, frequency, type of fuel used, amount of water boiled daily, time, method of procuring fuel, etc.). In order to estimate the full economic cost of the practice, the investigator also explored whether and how the persons responsible for boiling the water would otherwise spend the time used in boiling on other activities, and whether there was a economic cost that could reasonably be attached thereto. Finally, during the course of the study, 15 households were selected randomly from the study population to demonstrate the procedures they normally follow to boil their water.

Water Sampling and Analysis. Commencing at the first visit to each participating household and continuing once every 2 weeks for the ensuing 12 weeks, two 125 mL of water samples (one from the raw source water that the householder collected for use in the home and one from the water that the household member identified as stored drinking water) were collected and assayed for thermotolerant coliforms, a WHO-prescribed indicator of faecal contamination (*18*). For the stored drinking water sample, the time the water was treated before the visit also was recorded. The water samples were preserved between 4 and 10 °C and analyzed using the membrane filtration method in accordance with *Standard Methods for the Examination of Water and Wastewater* (*31*). Sample water was passed through a 0.45 μm membrane filter (Millipore, Bedford, MA) and incubated on membrane lauryl sulfate media (Oxoid Limited, Basingstoke, Hampshire, UK) at 44 ± 0.5 °C for 18 h in an Oxfam Delagua portable incubator (Robens Institute, University of Surrey, Gilford, Surrey, UK). The number of yellow colonies were counted and recorded as individual thermotolerant coliforms (TTCs) and reported as the number of colony forming units (CFUs) per 100 mL of analyzed sample water.

Cost of Boiling. Costs of boiling consist of a combination of direct and indirect costs. For direct costs, we include only the cost of the fuel consumed, it being assumed for this purpose that the other apparatus required (stove, kettle, etc.) are sunk costs associated with cooking and not wholly attributable to boiling water for drinking. Indirect costs include the monetized value of personal time used to purchase or collect fuel and to boil the water. Costs were assessed at the household level using information obtained from the household surveys and demonstrations and estimates of fuel consumption drawn from established formulas and laboratory experiments. The amount of fuel consumed to boil or heat water can be theoretically determined using the formula for heat energy, $Q = C_p m \Delta T$, where C_p is the specific heat capacity of water (kJ/kg°C), m is the mass of water (kg) and ΔT is the change in temperature of the water (°C). Using this formula, the amount of heat energy required to bring water up to 100 °C can be calculated. Then, using the published calorific value of each fuel, it is possible to calculate the amount of fuel required. The calculations assumed 8% heat transfer efficiency for burning wood in an open fire (*33*). As most costs involve a range of possible values based on various criteria, our cost estimates are designed to reflect this range.

Data Analysis and Ethics. Because bacterial counts tend to follow a skewed distribution, statistical analyses were performed after TTC counts were transformed to their log 10 values to satisfy the assumption of normality. For this purpose only, TTC count values of 0 were assigned a value of 1 so as not to lose the data in the log transformation. Additional information about data analysis and about ethics approvals for the study is provided in the Supporting Information.

Results

Household Demographic and Characteristics. The main household characteristics are summarized in Table 1. The study included 50 households with 263 persons (mean of 5.3 occupants per household). Overall, 10.3% of the study participants were children <5 years of age. Most women

TABLE 1. General Household Characteristics

	n	%
demographic characteristics		
number of households	50	
total population	263	
household size (mean, 95% CI)	5.3 (5.1–5.4)	
household income per capita per month (VND), (mean, 95% CI)	231 185 (187 000–275 170)	
type of house construction		
wooden houses on stilts	23	46
wooden walls, earth floor	8	16
wooden walls, cement floor	16	32
bricked houses	3	6
sanitation and hygiene practices		
sanitation facilities (all private)		
pit latrine	37	74
pour flush toilet	13	26
use soap for washing hands	39	78
soap available at the time of visit	37	74
water handling practices		
water source		
stream/spring/brook	39	78
open hand-dug wells	3	6
covered hand dug wells with electric pump	7	14
borehole	1	2
boiled water storage vessel		
thermo-flask	49	98
plastic jug	38	76
aluminum vessel	19	38
access water by pouring from vessel into cup	50	100

respondents had been to primary (40%) or secondary (32%) school. Houses were typically made of wood, either built on stilts or with earth or cement floors. All houses had sanitation facilities, mostly simple pit latrines (74%). The mean per capita monthly income was 231 185 Vietnamese Dong (VND) (range of 51 750–766 667) or U.S. $11.50 (range 3.20–47.90) at then-current exchange rates. This is significantly lower than average monthly income of 484 400 VND for the country as a whole for 2004 (*29*).

Water Sources, Collection, and Storage. Most households relied on unimproved water sources for drinking including mountain streams, brooks or springs (78%), covered dug wells with electric pumps (14%) or unprotected hand-dug wells (6%). Water was mainly supplied via plastic hose pipes, zinc pipes, or bamboo conduits from open collection systems constructed and shared by a few households (68%); others collected water in buckets. The collected water was then stored in a variety of tanks, barrels, or smaller vessels, most without lids. Water was drawn from the storage containers with plastic dippers (80%) or taps and boiled in covered, 2–3 L aluminum kettles. Boiled water was transferred into a thermoflask (98%), where it was used to make tea or drunk immediately as a hot beverage (96%), which is a common practice during the cold season in which the study was conducted. Water stored in the thermoflask was sometimes transferred to a second container, often a plastic jug (76%) or another aluminum vessel (38%) for later consumption.

Boiling Practices. All households reported boiling their drinking water, a condition for eligibility, and none reported practicing any other means of treating water. Forty-nine of the 50 households (98%) boiled over an indoor, open fire using wood which household members either collected themselves (89.8%) or purchased (10.2%); just one household used electricity. Wood was normally collected by the female head of household (63.4%), her husband (17.1%), or a daughter or son (12.2%). Households were using 22 kg of wood per day on average, and the mean time reported for collecting it was 1.57 h, though collected wood was also used for cooking, animal food preparation, and space heating. Boiling was normally undertaken by the female head of household (86%) or her mother/mother in law (10%). The mean number of times water was boiled daily was 2.6 (range 2–3) and the mean vessel size was 2.9 L, representing a mean of 7.5 L of treated water per day. All informants reported heating water until the surface bubbled. In the 15 demonstrations, however, only four (including the electricity user) stopped heating the water when surface boiling commenced while 11 continued to boil for an average of 3.5 min (range 2–5) thereafter. Among the 14 wood users who demonstrated their boiling practice, only 1 tried to put out the fire to conserve fuel; the others continued to use the fire to boil more water for cooking ($n = 7$), bathing, dish washing ($n = 6$), or space heating ($n = 1$). In response to the survey, the 50 households reported taking an average of 15.8 min (range 10–20) to boil water for drinking. This generally corresponded with the 15 boiling demonstrations in which the mean time to heat the water from an average initial temperature of 20 °C to the surface boiling temperature of 100 °C was 18 min/3L (range 16–20) for firewood boilers and 14 min for the electric boiler. Certain other information regarding boiling practices is presented in Table 2.

Cost and Affordability of Boiling. Because all but one of the 50 study households used firewood to boil their water, the cost estimates were limited to wood users. As it was not possible for households to accurately report how much fuel was used for boiling water versus other uses, we estimated the cost of fuel used exclusively for boiling based on the heat energy formula described in the methods section and added the time postboiling in which the demonstrations showed households continue to heat their drinking water. Full details on the estimates of fuel consumed, time spent, and the opportunity cost of such time are reported elsewhere (*30*). For the roughly 10% of households who purchased their wood, the mean cost of fuel used for boiling water was 26 900 VND (U.S. $1.68) per month, representing 1.04% (range 0.68–2.56%) of the study population mean household monthly income. For wood collectors, the mean cost of their time (valued at the mean study population income level per hour)

TABLE 2. Quantitative Information on Boiling Practices by the Study Households

characteristics	number of households	mean	range	SD
amount of time for collecting firewood per trip (hours)	41	3.024	2–4	0.474
amount of firewood collected per trip (kg)	41	42.80	20–60	13.419
number of times collecting firewood per month	41	15.732	10–20	3.457
amount of firewood purchased per month	5	560	150–800	258.360
cost of wood (VND/kg)	5	474	320–650	142.758
income per month of the employed persons who often boil water (VND/month)	11	1 081 818	(80 000–1 500 000)	222 792.198
number of times per day water is boiled	50	2.56	2–3	0.501
capacity of water boiling vessels (L)	50	2.92	2–3	0.274
time required to heat water to that boiling point (as defined by the boiler) using firewood (minutes)	49	14.551	10–15	1.259
time continue boiling after boiling point is reached (minutes)	34	1.941	1–5	0.885
total time of boiling water - using wood (minutes)	49	15.795	10–20	1.731
time required to wait until the water can be used for its desired purpose (minutes)	50	1.2	0–30	5.938

TABLE 3. Geometric Mean TTC Counts in Samples of Source and Boiled Drinking Water Taken at the Study Households at Each of Five Visits (TTC/100 mL)

	source			drinking	
	N	mean	95% CI	mean	95% CI
round 1	50	164.7	115.2; 235.5	3.9	2.5; 6.2
round 2	49	170.1	111.6; 259.3	6.5	4.2; 10.2
round 3	49	106.1	75.7; 148.7	2.8	2.1; 3.9
round 4	48	140.6	103.2; 191.4	4.4	2.9; 6.9
round 5	49	132.7	95.1; 185.3	4.3	2.8; 6.4

spent on collecting firewood for boiling water at the study households was 4 350 VND/month (U.S. $0.272) per month, representing 0.48% (range 0.11–1.30%) of their monthly incomes. The average indirect cost of time spent on preparing for boiling and heating water of the study households ranged from 24 600 VND to 39 000 VND (U.S. $1.54−2.40) per month using the low and high economic valuations on opportunity cost. This represents another 2.12−3.52% of their mean monthly income, though the range was as high as 14.06%.

Water Quality. Table 3 shows TTC counts for samples from source and treated water by visit. Source water showed consistent evidence of faecal contamination, with an overall geometric mean TTC count of 141 (95% CI: 120.7–164.7) per 100 mL. Stored drinking water showed considerable improvement in microbiological quality, with a geometric mean TTC count of 4.2 (95% CI: 3.5–5.1) per 100 mL. Analysis of paired water samples for each household demonstrated a 1.52 $\log_{10}$ reduction (95% CI: 1.43–1.61) in faecal coliforms after treatment; this is equivalent to a 97% reduction in TTC.

Figure 1 presents percentages of water samples falling under risk categories for faecal contamination: 0 TTC/100 mL (in compliance), 1–10 TTC/100 mL (low risk), 11–100 (medium risk), 101–1000 (high risk), and >1001 (very high risk). Overall, 37% of boiled water samples were free of faecal coliforms and 38.3% fell within the low risk category of 1–10 TTC/100 mL. Only a small proportion (2.5%) were classified as high risk and none had contamination levels above 1000 TTC/100 mL. In contrast, almost none of the source water samples had faecal coliforms below 100 TTC/100 mL (1.2%). Nevertheless, 60.5% of stored drinking water samples were positive for TTC, with 22.2% falling into the medium risk category (11–100 TTC/100 mL). Contamination levels of paired water samples were positively correlated ($r = 0.260$, $p < 0.001$). After adjusting for repeated measures over time, boiled water samples taken from plastic jugs and aluminum vessels were significantly more contaminated than water stored in thermoflasks ($p < 0.001$). Time (in hours) of sample collection since boiling was also significantly associated with faecal contamination ($p < 0.001$). Details on recontamination of boiled water in relation to storage and time of sampling since boiling are presented in table 4. Socioeconomic characteristics, sanitation, hygiene, and water handling practices were not significantly related to microbiological water quality before and after boiling, though the study was not powered to determine such associations.

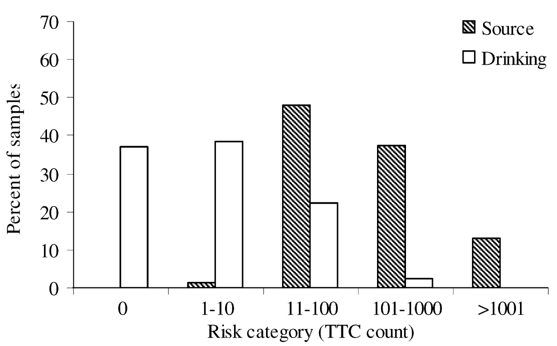

FIGURE 1. Percentage of water samples in by risk category.

Discussion

For the 1.1 billion people who lack access to improved drinking water supplies—and the millions more whose water is microbiologically unsafe—household water treat is increasingly viewed as means of accelerating the health gains associated with safe drinking water (*9*). Dozens of recent studies have evaluated the microbiological effectiveness and health impact of a number a point-of-use chlorination, filtration, solar disinfection, and hybrid approaches to treating water in the home (*7*). These alternatives may present some advantages over boiling in terms of time, convenience, safety, environmental impact, and sustainability. The purpose of this paper was to examine the microbiological effectiveness and cost of boiling as actually practiced by a vulnerable population.

Our results show that the practice of boiling in the study community significantly improves the microbiological quality of water, but does not fully remove the potential risk of waterborne pathogens. Although the 1.5 log reduction observed here is less than that reported in studies of certain other household water treatment options, log reduction values in the field are limited by the microbial challenge of the untreated water. One to three log reductions in bacterial indicators are similar to those reported in research-driven field trials of new technologies and are comparable to the

TABLE 4. Geometric Mean TTC Counts in Samples of Boiled Water for Different Storage Vessels and Time of Sample Collection since Boiling

		N	mean	95% CI	coefficient[a]	*p*-value
storage vessel	thermo-flask	99	1.8	1.5; 2.1		
	plastic jug	99	7.6	5.7; 10.1	2.3	<0.001
	aluminum vessel	44	8.1	5.2; 12.7	2.4	<0.001
time since boiling	<2 h	39	1.6	1.1; 2.1		
	2–4 h	73	2.2	1.7; 2.8	1.2	0.400
	4–8 h	40	5.0	3.5; 7.0	2.1	0.012
	8–16 h	45	7.2	4.8; 11.2	2.9	<0.001
	16–24 h	27	11.2	6.5; 19.1	3.7	<0.001
	>24 h	19	21.0	10.6; 41.5	7.2	<0.001

[a] In TTC/100 mL after adjusting for repeated measures over time and covariates.

performance of filters and other products in the few studies that have been undertaken to follow-up previously implemented household water treatment interventions (*34–38*). Perhaps more illustrative of the effectiveness of boiling as practiced in this community is the fact that it significantly reduced the portion of their drinking water that presented higher levels of risk associated with waterborne infection and disease. Finally, it is important to note that these results reflect the effectiveness of the water treatment method as actually practiced by a remote, vulnerable community, not in a research-driven assessment of an alternative method with an accompanying campaign to instruct and encourage households to use the method as is the case with most recent studies.

Our results also provide evidence that the source of faecal bacteria in the treated water is recontamination rather than poor boiling practices: time between boiling and sampling and transferring water to other vessels were both associated with higher levels of faecal contamination in stored water. This finding is consistent with previous studies that have explored the reasons for recontamination of water during collection, storage, and use in the home (*39, 27*).

The fuel cost of boiling for wood collectors in the study community was almost similar to the low estimate of fuel cost for wood boilers in India (*40*). Wood purchasers paid more than six times more for fuel than the estimated opportunity cost of wood collectors, or about the same as LP-gas users in India. As there are no other hardware costs for commencing the practice of boiling water (as households can be assumed to have a pot and fireplace for cooking), boiling represents the lowest cost of entry of any alternative water treatment options. However, the cost of continuing the practice annually (U.S. $3.26 for wood collectors and U.S. $20.16 for wood purchasers) is greater than the estimated cost of treating the same volume of water with sodium hypochlorite (U.S. $1.23), NaDCC tablets (U.S. $1.26), or using solar disinfection (U.S. $1.50) (*19*). The five-year cost of boiling (U.S. $16.30 and U.S. $100.80) would also exceed most filtration options, including ceramic filters, biosand filters, and certain commercial hybrid filters, even though such filters are capable of producing two or more times the 7.5 L boiled daily here.

With a fuel cost representing about 0.5–1.5% of the average monthly income of study households (in a comparatively low-income community compared to the country as a whole), the practice of boiling would appear to be affordable to most households. Although the opportunity cost of time spent treating the water more than doubles these cost and affordability figures, the amounts are still well below the estimates from Bangladesh reported by Gillman and colleagues (*20*). Even if households substituted an alternative method of treating their water for boiling, there would still be some time associated therewith and thus some corresponding opportunity cost. Moreover, it is not clear that such opportunity cost could actually be exchanged for cash in most cases here.

This study has important limitations that affect the generalizability of the results. First, the study community was not randomly selected and may not be representative of the country as a whole, much less other countries and settings. Second, the study was conducted only over a relatively small period of time during a single (dry and cold) season; the microbial load in source waters typically increases in rainy seasons, which may not only affect source water quality but household water treatment practices, and water may be cooled (and exposed) for longer periods in hotter climates. Third, the study was conducted in a completely rural setting; urban populations are more likely to purchase their fuel and the costs and affordability thereof may not correspond to the experience in rural settings. Fourth, boiling and postboiling storage and use of water are culturally distinctive and can be expected to vary considerably between countries and ethnic groups. Fifth, the study population in this case was not affected by a disaster, displacement, or other emergency; field testing of reportedly boiled water in an emergency response has shown higher levels of contamination (*29*). Finally, while efforts were made to confirm survey results with direct observation, the effect of the research on study participants reported and observed behavior cannot be assessed.

A more complete understanding of how boiling is actually practiced worldwide has potentially significant consequences. First, knowing the microbiological effectiveness of the practice establishes a benchmark: alternative methods for treating water in the home may not be less microbiologically effective without compromising health. Second, knowing the cost of boiling provides promoters of alternative methods with economic guidance that is more reliable than most willingness-to-pay and ability-to-pay studies. Combined with prevalence data on the extent to which boiling is practiced, it will also help define the size of the potential market. Third, knowing how boiling is actually practiced can lead the public sector to develop strategies and entrepreneurs to develop products that will help optimize the process. For example, our results show that households typically raise the temperature of water to a rolling boil—perhaps 30% higher than necessary to actually make the water safe for drinking—and often continue to boil for some time thereafter. This suggests opportunities for reducing cost (poverty) and environmental impact by developing simple indicators that will help households stop heating their water earlier when disinfection is complete. Vessels used to boil water could be reconfigured to help promote cooling and encourage direct use in order to minimize the risk of posttreatment recontamination. Finally, as boiling is the most common form of treating water at the household level—and the only method that might be said to have reached scale—advocates of household water treatment would do well to understand the practice in order to distill the lessons it may have for achieving scale for alternative methods.

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Supporting Information Available

Details on data analysis and ethics approvals for this study. This material is available free of charge via the Internet at http://pubs.acs.org.

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