Am. J. Trop. Med. Hyg., 79(3), 2008, pp. 407–413
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Microbiological Effectiveness and Cost of Disinfecting Water by Boiling in Semi-urban India

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Abstract. Despite shortcomings, boiling is the most common means of treating water at home and the benchmark against which emerging point-of-use water treatment approaches are measured. In a 5-month study, we assessed the microbiological effectiveness and cost of the practice among 218 self-reported boilers relying on unprotected water supplies. Boiling was associated with a 99% reduction in geometric mean fecal coliforms (FCs; $P < 0.001$). Despite high levels of fecal contamination in source water, 59.6% of stored drinking water samples from self-reported boilers met the World Health Organization standard for safe drinking water (0 FC/100mL), and 5.7% were between 1 and 10 FC/100 mL. Nevertheless, 40.4% of stored drinking water samples were positive for FCs, with 25.1% exceeding 100 FC/100 mL. The estimated monthly fuel cost for boiling was INR 43.8 (US$0.88) for households using liquid petroleum gas and INR 34.7 (US$0.69) for households using wood.

INTRODUCTION

Unsafe drinking water, along with poor sanitation and hygiene, is the main contributor to an estimated 4 billion cases of diarrhea disease annually, causing 1.8 million deaths, mostly among children younger than 5 years of age.[1] In India alone, > 450,000 deaths/yr are attributable to diarrheal disease, representing 9.1% of all deaths in children younger than 6 years of age.[2] An estimated 1.1 billion people lack access to improved water supplies; many more are forced to rely on water that is microbiologically unsafe.[3] 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.[4,5]

Boiling or heating with fuel is perhaps the oldest means of disinfecting water at the household level.[6] It is also the most widely used means of treating water in the home, with perhaps hundreds of millions of practitioners.[7] If practiced correctly, boiling is also one of the most effective, killing or deactivating all classes of waterborne pathogens, including bacterial spores and protozoan cysts that have shown resistance to chemical disinfection and viruses that are too small to be mechanically removed by microfiltration.[8] Moreover, whereas chemical disinfectants and filters are challenged by turbidity and certain dissolved constituents, boiling can be used effectively across a wide range of waters. In rural Kenya, pasteurization of water using a simple wax indicator to show householders 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 with a control group (odds ratio [OR] = 0.55, P = 0.0016).[9]

Governments, non-governmental organizations (NGOs), and others have promoted the practice of treating drinking water by boiling, both in developing countries where water is often of uncertain microbial quality[10] and in developed countries when conventional water treatment systems fail or water supplies are interrupted because of disasters or other emergencies.[11] Sources vary in the time recommend bringing water to a boil for necessary disinfection, including 1,[11] 10,[12] and even 25 minutes.[13] These longer times may have been generalized from recommendations for sterilizing medical devices rather than the water itself. The World Health Organization (WHO) *Guidelines for Drinking Water Quality* simply recommends bringing water to a rolling boil as an indication that a disinfection temperature has been achieved.[14]

Despite its extensive use, boiling water presents certain disadvantages that may limit its scalability as a means of routinely treating drinking water. First, once the water begins to cool, it is immediately vulnerable to recontamination from hands and utensils, because it contains no residual disinfectant and is often stored in open vessels without a tap.[15,16] Recent studies have shown that the stored drinking water in the home of families who reported boiling it often contains high levels of fecal contamination.[17,18] Second, more than one half of the world's population relies chiefly on wood, charcoal, and other biomass for their energy supplies.[19] 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.[20] Third, boiling can be an important cause of other health hazards, including respiratory infections, anemia, and stunting associated with poor indoor air quality[21] and burns, especially among young children.[22] Fourth, depending on the fuel used, boiling may be environmentally unsustainable and contribute to greenhouse gases. Finally, there is some evidence—although now > 30 years old—that the cost of boiling may be prohibitive for many low-income populations.[10]

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.[6] However, before householders are encouraged as a matter of public policy to consider such alternatives, it is useful to assess microbiological effectiveness and cost of boiling, not only theoretically or under controlled circumstances, but also as actually practiced

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in the field, so that such alternatives can be compared with the "benchmark" of boiling.

This paper reports on our assessment of boiling practices in semi-urban India, a country in which boiling is used to disinfect drinking water by 10.6% of Indian households.[23] It complements results from a recent study in rural Vietnam in which boiling was found to be more effective than shown for populations in post-emergency settings.[24] 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 of boiling to allow for comparisons with alternative methods for treating water in the home.

MATERIALS AND METHODS

Study settings. The 5-month study (July to November 2006) was conducted in Virar, Vasai, and Nalasopara, three sprawling semi-urban communities with an aggregate population in excess of 200,000 located within the Vasai district, ~60 km north of Mumbai in the state of Maharashtra, India. The study site was selected after informal surveys confirmed that the communities were comprised of members of all five socioeconomic classes (SECs) as defined by the Indian Socio-Economic Classification System and that significant numbers of householders drew their water from unprotected sources and reported boiling their water for drinking. The communities secure their water supplies from a number of sources, including municipal reticulated systems that operate a few hours most days, tanker trucks that fill cisterns, and groundwater (wells and boreholes). The municipal and tanker-supplied water is purportedly chlorinated; groundwater supplies are occasionally chlorinated by owners.

Enrollment of participating households. Households were eligible for enrollment in the study if, in response to an eligibility survey in the communities, they reported securing their source water from wells and that they either "always" or "almost always" boiled their water before drinking it. After a pre-investigation assessment of the differences in bacterial loads of samples from source and stored water in adjacent communities, we estimated a sample size (with 80% power and $\alpha = 0.05$) of 45 households from each of the five SEC classifications. In accordance with the study protocol, investigators were instructed to continue to solicit eligible households until they identified 45 from each SEC category. Study limitations and a lack of population data prevented the random recruitment of participants from the communities.

Surveys and boiling demonstrations. During the initial visit, the female head of each participating household provided information to a field investigator who filled in a pre-piloted structured survey. Information included household demographics; water collection, treatment, and storage practices; hygiene practices; and sanitation facilities. Once during the 5-month study period, 180 (83.3%) of the participating households provided information in response to a survey on the manner in which boiling was actually practiced in the home (definition of boiling, frequency, type of fuel used, amount of water boiled daily, time and method of procuring fuel, etc.); the balance of participating households were not available to provide such information. To estimate the full economic cost of the practice, the survey 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, a convenience sample of 26 households (14.4%) was selected randomly from the study population to show the procedures they normally follow to boil their water.

Water sampling and analysis. Starting at the first visit to each participating household and continuing once each month for the ensuing 4 months, two 125-mL water samples (one from the raw source water that the householder collected for use in the home and one from the water that the householder identified as treated and stored drinking water) were collected during unannounced visits and assayed for fecal coliforms (FCs), a WHO-prescribed indicator of fecal contamination.[14] The water samples were refrigerated at 4°C and analyzed within 24 hours of collection. Except as noted herein, analysis was performed using the membrane filtration method in accordance with *Standard Methods for the Examination of Water and Wastewater*.[25] A 100-mL sample was passed through a 0.45-μm membrane filter (Millipore, Bedford, MA) and incubated on mT-7 agar (Difco Laboratories, Detroit, MI) at 37°C for 2 hours, followed by 44°C for 24 hours.[26] The number of yellow colonies were counted and recorded as individual FCs and reported as the number of colony forming units (CFUs) per 100 mL of analyzed sample water. Duplicate 1-mL samples were analyzed by plate technique in duplicate on mT-7 agar. We report the mean result of such methods, except that where membrane filtration technique yielded contiguous growth of colonies too numerous to count (29% of source water samples and 22% of stored water samples), the mean of the pour plate counts is reported.

Estimating fuel consumption. 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).[27] We used the formula to calculate the amount of heat energy required to bring water up to various temperatures. We estimated the amount of fuel consumed by using the published calorific value of each fuel. The calculations assumed 56% heat transfer efficiency for heating water with liquid petroleum gas (LPG) over a stove and 20% heat transfer efficiency for burning wood in a cook stove.[27]

Cost estimates. 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. LPG cylinders are a standard 14.2 kg and cost 300 Indian rupees (INR) or INR 21.13/kg (US$0.02/kg). This is not a market price: the government provides a subsidy of INR 22.80 per domestic cylinder, and oil companies claim they are losing INR 175 per cylinder.[28] Thus, the price of LPG could increase significantly if subsidies are lifted or if prices increase with other global fuel costs. Indirect costs include the opportunity cost of the time used to purchase or collect fuel and to boil the water. Although most women who actually boil their water reported that they would not engage in any economic activity during the time they collect fuel or boil their water, cost analysis requires that an economic value nevertheless be attached to such time. Although we solicited information on income levels, it cannot be assumed that most women who actually boil the water from their households could generate that level of income for the time associated with boiling their water. We therefore elected to calculate the cost of their time using two values: a lower estimate used the lowest prevailing monthly income reported by the respondents, and a higher estimate based on the average wage in India of female agricultural workers. Estimates of the time spent procuring fuel were based on the household surveys, and estimates of the time spent on actually boiling were based on the boiling demonstrations.

Data analysis. Data were double-entered on Excel spreadsheets (Microsoft, Redmond, WA) and analyzed using Stata Release 8.0 (Stata Corp., College Station, TX). Statistical analyses of microbiological data were conducted after $\log_{10}$ transformation of FC count values. A paired *t* test was used to analyze FC counts of paired (source and drinking) water samples. A linear regression model adjusting for repeated samples within the same household was used to explore possible associations between bacterial counts in water samples and household characteristics. A χ^2 test was used to examine differences in categorical data (i.e., SEC and fuel type). Water sample results were treated analyzed as independent observations and not adjusted for repeated sampling at the same household. Costs are presented both in the local currency of INR and US dollars. For purposes of this paper, an exchange rate from August 16, 2006 of 1 INR for US$0.02 was used for reporting the US dollar equivalents of the Indian currency.

Ethics and consent. The study was reviewed and approved by Ethics Committee of the London School of Hygiene and Tropical Medicine. Prior to the commencement of the study, potential participants received complete details regarding the risks, expectations and obligations of householders participating in the study, and had an opportunity to ask and receive answers to any questions. Informed, written consent was obtained from the household head (usually, the senior male) at the beginning of the study. The participants were not subjected to risks of any kind as a result of the project, as no intervention and no change in their practices or behavior were introduced or encouraged. The investigators provided feedback and information to the participants at regular intervals. All data were treated confidentially, and recorded only on the basis of a householder identification number, with no disclosure of identifying information. Any medical conditions observed by investigators during visits to households were referred to local medical clinics.

RESULTS

Demographic and household characteristics. The study included 218 households with 1,167 persons (mean of 5.4 occupants per household). Participating householders reported drawing their source water from unprotected wells (72%) or boreholes (28%). Eighty-nine percent of participating households reported using a latrine (81% private); the balance practiced open defecation. Only 17 (9.7%) of the female head of household reported being engaged in any type of economic activity, whether or not in the home. None of SEC (SEC class, household size, type of household construction) or other covariates measured (type of well, presence and type of latrine, definition of boiling, type of fuel used, type of latrine, definition of boiling, frequency of boiling) were statistically associated with thermotolerant coliform (TTC) counts either at source or in stored household samples.

Reported boiling practices. Of 180 households responding to surveys regarding boiling practices, 157 (87.2%) reported using LPG as their primary source of fuel for boiling water, 18 (10%) used wood, 3 (1.7%) used electricity, and 2 (1.1%) used kerosene. Because of their minor representation, households using electricity and kerosene are included in the microbiological analysis but excluded from the cost analysis. Wood was more likely to be used by the lower SEC quintiles (D and E) and LPG by the higher SEC quintiles (A, B, and C; $P < 0.0001$). Most respondents (80.6%) reported that they boiled until the water surface erupted, 14.3% stopped when steam vapors could be observed, and 5.1% stopped when they observed bubbles from the bottom of the vessel; 73.7% reported placing a lid over the vessel during boiling. Most householders reported that the main reason for boiling drinking water was because of a recommendation by a physician (68.6%); recommendations by the respondent's mother or relative (5.7%) or the government (3.4%) were reported to have relatively little influence. The mean quantity of water boiled per day was 6.38 liters for users of LPG and 6.92 liters for users of wood, a relatively minor but statistically significant difference ($P = 0.0025$). The mean time that householders reported spending time boiling was 6.18 min/L for users of LPG and 6.42 min/L for users of wood, a difference that was not statistically significant. None of the post-treatment water handling practices measured (transferring water to another vessel, adding cold water to boiled water, covering storage vessel) was statistically associated with the level of TTC in stored water samples.

Boiling demonstrations. In field demonstrations, householders spent ~2 minutes preparing to boil their water (washing the vessel, filling the vessel, and placing the vessel on the heat source). Although users of LPG simply turned on the gas, wood users spent an additional 5 minutes starting the fire. Users of LPG spent only ~10% of this time actively over the stove; in contrast, wood users spent ~50% of the boiling time actively over the fire. Four of the 26 women stopped boiling their water once vapors appeared; the average temperature for this was 74.6°C; the remaining 22 women brought the water to a surface boil (100°C). Only two women continued to boil water once it reached a surface boil for 3 and 5 minutes each. All wood users boiled their water outdoors, and each had a secondary fuel source for use indoors, in case of rain (one each of LPG, kerosene, and electric). Of the two women who demonstrated using wood (the third used her secondary fuel source because of rain), one placed another vessel filled with water for bathing over the remaining embers/fire after the water for drinking was boiled. The other women attempted to extinguish the fire, and left the stove unused, despite some embers still burning.

Water quality. Table 1 shows FC counts for samples from source and treated water by sampling round for 216 participating households (two households having been lost to follow-up). Source water showed consistent evidence of fecal contamination, with an overall geometric mean FC count of 612.8 (95% confidence interval [CI]: 484.9–773.9) per 100 mL. Stored (and reportedly treated) household drinking water showed considerable improvement in microbiological quality, with a geometric mean FC count of 5.8 (95% CI: 5.0–6.6) per 100 mL. Overall, a comparison of paired water samples for

TABLE 1
Mean FC and 95% CIs

	Mean type	Source Mean	Source 95% CI	Source N	Stored Mean	Stored 95% CI	Stored N	P value
Round 1	Geometric	426.2	(261.5; 694.5)	218	6.1	(4.4; 8.3)	218	< 0.001
	Arithmetic	7 374.7	(5,888; 8,861.4)		56.6	(45; 68.2)		< 0.001
Round 2	Geometric	1 031.1	(615.4; 1,727.5)	218	6.1	(4.4; 8.3)	218	< 0.001
	Arithmetic	12 939.5	(10,948.9; 14,929.9)		55.3	(43.9; 66.6)		< 0.001
Round 3	Geometric	823.4	(484.8; 1,398.2)	218	7.2	(5.2; 9.9)	218	< 0.001
	Arithmetic	11 888.9	(10,117.7; 13,660.1)		64.9	(52.8; 77.2)		< 0.001
Round 4	Geometric	944.9	(566.0; 1,577.5)	217	6.0	(4.4; 8.2)	217	< 0.001
	Arithmetic	12,178.3	(10,390; 13,966.6)		54.9	(43.3; 66.5)		< 0.001
Round 5	Geometric	251.8	(144.3; 439.1)	217	4.0	(3.0; 5.2)	217	< 0.001
	Arithmetic	10,599.9	(8,748.0; 12,451.9)		36.3	(26.5; 46.1)		< 0.001
All	Geometric	612.8	(484.9; 773.9)	1,088	5.8	(5.0; 6.6)	1,088	< 0.001
	Arithmetic	10,995.5	(10,193.6; 11,797.4)		53.6	(48.6; 58.7)		< 0.001

each household showed a 2.1 $\log_{10}$ reduction (95% CI: 2.1–2.2) in fecal coliforms after treatment; this is equivalent to a 99% reduction in FC. Analysis of FC counts by demographic characteristics or boiling practices showed no statistically meaningful association between such variables and bacterial loads in water samples.

Figure 1 presents distribution of the 2176 water samples by $\log_{10}$ categories for fecal contamination: 0 (in compliance), 1–10, 11–100, 101–1,000 and > 1,001 FC/100 mL. Overall, 59.6% of stored water samples from self-reported boilers were free of FCs and 5.7% fell within 1–10 FC/100 mL. However, 25.1% fell between 101 and 1,000 FC/100 mL, and 9.5% were classified in the 11–100 FC/100 mL category. In contrast, only 17.5% of the source water samples conformed to WHO drinking water standards (0 FC/100 mL), and 59.4% were in excess of 1,000 FC/100 mL. Contamination levels of paired water samples were positively correlated (r = 0.1267, P < 0.001).

Fuel consumed. LPG has a reported calorific value of 49,543.8 kJ/kg and burns at a minimum efficiency of 58%, leaving 28,735.4 kJ/kg of available heat energy.[27] The specific heat capacity of water is 4.19 kJ/kg°C. Therefore, the amount of LPG required to bring 6 liters of water to 100°C from a starting temperature of 25°C is 65.6 g. Wood with 15% moisture has a calorific value of 16,000 kJ/kg, and it burns at an efficiency around 20%, leaving 3,200 kJ/kg of available heat energy.[27] Therefore, the amount of wood required to bring 6 liters of water to 100°C from a starting temperature of 25°C is 589.2 g. LPG users reported, in response to the surveys, that the mean time between purchasing a new cylinder of fuel was 33 days (95% CI = 31.7–34.9).

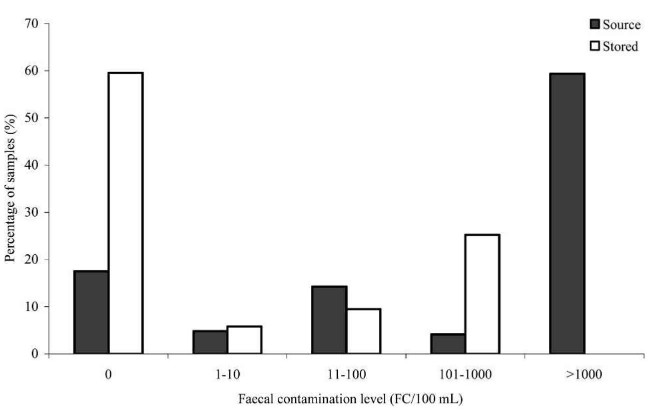

FIGURE 1. Percentage of water samples by TTC level (N = 2,176).

Fuel cost. Based on the foregoing estimates of fuel consumption for LPG users, participating householders used 13.9% (95% CI: 12.5–15.4) of their fuel for boiling water. The mean direct cost of LPG in bringing 1 liter of water to 100°C was INR 0.24 (US$0.005). Assuming householders boil 6 L/d (approximately the amount reported by both LPG and wood users), the monthly mean cost for fuel for LPG users is INR 43.8 (US$0.88). Because there were only limited data from persons who purchased wood, no estimate of the direct cost of wood could be made. The cost of collecting wood is treated as an indirect cost. Women have been reported to spend an average of 20 min/d collecting fuel in rural Maharashtra (World Bank, unpublished data, 2004). We used 13.9% of this time (the proportion of fuel used by LPG users on boiling water) to reflect the amount of wood collected for treating water. Assuming a mean valuation on time between the lowest prevailing wage and minimum wage, the cost of fuel for householders using wood is INR 0.19 per liter, for a monthly mean cost of INR 34.7 (US$0.69).

Economic cost. Table 2 summarizes cost per liter of boiling to disinfect water based on the assumptions, estimates, and valuations of time and fuel described above. For LPG users, all of whom are assumed to purchase their fuel, the total cost of boiling 1 liter of water ranged from INR 0.34 to INR 0.49, resulting in a mean cost of INR 0.41 (US$0.08). For wood users, all of whom are assumed to collect their own fuel, the cost ranged from INR 0.52 to INR 1.25, resulting in a mean cost of INR 0.88 (US$0.18). Assuming householders boil 6 L/d, the monthly mean total cost is INR 74.8 (US$1.50) for LPG users and INR 160.6 (US$3.21) for wood users. The economic cost for wood users is more than twice that of LPG users, despite lower fuel costs. This is because of the increased time spent by wood users starting the fire (5 versus 0 minutes for LPG users) and portion of their time spent attending to the heat source (50% versus 10% for LPG users).

DISCUSSION

For the 1.1 billion people who lack access to improved drinking water supplies—and the millions more whose water

TABLE 2
Mean cost (and, where applicable, range of cost) of disinfecting 1 liter of water by boiling

Item	LPG users		Wood users	
Direct costs				
Cost of fuel	INR 0.24 (0.21–0.27)		Cost of collecting wood treated as indirect cost.	
Indirect costs	Time valued INR 2.40/h (US$0.048/h)*	Time valued at INR 5.78/h (US$0.12/h)†	Time valued at INR 2.40/h (US$0.048/h)*	Time valued at INR 5.78/h (US$0.12/h)†
Procuring fuel	—	—	0.11	0.27
Preparing to boil	0.08	0.19	0.28	0.67
Boiling using LPG (10% of time)	0.025 (0.018–0.031)	0.06 (0.04–0.08)	—	—
Boiling using wood (50% of time)	—	—	0.13 (0.10–0.16)	0.31 (0.23–0.39)
Total indirect	0.10 (0.9–0.11)	0.25 (0.23–0.27)	0.52 (0.49–0.55)	1.25 (1.17–1.33)
Total cost	0.34 (0.30–0.38)	0.49 (0.47–0.51)	0.52	1.25 (1.17–1.33)

* Lowest prevailing wage reported by survey respondents in study communities.
† Average daily wage for a female agricultural worker, adjusted for inflation.[29]

is microbiologically unsafe—household water treat is increasingly viewed as means of accelerating the health gains associated with safe drinking water.[30] 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 drinking water in the home.[31] These alternatives may present some of advantages of 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 communities significantly improves the microbiological quality of water but does not fully remove the potential risk of water-borne pathogens. The 99% reduction observed here is similar to the 97% reduction reported in a similar study in Vietnam.[24] One to three log reductions in bacterial indicators are similar to those reported in field trials of new technologies and are comparable to the performance of filters and other products in the few studies that have been undertaken to follow-up previously implemented household water treatment interventions.[32–34] It is important to note that these results reflect the effectiveness of the water treatment method as actually practiced by a remote, vulnerable community, and not in a research-driven assessment of an alternative method with an accompanying campaign to instruct and encourage householders to use the method as is the case with most recent studies. Perhaps more illustrative of the effectiveness of boiling as practiced in these communities 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. This result was consistent with those obtained in the Vietnam study.

Nevertheless, 40.4% of stored (and reportedly treated) drinking water samples of these self-reported boilers showed evidence of fecal contamination, and one quarter of the samples contained high (101–1,000) levels of FCs. Because the boiling practices reported by, or actually observed in the homes of, study participants suggested that they were heating water to levels sufficient to kill such coliforms, it seems likely that the observed levels of contamination in stored water were caused either by the failure to follow the practice of boiling at all times or to re-contamination of boiled water. Re-contamination is a common problem where, as here, the treatment process does not leave a residual disinfectant (as chlorination would), and suitable vessels for safe storage are not always available.[16] Re-contamination was observed in the boiling study in Vietnam, and levels of contamination increased with elapse of time after boiling.[24] In this case, however, none of the socio-economic or other covariates we measured were statistically associated with microbial water quality in stored household drinking water apart from a correlation with source water contamination.

The estimated monthly fuel cost of boiling was US$0.88 for LPG users and US$0.69 for wood users. Because there are no other hardware costs for starting the practice of boiling water (because householders can be assumed to have a pot and stove or fireplace for cooking), boiling represents the lowest cost of entry of any alternative water treatment options. However, the cost of continuing the practice annually (US$10.56 for LPG users and US$8.28 for wood users) is greater than the on-going out-of-pocket cost of treating the same volume of water with sodium hypochlorite (US$0.98), or solar disinfection (US$1.20).[31] The 5-year cost of boiling (US$52.80 and US$41.40) would also exceed most filtration options, including ceramic filters, biosand filters, and certain commercial filters, even though such filters are capable of producing two or more times the 6 liters boiled daily here. The opportunity cost of time spent actually boiling the water significantly increases the economic cost of the method, but there are no data on which to compare with alternative methods of household water treatment.

It is important to note that, although the LPG estimate represents a true out-of-pocket expense, the wood estimate is not an actual monetary outlay but the opportunity cost of time spent collecting wood. Accordingly, it requires certain assumptions about the potential for alternative revenue-producing work and the wages that could be earned therefrom. The overall higher economic cost of boiling for wood users raises questions about the validity of this approach beyond pure economic analysis. On the other hand, research regularly shows that lower-income populations pay more for basic services such as water, electricity, and sanitary waste disposal than those earning higher incomes, thus aggravating their poverty.[35] It also suggests that the substantial government expenditures that the Indian government makes to subsidize LPG costs may not be benefiting the lower-income populations who do not have access to or cannot afford even the subsidized cost of LPG.

This study has important limitations that affect the generalizability of the results. First, the study communities were 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 and the end of the monsoon season. Seasonal variations in temperature may affect boiling practices, and variations in rainfall may impact the microbial loads of surface waters. Third, boiling and post-boiling storage and use of water are culturally distinctive and can be expected to vary considerably between countries and ethic groups. Fourth, 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.[18] Finally, although 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 should not be less microbiologically effective without compromising health. Second, knowing the cost of boiling provides promoters of alternative methods with economic guidance besides that supplied by 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 many householders raise the temperature of water to a rolling boil—perhaps 30% higher than necessary to actually make the water safe for drinking—and some continue to boil for a time thereafter. This suggests opportunities for reducing cost (poverty) and environmental impact by developing simple indicators that will help householders 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 to minimize the risk of post-treatment recontamination. Finally, 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 on a widespread basis. Advocates of alternative household water treatment methods should therefore take advantage of the lessons it may offer for achieving scale and apply them to such alternative methods.

Received February 2, 2008. Accepted for publication May 14, 2008.

Acknowledgments: The authors thank the communities of Virar, Vasai, and Nalasopara for cooperation in connection with this study and to Wolf-Peter Schmidt and Lucy Smith of the London School of Hygiene and Tropical Medicine and for their assistance.

Financial support: This study was funded in part by Hindustan Unilever Limited (HUL). NN, RG, DD, and NS are employees of HUL. HUL manufactures and sells household-based water filters and could benefit from research showing that boiling is less effective or more costly than its products.

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