Safe water treatment and storage in the home: A practical new strategy to prevent waterborne disease

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In many parts of the developing world, drinking water is collected from unsafe surface sources outside the home and is then held in household storage vessels. Drinking water may be contaminated at the source or during storage; strategies to reduce waterborne disease transmission must safeguard against both events. We describe a two-component prevention strategy, which allows an individual to disinfect drinking water immediately after collection (point-of-use disinfection) and then to store the water in narrow-mouthed, closed vessels designed to prevent recontamination (safe storage). New disinfectant generators and better storage vessel designs make this strategy practical and inexpensive. This approach empowers households and communities that lack potable water to protect themselves against a variety of waterborne pathogens and has the potential to decrease the incidence of waterborne diarrheal disease.

DIARRHEAL diseases remain a leading cause of illness and death in the developing world [1]. Providing potable water for drinking and washing is critical to reducing, diarrheal disease transmission in this setting [2]. However, improving source water quality alone does not always decrease diarrheal disease incidence [3]. Providing a safe drinking water source may fail to reduce diarrhea because transmission of diarrheal pathogens continues through foodborne or person-to-person routes of spread or because people are exposed to contaminated water during bathing and other activities. Drinking water also becomes contaminated after collection, either during transport or storage in the home.

Improvements in source water quality generally depend on expensive, long-term, centralized projects, such as construction of wells, water treatment plants, and water distribution systems. During the World Health Organization's (WHO's) Drinking Water Supply and Sanitation decade (1981 to 1990), an effort was made to increase access to potable water in developing countries but was nearly outstripped by population expansion and migration from rural to urban areas [4]. Safe drinking water for all remains an elusive and expensive goal.

In 1990, more than 1 billion people depended on rivers, streams, or other unsafe surface sources for drinking water [4]. In many developing countries, even municipal piped well water is unsafe, because of inadequately maintained pipes, low pressure, intermittent delivery, lack of chlorination, and clandestine connections. For example, Vibrio cholerae was repeatedly isolated from unchlorinated municipal water systems in Peru that caused large epidemics of cholera [5,6]. In Guayaquil, Ecuador, even central chlorination of the municipal water system was insufficient to maintain adequate free chlorine residuals at peripheral distribution sites, and drinking unboiled municipal water remained a primary source of cholera [7].

An inexpensive strategy is available to improve household drinking water until piped potable water is routinely available. The strategy has two components: water disinfection at the time water is collected (point-of-use disinfection) and water storage in vessels specifically designed to prevent recontamination (safe storage). However, successful implementation of this strategy will require focused educational campaigns stressing the role of contaminated water and domestic hygiene in disease transmission [8].

POINT-OF-USE DISINFECTION

When centralized water treatment systems are absent or inadequate, the responsibility for making drinking water safe falls to community residents by default. The traditional emergency prevention measure, boiling the water, is economically and environmentally unsustainable. It takes a kilogram of firewood to bring a liter of water to boil for a minute,[9] and a person requires a minimum of 2L of drinking water per day [10].

Alternatives to fuel wood, such as kerosene and other fossil fuels, are expensive and also pose environmental hazards,[11,12] while practical and inexpensive solar powered stills suitable for household use have not been developed. After cooling, boiled water can easily be recontaminated, especially if it is transferred to a storage container [10].

Chemical disinfectants are a practical alternative to boiling, although only the safest and least expensive disinfectants are suitable for household use in the developing world. Chlorine gas, the most commonly used disinfectant in water treatment plants, is hazardous ,and impractical. However, sodium and calcium hypochlorite are relatively safe, easy to distribute and use, inexpensive, and effective against most bacterial and viral pathogens [13]. When added to water in tightly covered containers, volatilization is minimal and hypochlorite disinfectants provide residual protection for many hours to days [14]. Commercial laundry bleach solutions (primarily sodium hypochlorite) and commercial bleaching powders (primarily calcium hypochlorite) are potential disinfectants. However, these preparations frequently contain impurities or additives to improve laundering that may be harmful if ingested. Concentrations of hypochlorite may vary, making it difficult to prepare standard dosing instructions. Too high a dose results in an unpleasant taste that may discourage use.

Recently, electrolysis cells have been developed that permit small-scale manufacture of a standard 0.5% sodium hypochlorite solution from common salt and water. These cells, which are easy to operate and can run on solar power, make local production of disinfectant feasible almost anywhere [15]. The cost of hypochlorite solutions produced by these generators ranges from US $2.50 to $8 per kilogram of available chlorine, depending on the costs of energy and salt and the production method used. At the higher cost, disinfecting 40 L of water a day, enough for the essential household purposes of a family of five, would cost about US $0.25 annually. A single generator can provide enough disinfectant for a town of 10,000 people and could eventually be incorporated into a municipal water treatment system once pipes are installed.

Other chemical disinfectants that have been used much less widely than hypochlorite also may have potential applications for point-of-use disinfection. These include iodine and mixtures of oxidants generated on-site (composed of various chlorine and oxygen-based compounds, such as ozone, chlorine dioxide, and short-lived free radicals). Other water treatments that may be applicable in some settings include floculation and acidification with aluminum potassium sulfate (alum potash), filtration through sand or cloth, and the use of copper sulfate. However, none of these treatments has demonstrated the safety and efficacy of chlorination. Disinfection can be achieved with relatively little effect on the taste or smell of treated water by using standard hypochlorite solutions to treat known volumes of water [10,14,16]. Unpleasant odors and tastes can be further reduced by letting treated water stand or by using mixed oxidants, which break down some of the organic byproducts of chlorination [10,15,16].

THE EFFECT OF WATER DISINFECTION IN THE HOME

Many observations suggest that treating water in the home can prevent illness. Recent epidemiologic studies [57,17] have demonstrated that persons whose families boil drinking water at home are at lower risk of cholera specifically and diarrhea in general. In one recent study,[18] acidification of drinking water with citrus fruit juice also protected against cholera. However, few formal prospective evaluations of point-of-use disinfection
have been reported.

In one study conducted in Bangladesh, [19] families of cholera patients were visited after the patient's hospitalization. Half of the families were taught to add alum potash to their stored household drinking water. In these households, fewer family contacts became infected with *V cholerae* than among families who did not use alum.

Alum potash treatment of household water also was evaluated in Myanmar [20]. Stored drinking water samples from 50 control households and from 50 households where alum treatment was used were tested for fecal coliform bacteria. Mean fecal coliform counts were similar in both households before the addition of alum but were lower in the treatment households 24 and 48 hours after alum was added.

Point-of-use disinfection using 10% sodium hypochlorite was evaluated in Brazil in 1985 [21]. Twenty families (112 persons) who collected their drinking water from a contaminated pond were randomly assigned to one of two groups. During the next 18 weeks, community health workers collected information on diarrheal illness from each family during thrice weekly household visits. For 9 weeks, sodium hypochlorite was added to one group's stored drinking water and a placebo (distilled water) was added to water used by the other group; treatment and placebo groups were switched during the second half of the study. Mean fecal coliform counts were significantly higher in placebo treated water samples than in samples of hypochlorite treated water. No significant difference in the average number of days of diarrhea per person-year was observed between the two groups, although the short duration, small sample size, and high dropout rate limited the study's ability to detect an association.

THE EFFECT OF WATER, STORAGE IN THE HOME

The risk of diarrheal disease due to contamination of drinking water during household storage:was noted in surveys conducted by the WHO in the 1960s [22]. The WHO team observed that "drinking water taken from the piped supply was stored for cooling in earthen jars which were, without exception, faecally contaminated. Thus, the availability of water had little impact in reducing the number of cases of diarrhea." The observation of water contamination during home storage has since been repeatedly confirmed. Data on inhouse water contamination are available from three sources: observational studies of stored water quality, field investigations of the impact of specific behaviors and water vessel characteristics on water quality and on health, and intervention studies using modified water storage vessels.

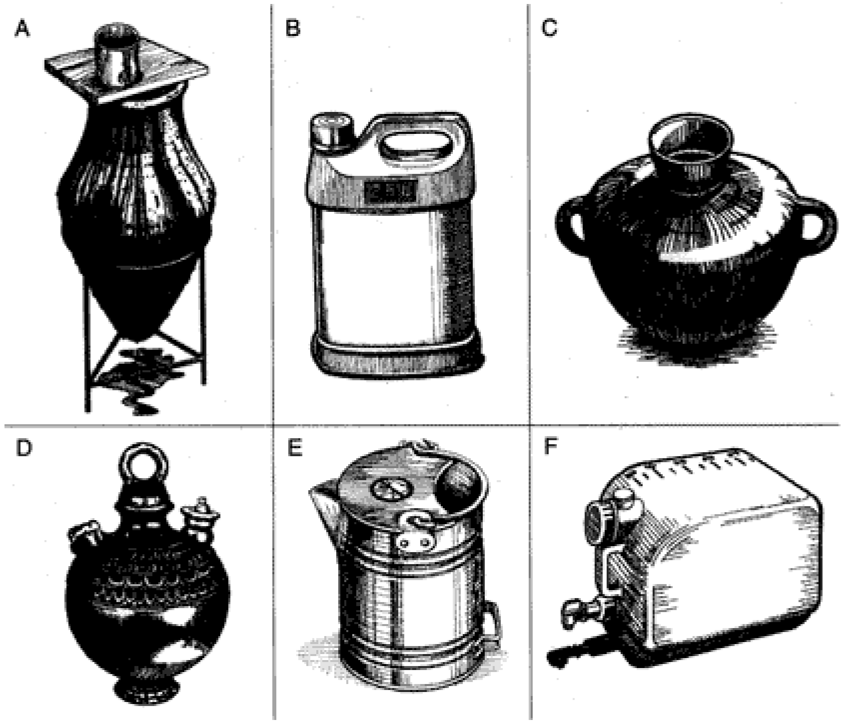
Observational Studies of Domestic Water Quality

In a recent review of water contamination occurring during home water storage [11], observational studies showed that mean coliform levels were substantially higher in household water containers than in water sources, four studies showed coliform levels in water storage containers and sources to be comparable, and only one study showed lower coliform levels in storage containers than in watersources [23]. In five other studies in which paired samples from individual water sources and household storage containers were compared, the results were similar; fecal coliform concentrations were generally, and sometimes dramatically, higher in stored water than in source water [23,24]. During the recent cholera epidemic in Peru, we sampled water from municipal taps and from stored household water from these taps and noted a thousandfold increase in mean fecal coliform counts [5].

Fecal (thermotolerant) coliform bacteria may not be ideal indicators for fecal contamination [25]. In some field studies, recognized enteropathogens were identified in stored water. For example, in Thailand, enterotoxigenic *Escherichia coli* was recovered from a drinking water jar used to store rainwater [26]; in Bangladesh, toxigenic *V cholerae* 01 was recovered from stored drinking water collected from safe tube wells [27]; and in Calcutta, Deb *et al* [28] isolated *V cholerae* 01 from stored water in 9% of households of cholera patients and in 2% of control households. Deb *et al* [28] observed that "people generally took stored water from the [open] bucket by dipping. ..thus resulting in contamination of otherwise safe water by their infected fingers."

During a cholera epidemic in Bahrain in 1981, investigators identified *V cholerae* 01 in stored household drinking water [29]. This isolation probably resulted from postcollection contamination, since tap water samples in the same homes and from all other tested water sources were negative for *V cholerae*. Similarly, in Myanmar, toxigenic *E coli* was identified in two of 40 water samples from household storage vessels but in none of 20 samples collected on the same day from the water sources [24]. In Egypt, two parasitic pathogens, *Strongyloides* and *Ascaris* were isolated from 10% to 15% of water samples collected from earthenware household storage vessels (Figure 1, A), but no pathogens were identified in source water samples.[34] These studies indicate that contamination with pathogens as well as indicator organisms occurs during home water storage.

Figure 1. Traditional water storage vessels and water storage vessels that have been modified to reduce contamination during storage. Storage vessel A is a traditional Egyptian zir[30]; B, plastic container used to sell vegetable oil in Zambia[31]; C, traditional cantero from El Salvador; D, sorai used in an intervention trial in India [32]; E, tin bucket used in an intervention trial in Malawi[33]; and F, plastic container meeting the Centers for Disease Control and Prevention/Pan American Health Organization design criteria and used in an intervention trial in Bolivia [14,15].



Field Investigations of Specific Behaviors and Storage Vessel Characteristics

Several field investigations have identified behaviors or storage vessel characteristics associated with contamination of water in the home or with disease resulting from contamination. For example, researchers investigating epidemics in Malawi [35] and Peru[5,6] reported that patients were more likely than healthy control subjects to live in households where stored drinking water was dipped out with hands or utensils. Similarly, in a recent investigation of epidemic Shigella dysenteriae type 1 infection in Zambia, stored water was more likely to be dipped out in patients' homes and more likely to be poured in the homes, of healthy neighbors, suggesting that hands and objects introduced into stored water were a source of contamination.[31] In this study, healthy subjects often stored their water in a narrowmouthed plastic vessel used to sell vegetable oil (Figure 1, B), whereas infected patients were more likely to use an open bucket into which hands could be inserted.

The design of a water storage vessel may help determine how well stored water is protected. In 1992, a microbiological survey of water stored in Texas homes without municipal water connections found coliform bacteria significantly less often in storage vessels with openings less than 10 cm in diameter, from which water was typically poured, than in containers with wider openings, into which hands and dipping utensils could more easily be introduced.[36]

Some traditionally designed containers make contamination less likely. For example, the narrownecked "cantero" or "tinaja" (Figure 1, C), a water storage vessel traditionally used in Central America, has a pleasing shape that may help protect stored water from contamination.

After contamination occurs, characteristics of the storage vessel may affect bacterial survival in stored water. In inoculation experiments with African domestic water storage vessels, *V cholerae* 01 survived as long as 7 days in clay pots, 22 days in plastic containers, and 27 days in metal drums.[37] Not surprisingly, survival times rarely exceeded 1 day in water with chlorine levels of 0.2 mg/L or greater.

Intervention Studies With Modified Water Storage Vessels
The effect of modifying the design of a water storage vessel on behavior, contamination, and disease has been assessed in several studies. In one study conducted in the Sudan,[30] fecal indicator organisms were documented in more than 80% of water samples collected from 350 zirs. The zir is a large earthenware jar in the form of an amphora used in Egypt and the Sudan (Figure 1, A).[30] Water is removed with a cup or ladle from the top, which is generally uncovered. To assess the impact of modifying traditional design, three new zirs were filled with clean water and placed in public locations. One had a tightly fitting lid and a faucet for withdrawing water. A second zir also was equipped with a faucet but had a loosely fitting lid, permitting easy access to the water from above. A third, traditional zir, had neither a faucet nor a lid. After 2 days, water in the traditional zir and the loosely covered zir showed evidence of fecal contamination. Water in the zir with the faucet and the tightly fitting lid remained uncontaminated even after an entire month had passed.

Deb et al[32] enrolled 91 families of cholera patients in a prospective study to determine whether the spread of cholera within households could be reduced. Thirty families received "sorais," narrownecked earthenware pitchers with spouts for home water storage (Figure 1, D), 31 families received chlorine tablets for use in their traditional household water storage buckets, and 30 families served as controls (continuing to use their traditional household storage buckets). Cholera infections detected by stool culture were most common among members of control families (17.3%), less common among families using chlorine tablets (7.3%), and least common among families using the new sorais (4.4%).

In another intervention study conducted in rural Thailand, 20 households received verbal educational messages during visits by study field workers on handwashing and domestic hygiene and were loaned new plastic water storage vessels with spigots.38 Educational messages alone were given to another 20 households in the same village, and 20 households served as controls. Provision of the storage vessel appeared to reinforce the educational messages; persons in this group were more likely to put the educational messages into practice and had significantly fewer *E coli* organisms detected by fingertip rinses. Water samples drawn from the vessels with spigots were the least contaminated of all stored water samples, suggesting that water handling within the home was the major source of stored water contamination.

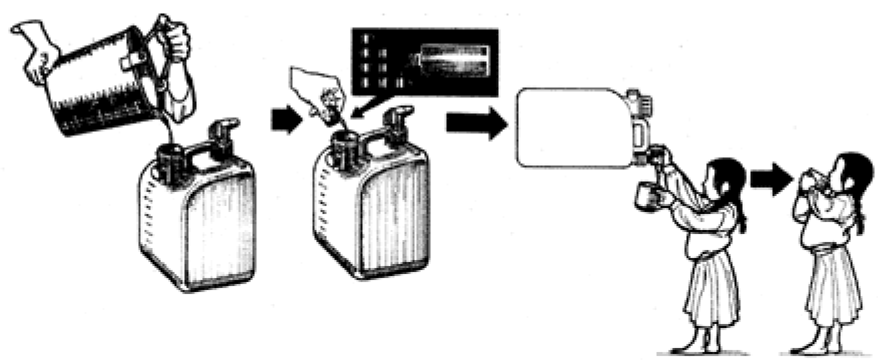
In a refugee camp in Malawi, locally produced tin water storage vessels with covers, spouts, and handles (Figure 1, E) were given to 84 families in exchange for their existing containers.[33] These families were compared with 315 families who collected and stored water in open buckets or clay pots. Although source water was free from fecal coliform bacteria, it quickly became contaminated through hand contact during rinsing or transportation. Fecal coliform counts were significantly lower in water from the new vessels compared with control vessels. During the 2 month study, children younger than 5 years in households using the new vessels experienced significantly fewer diarrheal episodes than children in control households. Despite being unsuitable for many household activities, such as washing clothes and bathing children, the intervention vessels were generally preferred over other containers.

DESIGN CRITERIA FOR WATER STORAGE VESSELS

A variety of different water storage vessel designs may protect water. To guide the design and approval of water storage vessels, the Centers for Disease Control and Prevention (CDC) and the Pan American Health Organization (PAHO) have proposed the following working design criteria.[15] For safe storage, a water storage vessel should have the following qualities:

1. Be constructed of translucent high-density polyethylene plastic or similar material that is durable, lightweight, nonoxidizing, easy to clean, inexpensive, and able to be locally produced;
2. Hold an appropriate standard volume (eg, 20 L) and have a stable base and a sturdy, comfortable handle for easy carriage;
3. Have a single opening 5 to 8 cm in diameter with a strong, tightly fitting cover that makes it easy to fill the container and add disinfectant but difficult to immerse hands or utensils;
4. Have a nonrusting, durable, cleanable spigot for extracting water;
5. Allow air to enter as water is extracted;
6. Have volume indicators and illustrations of safe water handling practices displayed on the outside of the vessel (Figure 2).

Figure 2.Illustrated directions on how to fill the water storage vessel, add the proper amount of disinfectant, and remove water for drinking can be attached to the side of the vessel.



Safe storage is eminently affordable. Water containers that meet the aforementioned criteria have been purchased by the PAHO and the CDC for prices ranging from US $4.60 to $7.25, depending on the place of manufacture and the transportation costs. A container made of highdensity polyethylene may last an average of 5 to 10 years and as long as 20 years, depending on wall thickness. This plastic is used to make milk containers in the United States and is recyclable. Safe containers also may be fabricated from other materials, such as earthenware or tin, but these may offer some disadvantages compared with high-density polyethylene in terms of durability, cost, weight, or other characteristics.

The design criteria can be met in various ways, and different designs may be appropriate for different situations. Designs for water storage vessels also can address public health concerns other than enteric illness. For example, the point-of-use disinfection and safe storage strategy may be integrated with filtration of household water that is used for Guinea worm eradication in Africa and Asia.[39] In Thailand, plastic screen covers for water storage vessels were designed to prevent the entry and breeding of Aedes aegypti, the mosquito vector of dengue fever.[40]

A NEW COMBINED INTERVENTION

The available evidence suggests that contamination of drinking water during storage in household vessels may contribute to disease transmission, and that improvements in the design of household water storage vessels coupled with pointofuse water treatment before storage can reduce this risk.

When source water quality is poor, safe water storage vessels alone cannot make water potable, but they can help to preserve water quality after treatment. A preliminary field trial of a new plastic storage container (Figure 1, F) and point-of-use disinfection was conducted in La Paz, Bolivia, in 1993.[14] Fortytwo families that relied on contaminated shallow wells for drinking water were randomly allocated to serve as controls (using traditional water storage containers generally wide-mouthed, uncovered, earthenware jars) or to receive the new water vessel with or without a 5% calcium hypochlorite disinfectant solution. During the study, fecal coliform bacteria and *E coli* were commonly detected in stored water in control households and in households using the new vessel without disinfectant. However, no fecal coliforms or E coli were detected in stored water samples from households that used both the chlorille solution and the intervention containers. The combined intervention enabled families to produce and store drinking water that met WHO standards for microbiological quality from nonpotable water sources.

Local manufacture and distribution of disinfectant solutions and water storage vessels are complementary activities that can be closely coordinated. Standard concentrations of disinfectant and standard water vessel volumes make dosing instructions simple. Inexpensive devices that measure the concentration of chlorine in water can facilitate quality control at the village level, while official endorsements by health ministries can help promote the local production, distribution, and use of safe household water storage vessels and disinfectants.

UNANSWERED QUESTIONS

Several questions need answers before this strategy can be widely recommended:

- **How much disease can be prevented?**

As with an experimental vaccine, randomized intervention trials are needed to measure the protective effect of the strategy. Disease-specific prevention will likely be greatest for diseases that are primarily waterborne (ie, cholera) and less for those that are water washed (ie, shigellosis, scabies, and impetigo) or water related (ie, malaria).[3] Surveillance for nondiarrheal diseases that are transmitted by contaminated drinking water, such as typhoid fever, hepatitis A, and dracunculiasis, should also be included in largescale intervention trials.

- **Does the impact of the disease prevented outweigh the cost of the intervention ?**

Preliminary data suggest intervention costs are low. The annual cost per family for both a special water storage vessel and the disinfectant, for the shortest estimated useful life of the vessel and the highest cost of hypochlorite, would be between US $1.17 and $1.62, an amount affordable almost anywhere in the world. A prevention effectiveness model for a Bolivian community of 10,000, in which the intervention was assumed to reduce diarrheal incidence by 20%, showed prevention of 600 cases of diarrhea, 100 hospitalizations, and five deaths during a 3 year period, at a net annual savings to society of US $184.[41] More data from field studies are needed to confirm these preliminary estimates.

- **How can the strategy be adapted to local customs and conditions?**

As with most public health prevention efforts, sustained success will require changes in human behavior. The principle of adding a standard volume of disinfectant to a standard volume of water is like the preparation of oral rehydration solutions, a widely used strategy for diarrheal disease treatment. As with oral rehydration solutions, considerable education and social marketing will be needed. Because the strategy is based on local production and consumption of a product, market forces may be used to promote its success. Local cooperatives, microindustries, and street vendor distribution networks may all have a role to play.

- **How can existing disinfectants be improved?**

Durability, ease of maintenance and repair, and cost of disinfectant generators will be critical factors in the developing world. Further studies of new disinfectant solutions are needed, particularly of combinations of mixed oxidants, to determine their effectiveness against chlorineresistant microbes, such as Giardia and Cryptosporidium. Differences in taste and smell also may be important in choosing a disinfectant.

- **How can water storage vessels be improved?**

As experience grows, further modifications will be developed to improve the effectiveness and acceptability of safe storage vessels. New designs can be field-tested using water contamination as the end point. Meeting local demands for different shapes, volumes, colors, and materials may enhance the appeal of the strategy.

- **In what other arenas can this strategy be applied?**

In the developing world, the combined strategy may be suitable for homes, schools, workplaces, markets where foods and beverages are prepared or sold, and health care facilities, including oral rehydration treatment centers. In developed countries, this intervention strategy can also be applied. For example, in Native American village homes in the Yukon Kuskokwim Delta in Alaska, water is stored in 30 gallon plastic trash barrels and drawn out by dipping.[42] Prompted by high rates of hepatitis A and diarrhea in village residents, the Indian Health Service recently , placed water tanks with covers and spigots in 14 homes and taught residents to add chlorine to each full tank. When existing water systems are temporarily disabled by natural disasters or where transient populations are housed in substandard conditions, as in many migrant worker camps, simple means to purify water could prove useful.

LOOKING TOWARD THE FUTURE

As long as households collect and store water from unsafe sources, practical point-of-use disinfection methods are the best means of enabling access to potable water. When combined with safe storage vessels, this strategy allows individuals, households, and communities to assume responsibility for purifying their own water and engenders a sense of community empowerment and self-determination. It offers a locally governable, economically viable, and environmentally sound intervention for rural and urban areas where safe water is not yet available. Water treated onsite and safely stored before use also can be put to good advantage in food preparation, dish washing, handwashing, bathing, and other activities, where it may reduce transmission of foodborne or waterwashed diseases. The changes in cultural perceptions and behaviors induced by this intervention may improve acceptability of subsequent health interventions such as latrines.

In Latin America, the cholera epidemic has entered its fourth year, having caused nearly 1 million cases and, 10,000 deaths; it is likely to continue for many years to come.[43] Elsewhere in the developing world, epidemic cholera remains unchecked; 78 countries reported cholera to the WHO in 1993, more than ever before.[44] Driven by the impetus of, epidemic cholera, sustainable measures to prevent waterborne diseases could become part of everyday life in many homes in the developing world. Further development of this simple household technology can potentially improve health and quality of life while protecting the environment.

We thank Paul Blake, MD, MPH, Anita HighsmIth, MS, Robert Quick, MD, MPH, and Leslie Roberts, PhD, MSPH, of the Centers for Disease Control and Prevention and Linda Venczel, PhD, and Vicente Witt of the Pan American Health organization for their continued inspiration and encouragement. All illustrations courtesy of Lee Oakley, Centers for Disease Control and Prevention.

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Suggested citation:

Mintz E, Reiff F, Tauxe R. Safe water treatment and storage in the home: A practical new strategy to prevent waterborne disease. JAMA 1995; 273: 948-953.