A novel technology to improve drinking water quality: a microbiological evaluation of in-home flocculation and chlorination in rural Guatemala

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ABSTRACT

An estimated 1 billion persons in low-income countries do not have access to improved drinking water. Chlorine, a useful water treatment agent, is less effective in turbid water, and lacks a visible effect, limiting its acceptability. A product incorporating precipitation, coagulation, flocculation, and chlorination technology (combined product) to reduce microbial, organic and heavy metal contaminants in water was evaluated. The combined product's microbiological efficacy in Guatemalan villagers' households was evaluated. One hundred randomly selected households from four neighboring Guatemalan villages were enrolled. Three groups received the combined product and either the Centers for Disease Control (CDC) water storage vessel, a covered bucket with spigot, or no vessel. One group received chlorine bleach and the CDC water storage vessel, and one group no intervention. Household water samples were collected for 4 weeks and *Escherichia coli*, chlorine, and turbidity levels were measured. Potable water was defined as having less than one *E. coli* per 100 ml. Eight (8%) baseline water samples were potable. Follow-up water samples were more likely to be potable than control samples (combined product and traditional vessel 83%; combined product and CDC vessel 92%; combined product and covered bucket with spigot 93%; chlorine and CDC vessel 92%; versus control 5%). Among combined product users, 98% reported improved water clarity compared with 45% of chlorine bleach users ($p<0.0001$). The combined product technology improved water potability as effectively as chlorine bleach; improved water clarity could motivate more persons to effectively treat their water.

Key words | chlorine, flocculant, Guatemala, water microbiology, water purification, water storage

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INTRODUCTION

Contaminated drinking water contributes directly to the annual 2.2 million diarrhea-related deaths (WHO 1999). In the year 2000, 1.1 billion persons remained without access to improved drinking water, and the number of persons drinking water contaminated by human sewage was much higher (United Nations 1996). Due to economic and political constraints, the universal provision of piped treated water is not currently feasible, leaving millions without access to safe drinking water (WHO 1992). Interim solutions are clearly needed. One approach has been the Centers for Disease Control (CDC) Safe Water System that combines locally produced sodium hypochlorite solution (chlorine bleach), storage in a narrow-mouth container (CDC water vessel), and a program to change behavior (Mintz *et al.* 1995). This system has been shown to improve water quality and reduce the incidence of diarrhea by 44% in Bolivia (Quick *et al.* 1999), 48% in Zambia (Quick *et al.* 2002), and 62% in Uzbekistan (Semenza *et al.* 1998).

Use of chlorine bleach to disinfect water has several limitations however: (1) chlorine resistant pathogens such as *Cryptosporidium* are unaffected (Meinhardt *et al.* 1996);

(2) dirt and other organic matter bind with chlorine, limiting its effectiveness; (3) promoting sustained daily use of chlorination is difficult, as adding chlorine bleach to contaminated water does not make the water appear any cleaner, and can lead to a worse taste and smell especially when there is a high concentration of organic molecules in the drinking water that bind with the chlorine.

Since 1995, through a Cooperative Research and Development Agreement, CDC has collaborated with the Procter & Gamble Company to develop and evaluate inexpensive, practical, safe drinking water strategies for use in developing countries (Sobel *et al.* 1998). Recognizing the limitations of chlorine bleach, an alternative household level drinking water disinfectant has been developed, referred to as the combined product. This product incorporates precipitation, coagulation, flocculation and chlorination, which are processes commonly used in water treatment plants. Precipitation pulls soluble contaminants out of solution. Coagulation and flocculation enable small suspended particles in water to aggregate into larger ones, which can then settle by gravity, and be removed by decanting and filtration. Along with the chemical compounds enabling flocculation, the combined product also contains large particles of calcium hypochlorite that provide a time-released source of free chlorine. Therefore, unlike chlorine alone, the combined product, by aggregating particles, removes organic matter, heavy metals, and large pathogens like *Cryptosporidium* from water, enabling more effective chlorination, and improvement of water clarity.

In June 2000 a laboratory-based study of the combined product using Guatemalan village source water (median 120 *Escherichia coli* colony forming units per 100 ml) was conducted. The combined product consistently produced water that met World Health Organization (WHO) bacteriological criteria for potability (less than 1 *E. coli* per 100 ml) (P. Souter, Procter & Gamble, unpublished data). The objectives of the current study were to evaluate the performance of the combined product when used in Guatemalan households, specifically to evaluate its effectiveness of chlorination and reduction of microbial contamination and turbidity compared with standard chlorination and traditional water handling practices. The acceptability of the combined product among rural Guatemalan households was also determined.

METHODS

Setting

The 4-week intervention study was conducted in November 2000 during the dry season, in four neighboring rural villages in San Juan Sacatepéquez, located in the southern Guatemalan highlands. Recent prior studies in this region have found high levels of contaminated drinking water, and high diarrheal disease rates (Steinberg & Arana 2000).

Interventions

There were four intervention groups: a group receiving chlorine bleach and a 20-litre, narrow-mouthed, water vessel with lid (CDC vessel), and three groups receiving the combined product. The combined product groups differed by the type of water storage vessel used and included those receiving the CDC vessel, those receiving a wide-mouthed bucket with spigot and lid, specially designed for combined product use to facilitate fast filtration (combined product system), and those using their own traditional vessel (Figure 1).

Chlorine bleach was bought locally and then diluted in distilled water. The solution was packaged in 250-ml opaque containers with 5-ml screw caps. Participants were instructed to put one capful into the 20-litre CDC vessel each time they filled it with water, which in distilled water would lead to a free chlorine concentration of 3 mg/l.

Procter & Gamble manufactured the combined product. Key components included ferric sulfate and calcium hypochlorite. The product was packaged in envelopes. Participants were instructed to put the contents of one envelope into 10 litres of water and stir for 30 sec, wait 5 min then repeat two more times. The treated water was then poured through a provided filter cloth (100% white cotton flannel) and stored in the designated vessel. The free chlorine concentration in distilled water treated with the combined product would be 3.6 mg/l. Participants were instructed to dispose of the precipitant and to store the combined product envelopes away from the reach of young children. Instructions for disinfectant use were

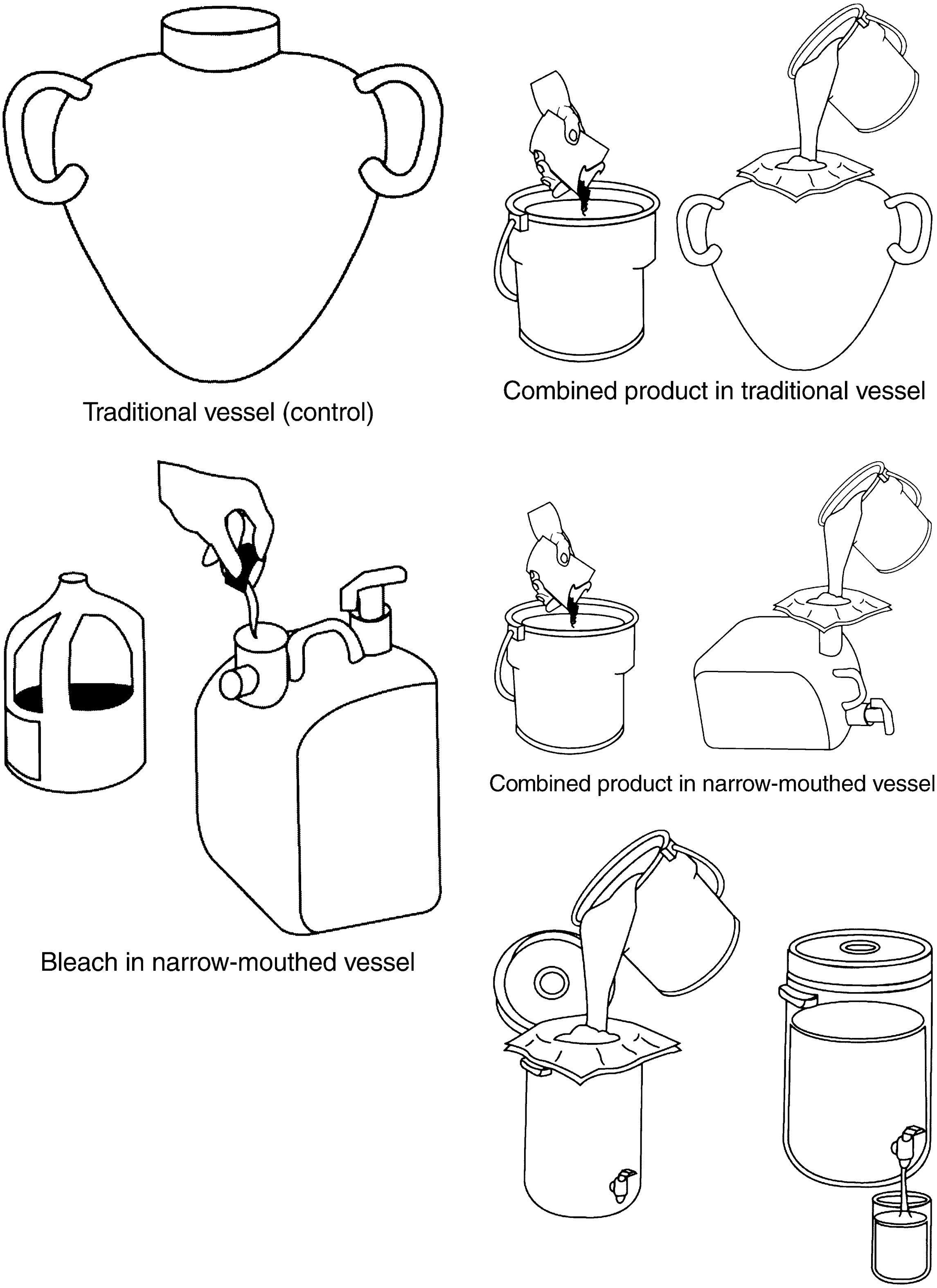

Figure 1 | Study groups to evaluate performance of the combined product.

printed on the CDC vessel and the combined product system, and each family was given a poster with instructions.

Study design

Based on recent census data, 100 households were randomly assigned to five study groups with 20 households in each group. These study groups were equally distributed within each of the four villages.

A baseline water sample was collected from each of the households, and a baseline survey was conducted of demographic characteristics, and water handling and sanitary practices of all participating families. After baseline data were collected, families in the intervention groups received group specific instructions about proper water treatment. The control group received no specific instructions on water handling practices. The vessels and disinfectants were then distributed to the intervention groups. Study personnel then accompanied each family to their home to observe and assist the first time the family treated their own water. All households were then visited weekly for 3 weeks. On each visit a water sample was collected and a questionnaire on intervention use and acceptability conducted with the female head of household when available. Study personnel counted the number of combined product envelopes on each visit, and replenished used envelopes. At the conclusion of the study, the CDC water vessel and chlorine bleach solution were distributed to all families and the combined product system and any remaining combined product envelopes were collected.

Laboratory methods

Household baseline water samples were collected from the container used for water storage in the home. During the intervention phase, three rounds of weekly water sampling were conducted during household visits. From families receiving either the CDC water vessel or the combined product system, water samples were collected directly from the vessel using the vessel's spigot. From families using traditional vessels, water samples were collected by either dipping or pouring water from the traditional storage vessel into an unsterile household cup.

All water samples were tested for chlorine, turbidity, and *E. coli*. Water samples were collected into 300 ml polypropylene containers for chlorine and turbidity determination. Free and total residual chlorine were measured using the N,N-diethyl-phenylenediamine (DPD) colorimetric method (PermaChem, Hach Company, Loveland, CO)*. Turbidity was measured by a portable meter (2100P Portable Turbidimeter, Hach Company, Loveland, CO)* and reported in nephelometric turbidity units (NTU). For bacterial assessment, 100 ml water samples were collected into Whirl-Pack™ bags*. Chlorine in the water samples was neutralized with 1% sodium thiosulfate solution. Samples were transported in a cooler to the Medical Entomology Research and Training Unit laboratory for culturing within 4 h of collection. Samples were processed with the Colilert Quantitray 2000 kit (IDEXX Laboratories, Inc., Westbrook, ME)*. Media reagent was added to the water samples and shaken until dissolved. The sample mixture was then poured into the Quantitray, sealed and incubated for 24 h. The trays were then analyzed for color change and fluorescence. A most probable number (MPN) table was used for quantification.

Statistical analysis

Select water quality measurements were used in accordance with the World Health Organization's guidelines for household chlorinated drinking water (WHO 1998): turbidity less than 5 NTU; free chlorine greater than or equal to 0.5 ppm; and no detectable *E. coli* present in any 100-ml sample. In order to calculate the geometric mean *E. coli* MPN for values less than 1, 1 was substituted. Epi Info, Version 6.04d (USD, Inc., Stone Mountain, GA) software was used for descriptive and univariate data analysis. Student's *t*-test, the chi-square test for proportions, and two-tailed Fisher's exact tests were used in the analysis as appropriate. The intervention phase mean turbidity, free chlorine, and geometric mean *E. coli* MPN

*Inclusion of trade names is for identification only and does not imply endorsement by CDC or the Department of Health and Human Services.

results were calculated first for each of the households and then the mean result for each of the groups was calculated. These means were then compared to the traditional practice group using the Student's *t*-test.

Ethics

Informed consent was obtained from each of the households prior to enrollment in the study. The study was reviewed and approved by an Institutional Review Board at CDC and the Ethics Committee Review Board of the Universidad del Valle de Guatemala.

RESULTS

Baseline survey

One hundred households were enrolled into the study including 618 people (median family size 6 persons; range 1–10); 317 (51%) were male. The median age of persons in this sample was 18 years (range 1 month to 87 years). The median age of the baseline survey respondents was 35 years (range 16–69); 94 (94%) were female. Eighteen (18%) of the female heads of household knew how to read and write, and 79 (80%) spoke predominantly in an indigenous language to their children (Cakchiquel). The median number of rooms per house was 2 (range 1–6), and the median number of persons per room was 3 (range 0.5–10). Eighty-one (81%) of the households had electricity, and 71 (76%) had latrines, but 75 (75%) reported that some household members defecate outside of the latrines near the house.

The main water sources for the 100 households included springs (61%), wells (34%), bottled water (2%), truck (1%), river (1%), and a faucet (1%). All respondents stored water for drinking in their homes. Ninety-eight percent used a wide-mouth (greater than 10 cm diameter) storage vessel; to retrieve water, 95% regularly dipped an object into the stored water. The median reported amount of drinking water used daily per household was 7 litres (range 1–20 litres).

Eighty percent of respondents thought their drinking water was clean, however 52% thought their drinking water could, at times, make a family member ill. Thirty-one percent said they boiled their drinking water, and 8 (8%) stated they almost always boiled their drinking water. Thirteen percent said they had used chlorine as a water disinfectant, and 2 (2%) stated they used it regularly.

Water quality

The baseline water results did not differ significantly among the five study groups. At baseline, 58% of the 100 stored household water samples met WHO turbidity standards and the mean was 7.7 NTU (Table 1). During the intervention phase, there was a tendency toward lower turbidity levels among the combined product groups (4.3 to 4.6 NTU), compared with the chlorine bleach (6.3 NTU) and traditional practice groups (7.6 NTU) (Table 2). These differences however, were not statistically significant.

None of the baseline water samples had adequate chlorination levels (Table 1). During the intervention phase, the mean free chlorine levels for all intervention groups were greater than 0.5 ppm and this differed significantly from the traditional practice group (Table 2). Fifty (83%) of the chlorine and CDC vessel samples had adequate chlorine levels, compared to 44 (73%) of combined product and traditional vessel samples and 56 (93%) of combined product system samples.

Only 8 (8%) of the baseline water samples met bacteriological standards (Table 1). During the intervention phase, the geometric mean *E. coli* MPN for all intervention groups ranged from 1 to 418 per 100 ml, and differed significantly from the traditional practice group MPN of 938 per 100 ml. Fifty-five (92%) of treated household water samples from the chlorine and CDC vessel group met bacteriological standards. Similar proportions were noted among the combined product groups, from 50 (83%) in combined product and traditional vessel samples to 55 (93%) in the combined product system samples (Table 2).

Table 1 | Baseline (pre-intervention) turbidity, free chlorine, and most probable number *Escherichia coli* from household water storage vessels, San Juan Sacatepéquez, Guatemala, November, 2000

		Turbidity		Free chlorine		*E. coli*	
Study group	**N**	**Mean NTU**	**<5 NTU (%)**	**Mean ppm**	**≥0.5 ppm (%)**	**Mean MPN**	**<1/100 ml (%)**
Traditional practice	20	8.2	13 (65)	0	0 (0)	510	2 (10)
Chlorine and CDC vessel	20	11.3	8 (40)	0	0 (0)	324	2 (10)
Combined product and traditional vessel	20	6.2	12 (60)	0	0 (0)	753	2 (10)
Combined product and CDC vessel	20	5.3	11 (55)	0	0 (0)	2,553	1 (5)
Combined product system	20	7.3	14 (70)	0	0 (0)	1,435	1 (5)
Total	100	7.7	58 (58)	0	0 (0)	1,115	8 (8)
p value		0.72	0.36	0.15	1.0	0.62	0.94

Table 2 | Intervention phase turbidity, free chlorine, and most probable number *Escherichia coli* from household water storage vessels, San Juan Sacatepéquez, Guatemala, November, 2000

		Turbidity (NTU)			Free chlorine (ppm)			*E. coli* (MPN)		
Study group	**N**	**Mean***	***p* value**	**<5 (%)**	**Mean***	***p* value**	**≥0.5 (%)**	**Mean***	***p* value**	**<1/100 ml (%)**
Traditional practice	60	7.6	Ref	36 (60)	0.0	Ref	0	938	Ref	3 (5)
Chlorine and CDC vessel	60	6.3	NS	36 (60)	1.6	<0.001	50 (83)	6	<0.001	55 (92)
Combined product and traditional vessel	60	4.6	NS	41 (68)	1.5	<0.001	44 (73)	418	<0.001	50 (83)
Combined product and CDC vessel	60	4.3	NS	44 (73)	1.4	<0.001	49 (82)	1	<0.001	55 (92)
Combined product system	59	4.4	NS	42 (71)	2.3	<0.001	55 (93)	1	<0.001	55 (93)

*The mean value for each of the households (three visits) was first calculated, then the mean for each group.
NS=not significant.

Intervention survey

Among households randomized to an intervention group, 80 (100%) reported using their intervention at least once, and 64 (80%) reported always using their intervention for treating their drinking water. The reported frequency of intervention use did not differ among the chlorine or combined product intervention groups.

When asked weekly how the treated water compared to standard drinking water, combined product users reported improved clarity 92% (165/179) of the time, compared with 51% (30/59) of the time for chlorine bleach users ($p<0.001$). Among all intervention users, only 7% (16/237) of the time was worse smell reported, and only 3% of the time (7/238) was worse taste, and these results did not differ between the chlorine and combined product intervention groups. No accidental ingestions of the combined product or chlorine bleach were reported.

DISCUSSION

This study showed that the combined product, when used by families with highly contaminated drinking water in a variety of vessels, effectively chlorinated water and reduced bacterial contaminants to the same degree as chlorine bleach. The combined product was well accepted and improved the clarity of the water.

The lack of a significant difference in turbidity levels between combined product users and chlorine bleach users may be due to the study being conducted during the dry season, when source water tends to be less turbid as evidenced by the low turbidity of the baseline samples. The lack of turbid samples made it difficult to measure the combined product's capacity to reduce turbidity.

The combined product adequately chlorinated household water samples and reduced *E. coli* counts as well as chlorine bleach, confirming its ability to serve as an effective water disinfectant. The higher levels of *E. coli* in treated water samples among users of the combined product and the traditional vessel compared with other combined product users, was probably due to the use of unsterile household cups to collect water samples. Further studies conducted in areas of high source water turbidity are warranted to determine if the combined product could out-perform chlorine bleach by significantly lowering turbidity which could allow for more effective chlorination.

The majority of combined product users reported the water appearing clearer after treatment, despite no considerable reduction in turbidity. The process of precipitation, coagulation, flocculation and filtration may be a powerful visual cue that could foster sustained behavioral change and lead to long-term use of the combined product water disinfectant. This finding is particularly significant as there has been quite limited success in promoting sustained use of chlorine bleach alone as a household water disinfectant (Olsen & Quick 1999). Although most participants used the combined product throughout the 3-week intervention study, further studies to assess acceptability are warranted, optimally when the materials are not provided for free.

The results of the combined product in effectively disinfecting household drinking water are promising, but larger, longer-term studies will be needed to assess its impact on health. Also, field studies to determine the combined product's ability to reduce *Cryptosporidium* and heavy metal contaminants, such as lead and arsenic, are warranted.

CONCLUSIONS

Childhood mortality from diarrheal disease in Latin America remains high (PAHO 2002). In settings where residents typically drink water contaminated with human feces, empowering individual families to disinfect their household drinking water could prevent excess morbidity and mortality from waterborne diseases. The combined product appears not only to offer an alternative method for disinfecting drinking water, but it has private sector backing. The private sector will continue to modify the combined product to respond to the needs of the users and, through advertising, will likely promote behavior change, which could lead to increased uptake and sustained use of the combined product. The combined product, once available commercially, may be cost-prohibitive to some of the world's poorest persons. However, for those who could afford it, the combined product's novel product design and promotion of use, could lead to improved global access to safe drinking water.

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