Use, Acceptability, Performance, and Health Impact of Hollow Fiber Ultrafilters for Water Treatment in Rural Kenyan Households, 2009–2011

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Abstract. Diarrheal illness remains a leading cause of morbidity and mortality in children < 5 years in developing countries, and contaminated water contributes to diarrhea risk. To address this problem, a novel hollow fiber ultrafilter (HFU) was developed for household water treatment. To test its impact on water quality and infant health, we conducted a cluster-randomized longitudinal evaluation in 10 intervention and 10 comparison villages in Kenya, attempting to enroll all households with infants (< 12 months old). We conducted a baseline survey, distributed HFUs to intervention households, made biweekly home visits for 1 year to assess water treatment practices and diarrhea in infants, and tested water samples from both groups every 2 months for *Escherichia coli*. We enrolled 92 infants from intervention households and 74 from comparison households. During the 1-year study period, 45.7% of intervention households and 97.3% of comparison households had at least one stored water sample test positive for *E. coli*. Compared with comparison households, the odds of *E. coli* contamination in stored water was lower for intervention households (odds ratio [OR]: 0.42, 95% CI: 0.24, 0.74), but there was no difference in the odds of reported diarrhea in infants, adjusting for covariates (OR: 1.19, 95% CI: 0.74, 1.90). Although nearly all water samples obtained from unprotected sources and filtered by the HFU were free of *E. coli* contamination, HFUs alone were not effective at reducing diarrhea in infants.

INTRODUCTION

Diarrheal illness remains a leading cause of morbidity and mortality in children < 5 years in developing countries.¹ Contaminated drinking water, inadequate sanitation, and poor hygiene are important contributors to this burden of disease.² Whereas an estimated 785 million people use limited water services, unimproved water, or surface sources, approximately 1.8 billion people use unsafe water.^{3,4}

Sustainable Development Goal 6 (SDG6) calls for universal access to consistent, piped, treated water supplies in every household in low-income countries.⁵ However, achievement of SDG6 remains challenging in many countries because of cost, population growth and movement, technical challenges, and climate change.^{6,7} As a result, alternative interventions are needed to protect the health of populations lacking consistent access to safe drinking water in the interim.

A number of field trials have provided evidence that simple, low-cost interventions at the household and community level are capable of improving the quality of stored drinking water⁸ and reducing the risk of diarrheal disease.⁹ Despite evidence that these interventions can improve health, household water treatment uptake remains modest in low-income countries,¹⁰ and sustained use of these interventions has been challenging.¹¹ One novel technology developed to combat this issue is a hollow fiber ultrafilter (HFU) (Lifestraw Family 1.0 filter, Vestergaard.com), consisting of a 2.5-L plastic bucket, tubing, a 30-cm filter cartridge, a plastic spigot for dispensing disinfected water, and a bulb with second spigot for backwashing the filter (Figure 1). In laboratory studies, an HFU has been shown to be > 99.9% effective in removing bacteria, viruses, and protozoa from water.¹² Through gravity-fed ultrafiltration,

water is forced through a tube into the purification cartridge, which contains millions of capillary membranes with a 20-nm pore size that remove contaminants. Although this technology has undergone laboratory¹² and field-testing,^{12,13} the performance of the HFU in improving household water quality and its health impact in low-income countries has yet to be fully evaluated. In September 2009, we initiated a longitudinal randomized controlled trial testing the use, acceptability, performance, and health impact of these HFUs in a rural district of western Kenya.

METHODS

Study design. The trial included a baseline survey; 25 bi-weekly home visits (once every 2 weeks) to assess filter use and diarrheal episodes; testing of source, filtered, and stored water samples for *Escherichia coli* contamination every 2 months; and a qualitative assessment of filter acceptability.

Study population. We conducted the trial in Nyando district in Nyanza Province, Kenya, a largely rural area with a population of roughly 300,000 people, located 30 km east of Kisumu, the provincial capital. In 2009, Nyanza Province had the highest mortality rate for children < 5 years in Kenya with 149 deaths per 1,000 live births; 16% of children < 5 years were reported to have had diarrhea in the preceding 2 weeks.¹⁴

For this trial, we randomly selected 20 of 60 villages enrolled in the Nyando Integrated Child Health and Education Project.¹⁵ All households in selected villages with infants (< 12 months old) were eligible to enroll in the study. If households had more than one infant, enumerators randomly selected one infant in the household to participate in the study.

Baseline data collection. In September 2009, a baseline survey was conducted at all enrolled households to examine demographic and socioeconomic characteristics and water, sanitation, and hygiene practices. During the survey, fieldworkers also tested household-stored water for the presence of free chlorine residual (FCR), using the N, N-diethyl-p-

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FIGURE 1. LifeStraw Family filter. This figure appears in color at www.ajtmh.org.

phenylenediamine colorimetric method (LaMotte Co., Chestertown, MD).

Implementation of intervention. We randomly allocated villages into intervention and comparison groups, with 10 villages per group. In March 2010, study participants from households in intervention villages attended a community meeting where they received an HFU and instructions on proper use and cleaning of the filter. Participants were encouraged to hang the filter in a location where it would be inaccessible to small children but easily accessible to other members of the household. Comparison villages continued to use their usual practices for collecting, disinfecting, and storing drinking water.

Home visits. Following the distribution of HFUs, field-workers returned to the villages at 2-week intervals from April 2010 through March 2011 to ask participants about water sources, water treatment methods, filter use, and occurrence of diarrhea (defined as ≥ 3 loose stools in a 24-hour period) in the child during the previous 48 hours and to test stored drinking water for residual chlorine. Every 2 months, field-workers supplemented biweekly data collection with additional information about reported HFU use or nonuse. We collected 100 mL source water samples in Whirl-Pak™ bags (Whirl-Pak, Madison, WI), which were stored on ice and transported to the laboratory within 4–6 hours of collection for *E. coli* quantification. We asked heads of intervention households to pour source water into the filter (influent water), from which we obtained 100 mL effluent samples, as well as stored drinking water, if available, in Whirl-Pak bags and processed them in the same fashion as source water. We tested all water

samples from both groups of households for *E. coli* contamination using the Colilert®/Quanti-Tray/2000 method to determine the most probable number (MPN) *E. coli* per 100 mL of water (IDEXX Laboratories, Inc., Westbrook, ME). If an HFU broke over the course of the study, participants informed field-workers by phone or in person, and field-workers replaced it with a new HFU within 2 days to minimize the time without filter coverage.

Data collection and analysis. Survey data were collected by field-workers using personal digital assistants, uploaded into Microsoft Access databases, and analyzed using SAS version 9.4 (Cary, NC). Households with high rates of missing biweekly responses ($> 20\%$) were excluded from analyses. To test whether the intervention and comparison groups were different by selected characteristics, we used the chi-square or Fisher's exact test (as appropriate) for categorical variables and Wilcoxon's rank sum test for continuous variables. Reported household assets were used to calculate wealth index quartiles as a proxy measure of socioeconomic status (SES) through principal component analysis.¹⁶ We used WHO definitions to categorize water sources as unimproved or improved.¹⁷ Improved sources included household connections, public standpipes, boreholes, protected hand-dug wells and springs, and rainwater catchment.

Multivariable logistic regression was used to assess the association between diarrhea and the treatment group (intervention versus comparison). We created biweekly binary variables for diarrhea, with a value of 1 applied to infants with one or more diarrhea episodes reported during the biweekly home visits and a value of 0 applied to infants with no reported diarrheal episodes. Similarly, we applied a value of 1 for *E. coli* contamination (≥ 1 MPN/100 mL) in water samples obtained on a bimonthly basis and 0 for no detection (< 1 MPN/100 mL) and treated it as a binary outcome variable in the analysis to assess association between *E. coli* contamination and HFU use. In each analysis, the treatment group was the main exposure variable. In both analyses, we controlled for the respondent's age (in years), whether the mother had completed primary school, the type of water source (improved versus unimproved), and FCR (presence [defined as ≥ 0.1 mg/L] versus absence) in drinking water over the study period.

Potential correlations between repeated outcome measurements per household over the study period and between households within the same community were considered using the generalized estimating equation approach with a compound symmetry correlation structure in three-level hierarchical modeling. We also conducted a sensitivity analysis of the models including all households that had at least one biweekly home visit.

Qualitative assessment. To better understand factors that may influence an individual's decision to use the HFU, a qualitative assessment was also conducted during the field trial. A discussion guide was developed using modified precepts of the grounded theory. Villages were selected based on the timeline of when they had last been seen by the enumeration teams, and target respondents were women who participated in the trial. In-depth interviews and focus group discussions (FGDs) were conducted in January 2011. Qualitative data were collected through digital recordings of discussions. Transcripts of FGDs and key informant interviews were analyzed using ATLAS.ti software (atlasti.com, Berlin, Germany). Data were coded using open-ended, axial, and selective coding for dominant themes and concepts.

Ethical considerations. The protocol was approved by Institutional Review Boards at the Kenya Medical Research Institute (protocol 1176) and the CDC (protocol 5039). We obtained written informed consent from all participants for both quantitative and qualitative data collection.

RESULTS

Baseline survey. We enrolled 224 households—119 households in the intervention group and 105 households in the comparison group. Of these, 27 (22.7%) households in the intervention group and 31 (29.5%) in the comparison group were excluded from analyses because of a high percentage of missing biweekly responses. Demographic characteristics between the included and the excluded households did not differ (data not shown). We also conducted a sensitivity analysis comparing results from all households (included and excluded) to included households only, and the findings did not change appreciably.

At baseline, the median respondent age was 26 years (range, 16–68 years) and 64.5% of mothers had completed primary school (Table 1). There were no differences in age, education level of mothers, or household SES characteristics between intervention and comparison groups.

Of 165 respondents, 73 (44.2%) reported using surface water as their primary source of drinking water at baseline, 75 (45.2%) reported using an improved source, including 45 (27.3%) reporting rainwater, and 17 (10.3%) reporting a covered well (Table 2). All households reported storing their drinking water; 86.5% of households reported storing drinking water in clay pots, and 95.7% of households in both groups covered their storage containers with a lid. Approximately 90% of households responded that they did something to their water to make it safe for drinking. At baseline, 96% of respondents reported treating water with WaterGuard, a locally available, point-of-use chlorination product. There was no difference in the percentage of stored water samples that tested positive for residual chlorine in intervention and comparison households (15.9% versus 8.3%, $P = 0.15$).

Home visits. A total of 2,196 biweekly visits were completed in 92 intervention households, and 1,761 biweekly visits were completed in 74 comparison households. In both intervention and comparison households included in the analysis, a median of 24 visits per household were completed (range, 20–25 visits).

During 3,952 total biweekly home visits, the use of an improved water source was reported in 2,096 (53%) visits (50.5% intervention and 56.2% comparison) (Table 3). Drinking water treatment was reported on the day of home visits

during 24.6% of intervention group visits and 9.4% of comparison group visits. Caregivers in intervention households reported that water consumed by their infant was most commonly treated that week with an HFU (81.0%), WaterGuard (41.5%), or was left untreated (23.4%). Caregivers in comparison households reported that water consumed by their infant was most commonly treated that week with WaterGuard (58.5%), boiled (7.8%), or was left untreated (37.2%). Less than 10% of both intervention and comparison households reported giving their infant drinking water that had been boiled or treated with PUR, a flocculent/disinfectant product intended to treat drinking water. Stored water samples from households were tested positive for FCR in 4.9% of visits to intervention households versus 5.8% of visits to comparison households.

Hollow fiber ultrafilter use. Enumerators observed that the HFU appeared to be hanging in a position that would facilitate use at 2,068 (94.6%) of 2,178 home visits. A visibly wet filter was observed at 985 (45.5%) household visits. Observed filter use increased from home visit rounds 3 through 19, but then decreased to much lower levels from round 20 through 25 (Figure 2).

During 1,258 home visits in which respondents reported not using the HFU since the previous visit, the reasons for nonuse included water flow too slow (74%), filtration takes too long (63%), inflow reservoir too small (61%), other methods can treat larger volumes of water (58%), another method is safer (35%), and children cannot use it when caregivers are away (33%).

Microbiologic performance. Among bimonthly water samples in intervention households, the median *E. coli* concentration for source (influent) water ranged from 53 to 283 MPN/100 mL and the percentage of samples with undetectable *E. coli* ranged from 6.9% to 13.5% (Table 4). For effluent water samples, the median *E. coli* concentration was < 1 MPN/100 mL in all surveillance rounds and the percentage of samples with undetectable *E. coli* ranged from 92.9% to 95.5%. For stored water samples, the median *E. coli* concentration ranged from < 1 to 6 MPN/100 mL and the percentage with < 1 MPN/100 mL ranged from 30.0% to 55.0%. For comparison households, median *E. coli* levels ranged from 19 to 1,986 MPN/100 mL for source water samples and 8 to 32 MPN/100 mL for stored water samples.

After adjusting for covariates in multivariable analysis, the odds of *E. coli* contamination in stored water was lower for intervention than comparison households (OR: 0.42, 95% CI: 0.24, 0.74) (Table 5) and for households using an improved water source than for those using an unimproved water source (OR: 0.37, 95% CI: 0.23, 0.59). For households with stored drinking water that tested positive for FCR, the odds of *E. coli*

TABLE 1

Baseline demographic and socioeconomic characteristics of intervention and control households, hollow fiber ultrafilter evaluation, Kenya, September 2009

	Total, N = 166	Intervention, N = 92	Comparison, N = 74	P-value
Age (years), median (range)	26 (16–68)	27 (16–68)	26 (16–43)	0.59
Mother's education (n, %)				0.92
≥ Primary school	107 (64.5)	59 (64.1)	48 (64.9)	
Socioeconomic quartiles (n, %)				0.46
First quartile (poorest)	48 (28.7)	22 (23.9)	26 (35.1)	–
Second quartile	36 (21.6)	22 (23.9)	14 (18.9)	–
Third quartile	41 (24.6)	24 (26.1)	17 (23.0)	–
Fourth quartile (wealthiest)	41 (24.6)	24 (26.1)	17 (23.0)	–

TABLE 2

Distribution of main water source, drinking water storage, treatment, and chlorination in stored water at baseline, hollow fiber ultrafilter evaluation, Kenya, September 2009

	Total,* N = 165 (%)	Intervention,* N = 92 (%)	Comparison,* N = 73 (%)	P-value
Main water source (n, %)				0.42
Unimproved				
Surface water	73 (44.2)	36 (39.1)	37 (50.7)	
Open well	17 (10.3)	11 (12.0)	6 (8.2)	
Improved				
Borehole	10 (6.1)	8 (8.7)	2 (2.7)	
Rainwater	45 (27.3)	24 (26.1)	21 (28.8)	
Covered well	17 (10.3)	11 (12.0)	6 (8.2)	
Piped water	3 (1.8)	2 (2.2)	1 (1.4)	
Water storage (n, %)				0.43
Clay pot	141/163 (86.5)	77/91 (84.6)	64/72 (88.9)	
Other storage container	22 (13.5)	14/91 (15.4)	8/72 (11.1)	
Water treatment (n, %)				0.57
WaterGuard	149 (90.3)	82 (89.1)	67/73 (91.8)	
Boiling	1 (0.7)	0 (0)	1 (1.5)	1.00
PUR	5 (3.4)	3 (3.7)	2 (3.0)	0.45
Filtering	9 (6.0)	5 (6.1)	4 (6.0)	1.00
Observed chlorination in stored water	20/160 (12.5)	14/88 (15.9)	6/72 (8.3)	0.15
Observed lid	156/163 (95.7)	85/91 (93.4)	71/72 (98.6)	0.10

* Discrepancies from total N are due to missing values.

contamination was lower than for households with no detectable FCR (OR: 0.34, 95% CI: 0.13, 0.93).

Diarrhea prevalence. Among intervention households, 43 (46.7%) infants aged < 12 months were reported to have ≥ 1 diarrheal episode over the duration of the study; 36 (48.7%) infants living in comparison households had ≥ 1 diarrheal episode. After adjusting for other covariables, there was no difference in the odds of reported diarrhea between infants in intervention and comparison households (OR: 1.19, 95% CI: 0.74, 1.90) (Table 6). The odds of diarrhea was lower in infants of mothers with at least a primary school education than in infants of mothers with less education (OR: 0.60, 95% CI: 0.38, 0.95). There were no differences in the odds of infants having reported diarrhea between households with and without an improved water source, or with or without confirmed FCR in their stored water. Sensitivity analyses that included all households, regardless of the number of biweekly home visits, did not appreciably change *E. coli* and diarrhea results (data not shown).

Qualitative assessment of perceptions of HFU. A total of four FGD (median: four participants) and seven key informant

interviews were conducted. Data were collected over a 2-week period, and coding revealed redundancy of themes identified by participants, which signified theoretical saturation, indicating that a sufficient number of interviews were conducted.

A majority of discussants were able to provide accurate understanding of proper HFU use; nearly all indicated that they felt it was simple to use. Participants commonly reported that the filter's water was used exclusively for their child. Water was primarily reported as being for drinking purposes only, although several respondents indicated that they used the filtered water for cooking and washing utensils. Water treated by HFUs was perceived as being comparable with chemical treatment products in terms of safety but was also described as being safe "*even for a young baby*," implying that it did not upset an infant's stomach like other treated water might.

Although many respondents indicated that they appreciated the HFU's ability to produce immediately potable water, nearly all were unsatisfied with the amount of time required to filter water with the HFU. The flow of water from the tap was described as "slow," with several respondents questioning

TABLE 3

Results of home visits for reported household water source, treatment method, child water consumption, and presence of chlorine in stored water over 25 biweekly visits, by treatment group, hollow fiber ultrafilter evaluation, Kenya, April 2010–March 2011

	Total,* n (%)	Intervention,* n (%)	Comparison,* n (%)	P-value†
Water source				< 0.001
Improved	2096/3,952 (53.0)	1,108/2,193 (50.5)	988/1,759 (56.2)	
Unimproved	1856/3,952 (47.0)	1,085/2,193 (49.5)	771/1,759 (43.8)	
Treated drinking water	706/3,952 (17.9)	540/2,193 (24.6)	166/1,759 (9.4)	< 0.001
Drinking water treatment for infants	3,926/3,948 (99.4)	2,178/2,192 (99.4)	1,748/1,756 (99.5)	0.44
Hollow fiber ultrafilter	1768 (45.0)	1765 (81.0)	3 (0.2)	< 0.001
WaterGuard	1851 (47.2)	768 (41.5)	1,083 (58.5)	< 0.001
Boiling	156 (4.0)	20 (0.9)	136 (7.8)	< 0.001
PUR	12 (0.3)	7 (0.3)	5 (0.3)	0.84
Untreated	848 (21.6)	198 (23.4)	650 (37.2)	< 0.001
Chlorine present in stored water				0.33
Positive (≥ 0.1 mg/mL)	201/3,795 (5.3)	103/2,100 (4.9)	98/1,695 (5.8)	
Negative	3,593/3,795 (94.7)	1,996/2,100 (95.1)	1,597/1,695 (94.2)	

* Discrepancies from total N are due to missing values.

† Crude analysis using the chi-square or Fisher's exact test as appropriate.

A majority of respondents hung their HFU filters in their homes. Once they were hung, these filters were rather difficult to reach unless a piece of furniture was situated directly below them. One mother demonstrated how she stretched to reach the filter while carrying her child; another mother who had recently delivered a child indicated that she was unable to use hers while pregnant because of the strain of reaching. Lower hanging HFUs were reported to be used more regularly because they were more accessible.

DISCUSSION

A number of barriers to the effective use of HFUs still persist that could have contributed to the lack of health impact among intervention households. First, HFUs do not provide residual protection for stored water. In the intervention group, the median *E. coli* MPN was greater in water from storage containers than from filter outflow. This is consistent with several other studies, which found that improperly stored drinking water can become increasingly contaminated over time.^{8,20} Because HFUs do not provide residual protection in drinking water, it is possible that stored water was exposed to *E. coli* and other pathogens through contaminated storage vessels or hands touching stored water.^{20,21} Whereas WaterGuard and other chlorination products that provide residual protection for ≥ 24 hours have been promoted as an effective method for treating drinking water in Kenya for years, studies

TABLE 4

Comparison: *E. coli*

IQR = interquartile range; *E. coli* = *Escherichia coli*; MPN = most probable number.

* Reduction of *E. coli* from influent water to the sampled stored water.

† Reduction of *E. coli* from source water to the sampled stored water.

TABLE 5

Adjusted odds ratio of *E. coli* contamination for the intervention and comparison group in stored water, adjusting for demographic factors and chlorination, hollow fiber ultrafilter evaluation, Kenya, March 2010–April 2011

	aOR (95% CI)	P-value
Treatment group		
Intervention (hollow fiber ultrafilter)	0.42 (0.24, 0.74)	0.002
Comparison (customary treatment)	Referent	
Respondent age (years)	1.00 (0.97, 1.03)	0.92
Education		
≥ Primary school	1.05 (0.63, 1.73)	0.86
< Primary school	Referent	
Water source		
Improved	0.37 (0.23, 0.59)	< 0.001
Unimproved	Referent	
Observed chlorination in stored drinking water		
Positive	0.34 (0.13, 0.93)	0.03
Negative	Referent	

aOR = adjusted odds ratio; *E. coli* = *Escherichia coli*.

have observed low uptake of sodium hypochlorite as a point-of-use water treatment option,^{22–25} consistent with findings in this study.

Second, untreated water may not have been the only transmission pathway for enteric pathogens in this population of young children. There are several environmental factors that cause diarrhea in children, including inadequate sanitation or hygiene practices, consumption of contaminated food, handling of animals, and other environmental factors.^{26,27}

Third, intervention households may not have exclusively given filtered drinking water to their young children. To effectively reduce disease risk, consistent access to treated drinking water is required.^{28,29} During biweekly visits, less than 25% of intervention households reported treating their drinking water on the day of the home visit. Focus group discussions revealed that slow filter flow was consistently and repeatedly cited as a major obstacle to regular filter use. Focus group discussion results also indicated that small HFU reservoir size and the need to hang the filter made water treatment less convenient and more complicated.

The Lifestraw Family 2.0, also developed by Vestergaard, uses a modified tabletop filter design with a 7-L water storage

reservoir in an attempt to address some of the barriers to the use of the Lifestraw Family 1.0 filter. A recent study in Rwanda found higher usage with the Lifestraw Family 2.0 than Lifestraw Family 1.0 that we used in this study.³⁰ These findings highlight that convenience and ease of use are important factors contributing to the consistent use of water treatment technologies. However, a review by the WHO found that Lifestraw Family 1.0 might be slightly more effective at removing bacteria, protozoa, and viruses than Lifestraw Family 2.0.³¹ Future studies should further examine whether the actual use of each of the two Lifestraw Family filters, which are both currently being marketed (Vestergaard.com), reduces water contamination.

This study had several important limitations. First, because only one district was included in the study, the results were not necessarily representative of western Kenya. Second, it is possible that courtesy bias may have resulted in overreporting HFU use or underreporting diarrhea. Third, because data on reported diarrhea were collected biweekly and water quality was tested bimonthly, we could not examine temporally associated water quality and reported illness data. Fourth, repeated home visits may have resulted in a Hawthorne effect in which water treatment behavior may have increased among participants who knew that behavior was being observed. Finally, diarrheal illness was not confirmed in the infants, which would have been a more reliable outcome measure than reported disease^{32,33} but was beyond the scope of the project budget.

In conclusion, bimonthly water testing suggested that HFUs improved microbiologic water quality over this year-long study, but their use did not appear to reduce diarrhea in infants. Responses from study participants suggested that improvements to the HFU design, including improved flow rate, increased reservoir size, and more convenient installation in the home could make the HFUs more desirable, and perhaps lead to increased use. In fact, recent improvements to the HFU, including a tabletop design with a larger reservoir, have resulted in higher levels of use in one evaluation,³⁰ although questions about performance of the new design remain. Further study is necessary to assess filter efficacy, acceptability, and health impact.

Received November 20, 2019. Accepted for publication March 4, 2020.

Published online April 6, 2020.

Acknowledgments: We are grateful to the Safe Water and AIDS Project of Kisumu, Kenya, for providing excellent field support. We thank the participating households for their good-natured participation in this field trial.

Financial support: This work was supported by a grant from Vestergaard and the U.S. Agency for International Development.

Disclaimer: The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the Centers for Disease Control and Prevention.

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TABLE 6

Adjusted odds ratio (aOR) of reported diarrhea in children ≤ 12 months for the intervention and comparison group, adjusting for demographic factors and chlorination, hollow fiber ultrafilter evaluation, Kenya, March 2010–April 2011

	aOR (95% CI)	P-value
Treatment group		
Intervention	1.19 (0.74, 1.90)	0.48
Comparison	Referent	
Respondent age (years)	0.98 (0.94, 1.01)	0.14
Education		
≥ Primary school	0.60 (0.38, 0.95)	0.03
< Primary school	Referent	
Water source		
Improved	1.15 (0.78, 1.71)	0.49
Unimproved	Referent	
Observed chlorination in stored drinking water		
Positive	0.93 (0.42, 2.07)	0.86
Negative	Referent	

aOR = adjusted odds ratio.

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