Am. J. Trop. Med. Hyg., 105(1), 2021, pp. 261–266
doi:10.4269/ajtmh.20-1516

Fecal Contamination on the Household Compound and in Water Sources are Associated with Subsequent Diarrhea in Young Children in Urban Bangladesh (CHoBI7 Program)

Tahmina Parvin,[1] Elizabeth D. Thomas,[2] Md. Sazzadul Islam Bhuyian,[1] Ismat Minhaj Uddin,[1] Md. Tasdik Hasan,[3] Zillur Rahman,[1] Indrajeet Barman,[1] Fatema Zohura,[1] Jahed Masud,[1] Marzia Sultana,[1] Anne Westin,[2] Fatema-Tuz Johura,[1] Shirajum Monira,[1] Shwapon Kumar Biswas,[1,4] David A. Sack,[2] Jamie Perin,[2] Munirul Alam,[1] and Christine Marie George[2]*

[1]*International Centre for Diarrhoeal Disease Research, Bangladesh (icddr,b), Dhaka, Bangladesh;* [2]*Department of International Health, Johns Hopkins Bloomberg School of Public Health, Baltimore, Maryland;* [3]*University of Liverpool, Liverpool, United Kingdom;* [4]*Ministry of Health & Family Welfare, Dhaka, Bangladesh*

Abstract. We investigated the environmental and individual-level risk factors for diarrheal disease among young children in slum areas of Dhaka, Bangladesh. A prospective cohort study was conducted among 884 children under 5 years of age. Caregiver reports were collected on sociodemographic factors and hygiene behaviors. Diarrhea surveillance data was collected monthly based on caregiver-reported diarrhea for children in the past 2 weeks during the 12-month study period. Unannounced spot checks of the household compound were performed at 1, 3, 6, 9, and 12 months after enrollment to check for the presence of feces (animal or human) and the presence of animals in the child's sleeping space, to assess child and caregiver hands for the presence of dirt, and to collect samples of the household's source and stored drinking water. Children with feces found on the household compound during spot checks had a significantly higher odds of diarrhea (odds ratio: 1.71; 95% confidence interval: 1.23–2.38). Children residing in households with > 100 colony forming units/100 mL *Escherichia coli* in source drinking water had a significantly higher odds of diarrhea (OR: 1.43; 95% CI: 1.06–1.92). The presence of feces on the household compound and source drinking water with > 100 colony forming units/100 mL *E. coli* were significant risk factors for diarrheal disease for children < 5 years of age in slum areas of Dhaka, Bangladesh. These findings demonstrate the urgent need for comprehensive interventions to reduce fecal contamination on the household compound to protect the health of susceptible pediatric populations.

BACKGROUND

Diarrheal disease is a leading cause of death for children under 5 years of age globally.[1] In Bangladesh, there are estimated to be 28 million diarrheal episodes among children under 5 years of age annually.[2] Diarrheal disease is associated with undernutrition in young children, which is estimated to be an underlying cause of death for half of young children globally.[3] Furthermore, enteric infections, even those that are asymptomatic, can contribute to impaired growth and environmental enteropathy in young children.[4] Identifying risk factors for diarrhea among susceptible pediatric populations helps to prioritize interventions needed to reduce enteric infections among young children.

Young children often put objects and surfaces they come into contact with in their mouths; this mouthing behavior is a normal part of child development.[5] However, in settings with high fecal contamination, ingestion of soil and dust presents an exposure route to feces and risk for enteric infections.[6–9] Mouthing of fomites, such as children's toys, utensils, and plates, can also serve as an exposure route to enteric pathogens.[9–12] Geophagy, the consumption of soil, dirt, or mud, and child mouthing of feces and fomites have been associated with environmental enteropathy, diarrhea, and growth faltering in young children.[13–17]

Previous studies have also identified unimproved drinking water sources, poor water storage practices, not treating drinking water in the home, lack of caregiver handwashing with soap, lack of caregiver awareness of hygiene practices, visible feces on the household compound, and unsafe child feces disposal as risk factors for diarrheal diseases.[18–33] A study in rural Bangladesh found that drinking water contaminated by *Escherichia coli* was associated with subsequent diarrhea in children.[34] Another study in Bangladesh found an association between drinking water with *E. coli* and diarrhea.[35] Previous studies in urban and rural Ethiopia found a significant association between pediatric diarrhea and the presence of feces in the yard, having an unimproved water source, fecal contamination of household stored drinking water, lack of handwashing with soap at a key time, and having an improved sanitation facility.[22,24,36,37] A recent study in rural Uganda found unprotected water sources as a risk factor for diarrhea for children under 5 years of age.[29] In South Africa, using an outdoor tap to obtain drinking water was associated with pediatric diarrhea.[38] In addition, in a multi-country study conducted in Pakistan, Kenya, Mali, and Mozambique, using a shared sanitation facility was associated with diarrhea for children under 5 years of age.[39] Further evidence, however, is needed of risk factors for diarrheal diseases in urban settings such as Dhaka, Bangladesh.

The Cholera Hospital-Based Intervention for 7 Days (CHoBI7) was developed in Dhaka, Bangladesh, and promotes handwashing with soap and drinking water treatment among the household members of hospitalized diarrhea patients. A randomized controlled trial (RCT) of the original CHoBI7 program, which targeted the household members of cholera patients, resulted in a significant reduction in symptomatic cholera infections among intervention household members as well as increased odds of handwashing with soap and improved water quality in intervention households 6 to 12 months post intervention.[40] In an effort to scale the CHoBI7 program across Bangladesh, the scope of this intervention was expanded to target household members of all hospitalized diarrhea patients, and a mobile health (mHealth)

* Address correspondence to Christine Marie George, Department of International Health, Program in Global Disease Epidemiology and Control, Johns Hopkins Bloomberg School of Public Health, 615 N. Wolfe Street, Room E5535, Baltimore, MD 21205-2103. E-mail: cmgeorge@jhu.edu

component was added to remove the need for home visits for intervention delivery.[41,42] A recent RCT of the CHoBI7 mHealth program resulted in significantly lower pediatric diarrhea and stunting as well as improved drinking water quality and handwashing with soap.[43] A prospective cohort study nested within this RCT investigated potential risk factors for growth faltering among children under 5 years of age, and found that children with caregiver reports of mouthing soil and children with animals in their sleeping space had a significant reduction in height-for-age Z-scores from baseline to the month 12 follow-up.[44] A second cohort study in this population assessed the association between soil- and object-to-mouth contacts and diarrhea prevalence for children under 5 years of age, and found that the odds of having a diarrhea episode in the subsequent month were significantly higher for children with caregiver reports of mouthing feces within the past week.[16] Additional publications document the CHoBI7 mHealth program effect on handwashing with soap while in the hospital,[45] diarrheal disease knowledge,[46] process evaluation for CHoBI7 mobile health program delivery,[47] and recent formative research to develop a CHoBI7 Baby WASH mHealth program targeting safe child feces disposal, improved food hygiene, and safe child mouthing practices.[48]

This prospective cohort study, also nested within the recent CHoBI7 mHealth program RCT, adds to this body of literature by investigating the environmental and individual-level risk factors for diarrheal disease among children under 5 years of age residing in slum areas of Dhaka, Bangladesh. We hypothesized that fecal contamination on the household compound and unsafe household hygiene practices would be associated with pediatric diarrhea in this setting.

METHODS

Study design. This study was conducted from December 2016 to April 2019 and recruited diarrhea patients presenting with three or more loose stools over a 24-hour period from two tertiary hospitals—Mugda General Hospital (government hospital) and the International Center for Diarrheal Disease Research, Bangladesh Dhaka Hospital (private hospital). After the recruitment of diarrhea patients, their corresponding household members were also enrolled. The eligibility criteria for diarrhea patients were the following: 1) have had three or more loose stools over the past 24 hours, 2) plan to reside in Dhaka for the next 12 months, 3) not have a basin for running water in their home (mostly those residing in slum areas of Dhaka), 4) have a child under 5 years of age in their household (including themselves), and 5) have a working mobile phone in the household. The methodology for delivery of the CHoBI7 mHealth program is published elsewhere.[41,43]

To investigate the risk factors for diarrhea in children, we compared individual- and household-level characteristics among 884 children under 5 years of age enrolled in the RCT of the CHoBI7 mHealth program. At baseline, caregivers of children under 5 years of age were administered a questionnaire on sociodemographic factors, including household literacy, latrine type, roof type, wall type, and refrigerator and animal ownership. Diarrhea surveillance data were collected monthly based on caregiver-reported diarrhea in the past 2 weeks for children under 5 years of age during the 12-month study period. Diarrhea was defined according to the WHO definition of having loose stools three or more times within 24 hours.[49] Caregivers were also asked questions on hygiene behaviors during monthly visits to determine child feces disposal practices. Safe feces disposal was defined as feces disposal in a latrine/toilet or buried.

Unannounced spot checks were performed of the household compound at 1, 3, 6, 9, and 12 months after enrollment to check for the presence of feces (animal or human) or animals in the child's sleeping space, to assess child and caregiver hands for the presence of dirt, and to collect a sample of the household's drinking water. The household compound included indoor and outdoor living spaces. Unannounced spot checks occurred between 8 AM and 5 PM. There was no set time for unannounced spot checks because we did not want the households to prepare for our arrival.

Water samples were collected from both the source and stored drinking water using sterile polyethylene water bottles (500 mL). Water samples were stored in a cooler box and transported to the laboratory within 6 hours of collection to test for *E. coli* by bacterial culture method using previously published methods.[50,51] Two cutoffs were used for water *E. coli* concentrations: 1) the WHO water quality guideline of < 1 colony-forming unit (CFU)/100 mL of *E. coli* in drinking water and 2) the WHO classification of high risk for drinking water supplies cutoff of 100 CFU/100 mL *E. coli*.[52]

The check of child and caregiver hand cleanliness during unannounced spot checks was conducted according to previously published methods.[53] This indicator was used as a proxy measure of child and caregiver hygiene practices. For the hand cleanliness check, research assistants assessed the respondent's fingernails, finger pads, and palms on both the left and right hands for cleanliness and assigned one of the following codes for each part of the hand: visible dirt, unclean appearance, and clean appearance. An intensive training was conducted on how to assess hand cleanliness before the study was conducted. For this analysis, a child or caregiver with "visibly soiled hands" was defined as an individual with a code of visible dirt for all parts of the hand (e.g., finger pads, nails, and palms).

Ethical approvals. Informed written consent was obtained from a parent or guardian for all study participants. The study procedures were approved by the Research Ethical Review Committee of International Centre for Diarrhoeal Disease Research, Bangladesh (PR-15133) and the Institutional Review Board of the Johns Hopkins Bloomberg School of Public Health (6785).

Statistical analysis. To investigate the association between prevalence of diarrhea and potential risk factors, logistic regression models were performed using generalized estimating equations for clustering at the household level.[54] The presence of potential risk factors as assessed by spot checks and caregiver reports were the predictors and caregiver-reported child diarrhea during the subsequent visit 1 month later was the outcome. Diarrhea prevalence was measured from monthly clinical surveillance visits conducted from the month 1 to the month 12 follow-up. All logistic regression models were adjusted for study arm, number of sleeping rooms, roof type, wall type, baseline age, refrigerator ownership, and whether the index diarrhea patient was a child under 5 years old. We controlled for these variables because of their potential effect on diarrhea prevalence. We examined the bivariate association between diarrhea prevalence and one risk factor at a time. STATA 13.0 software was used for the analysis.

RESULTS

A total of 884 children under 5 years of age from 769 households were included in this analysis. Seventy-two percent (638/884) of these children were index diarrhea patients. The median baseline age was 11 ± 15 months (median ± SD; range: 1–59 months) (Table 1). Fifty-seven percent of children (504/884) were under 1 year of age. Forty-three percent (379/884) of children were female. The average number of individuals living in a household was 4 ± 1 (median ± SD; range: 2–12). Eighty-six percent (762/884) of children resided in households with at least one household member who could read and write, and 80% (703/884) of children had a caregiver who reported being able to read and write themselves. Ninety-six percent (848/884) of children resided in a household with a concrete floor, 72% (635/884) of children resided in a household with concrete walls, and 31% (270/884) of children resided in a household with a concrete roof. Seventy-seven percent (677/884) of children resided in households with one room for sleeping.

At baseline, 7% (62/841) of children resided in households reporting animal ownership, and 3% (23/820) of children had animals present in their sleeping spaces. Eight percent (68/876) of children lived in households using an unimproved latrine (flush or pour flush latrine to other than a sewer system or septic tank, a pit latrine without slab or with broken slab, or a hanging latrine). Nineteen percent (151/805) of caregivers reported unsafe child feces disposal. Twenty-four percent (206/876) of households had feces present on the household compound during the baseline unannounced spot check. At baseline, 27% (180/658) of children and 19% (133/692) of caregivers had visibly dirty hands. Eighty-two percent (625/763) of water source samples and 71% (543/766) of household stored water samples had > 1 CFU/100 mL *E. coli* at baseline. Fifty-five percent (421/763) of water source samples and 45% (342/766) of stored water samples had > 100 CFU/100 mL *E. coli* at baseline.

The prevalence of diarrhea during the study period was 18% (1,195/6,786); 6,786 diarrhea surveillance visits were conducted during the study period. Children with any type of feces found on the household compound during spot checks had a significantly higher odds of having diarrhea at the subsequent visit (odds ratio: 1.71; 95% confidence interval: 1.23–2.38) (Table 2). Children residing in households with > 100 CFU/100 mL *E. coli* in source water also had a significantly higher odds of having diarrhea at the subsequent visit (odds ratio: 1.43; 95% confidence interval: 1.06–1.92). No other significant risk factors for diarrhea were identified.

TABLE 1
Baseline characteristics of study population in urban Bangladesh

Characteristic	%	N	Total*
Children < 5 years of age			884
Baseline age (months)			
Median ± SD (min–max)	11 ± 15 (1–59)		
0–12 months	57	504	884
12–24 months	19	169	884
24–36 months	8	72	884
36–48 months	11	95	884
48–60 months	5	44	884
Average number of individuals living in a household, median ± SD (min–Max)	4 ± 1 (2–12)		
Female	43	379	884
Literacy of household members (at least one household member who could read and write)	86	762	884
Literacy of caregivers	80	703	884
Caregiver reported unsafe child feces disposal	19	151	805
Unimproved latrine	8	68	876
Household source water with < 1 CFU/100 mL *Escherichia coli*	18	138	763
Household source water with > 100 CFU/100 mL *E. coli*	55	421	763
Household stored water with < 1 CFU/100 mL *E. coli*	29	223	766
Household stored water with > 100 CFU/100 mL *E. coli*	45	342	766
Household refrigerator ownership	45	395	884
Household animal ownership	7	62	841
Animals in the child sleeping space	3	23	820
Feces present on the household compound	24	206	876
Children with visibly dirty hands	27	180	658
Caregiver with visibly dirty hands	19	133	692
Household roof type			
Concrete	31	270	884
Other	69	614	884
Household floor type			
Concrete	96	848	884
Other	4	36	884
Household wall type			
Concrete	72	635	884
Other	28	249	884
Sleeping rooms in household			
One sleeping room	77	677	884
More than one sleeping room	23	207	884

*The total varies because some variables have missing data.

DISCUSSION

In this prospective cohort study, we investigated risk factors for diarrheal disease among children under 5 years of age in slum areas of urban Dhaka, Bangladesh. We found that the presence of feces on the household compound and having a drinking water source with a high level of *E. coli* were important risk factors for diarrheal disease among young children. These findings demonstrate the urgent need for interventions targeting fecal contamination on the household compound and drinking water treatment to protect the health of susceptible pediatric populations.

The presence of feces on the ground of the household compound was associated with subsequent diarrhea in young children. This finding is consistent with the study by Getachew et al.[24] in rural Ethiopia, which found that the presence of feces around the household compound was associated with a two times higher odds of diarrhea. A study in Mozambique also found that the presence of feces or soiled diapers on the household compound was associated with higher protozoan infections.[55] In rural Kenya, frequent observation of fresh rodent excreta outside the household was found to be a significant risk factor for diarrhea.[56] Studies in Madagascar and Ethiopia found that the presence of garbage in the compound was a risk factor for diarrhea in children under 5 years.[36,57] The association identified in our present study is likely because feces on the household compound contributed to fecal contamination of drinking water sources that are often illegal

Table 2

Associations between individual-and household-level risk factors and diarrhea prevalence for children under 5 years from over the 12 month surveillance period. in urban Bangladesh

Risk factor	Total*	*N*†	%	Diarrhea prevalence, OR (95% CI)‡
Baseline characteristics				
Unimproved latrine§	2,275	56	2.46	1.83 (0.82–4.13)
Household without a refrigerator	6,786	3534	52.08	1.24 (0.99–1.57)
Household animal ownership	2,272	178	7.83	1.51 (0.95–2.40)
Monthly surveillance				
Household source water with < 1 CFU/100 mL *Escherichia coli*	2,225	364	16.36	0.74 (0.45–1.22)
Household source water with > 100 CFU/100 mL *E. coli*	2,225	1,171	52.63	**1.43 (1.06–1.92)**
Household stored water with < 1 CFU/100 mL *E. coli*	2,263	412	18.21	1.12 (0.76–1.67)
Household stored water with > 100 CFU/100 mL *E. coli*	2,263	981	43.35	1.19 (0.89–1.60)
Animals in the child sleeping space	2,269	80	3.53	1.26 (0.56–2.83)
Caregiver reported unsafe child feces disposal	6,760	418	6.18	1.28 (0.93–1.75)
Feces present on the household compound‖	2,275	502	22.07	**1.71 (1.23–2.38)**
Children with visibly dirty hands	2,118	529	24.98	1.01 (0.72–1.42)
Caregiver with visibly dirty hands	2,015	418	20.74	1.15 (0.79–1.68)

CI = confidence interval; OR = odds ratio.
* Total number of surveillance visits. The total differs because some assessment were performed in a randomly selected households, and some data were missing.
† Number of surveillance visits with that risk factor.
‡ Confidence intervals estimated with generalized estimating equations accounting for clustering within households. Significant findings are bolded. All associations are adjusted for study arm, refrigerator ownership, sleeping room, roof type, wall type, baseline age, and whether the index diarrhea patient was a child under 5 years old.
§ Unimproved latrine is defined as a flush or pour flush latrine to other than a sewer system or septic tank, a pit latrine without slab or with broken slab, or a hanging latrine.
‖ The household compound included indoor and outdoor living spaces. This space was defined by household members at the beginning of the spot check.

connections to the municipal water supply[58–61] and contributed to pediatric exposure to fecal pathogens through child mouthing behaviors.[13–16]

High *E. coli* (> 100 CFU/100 mL) in source water was a significant risk factor for diarrhea in young children in this study. This finding are also consistent with previous studies that have found unimproved and unprotected water sources, which are more prone to fecal contamination, to be associated with pediatric diarrhea.[29,33,37] Our finding that source water quality was related to diarrheal diseases among young children is in contrast to Jensen et al.,[63] who found no association between the amount of *E. coli* in drinking water sources and diarrhea among children under 5 years of age.[64] In our study, stored water was also highly contaminated, however was not observed to be significant risk factor for diarrhea. We are not sure why source water was more strongly associated with diarrhea prevalence compared with stored water despite the proportion of *E. coli* present being similar. Future studies should look at this association. Our findings suggest that effective municipal-level water treatment and monitoring may be one long-term intervention approach to reduce exposure to fecal pathogens along this pathway, though household-level point-of-collection or post-collection water treatment may also be required as a short-term option.[64]

This study has some limitations. First, we did not include *E. coli* sampling of food, soil, or hands. This sampling would have provided valuable information on other potential pathways for fecal contamination in these households. Second, our measures of environmental contamination were proxies for pathogen exposure. Future studies should measure enteric pathogens in child stool samples. Third, caregiver-reported diarrhea in the last 14 days can be prone to reporting bias.[65] Lastly, we did not differentiate between human and animal feces in our observations. Although animal ownership in this population was low (7%), animals belonging to adjacent households could have contributed to the observed contamination. There is a need for more comprehensive, or "transformative," WASH (Water, Sanitation, and Hygiene) interventions that address exposure to both human and animal feces in urban settings.[66,67] Such interventions may require inclusion of multiple, adjacent households that share compound space and water sources.

This study has several strengths. 1) The monthly surveillance visits were conducted throughout the year, which allowed us to account for seasonal variability in risk factors. 2) The study included unannounced spot checks and *E. coli* analyses in addition to caregiver-reported behaviors. Most studies rely only on caregiver-reported behavior. 3) The prospective design of the study allowed us to investigate the association between potential risk factors and subsequent diarrhea. 4) Nesting of this study in an RCT limits the sources of bias.

CONCLUSION

Fecal contamination on the household compound and of household drinking water sources were associated with subsequent pediatric diarrhea among young children living in slum areas of Dhaka, Bangladesh. These findings highlight the need for interventions to reduce fecal contamination on household compounds and in drinking water sources to reduce diarrheal disease risk and improve child health in this population.

Received November 27, 2020. Accepted for publication March 11, 2021.

Published online June 7, 2021.

Note: Supplemental table appears at www.ajtmh.org.

Acknowledgments: This research was supported by a USAID grant awarded to Johns Hopkins School of Public Health. We thank USAID for their support. The authors thank the study participants and the following individuals for their support with the implementation of this study: Professor Abul Khair Mohammad Shamsuzzaman, Professor Be-Nazir Ahmed, Fosiul Alam Nizame, Khobair Hossain, Rafiqul Islam, Maynul Hasan, SM. Arifur Rahman, Abdullah Al Morshed, Zakir Hossain, Kabir Hossain, Amal Sarker, Abul Bashar Sikder, Abdul Matin, Sadia Afrin Ananya, Lubna Tani, Farhana Ahmed, Tahera Taznen, Marufa Akter, Akhi Sultana, Nasrin Akter, Laki Das, Abdul Karim, Shirin Akter, Khan Ali Afsar, and Wasim Ahmed Asif. We also thank hospital staff for their support. icddr,b acknowledges the governments of Bangladesh, Canada, Sweden and United Kingdom for providing core/unrestricted support.

Authors' addresses: Tahmina Parvin, International Centre for Diarrhoeal Disease Research, Bangladesh (icddr,b), Infectious Disease Division, Dhaka, Bangladesh, E-mail: tparvin@icddrb.org. Elizabeth D. Thomas, David A. Sack, Jamie Perin, Christine Marie George, Johns Hopkins University Bloomberg School of Public Health, International Health, Baltimore, MD, E-mails: liz.thomas@jhu.edu, dsack1@jhu.edu, jperin@jhu.edu, and cmgeorge@jhu.edu. Md. Sazzadul Islam Bhuyian and Fatema Zohura, International Centre for Diarrhoeal Disease Research, Bangladesh (icddr,b), Infectious Disease Division, Dhaka, Bangladesh, E-mails: sazzadul.islam@icddrb.org and fzohura@icddrb.org. Ismat Minhaj Uddin, Md. Tasdik Hasan, Jahed Masud, Marzia Sultana, and Fatema-Tuz Johura, International Centre for Diarrhoeal Disease Research, Bangladesh (icddr,b), Infectious Disease Division, Dhaka, Bangladesh, E-mails: ismat.minhaj@icddrb.org, tasdikhdip@yahoo.com, jahed@icddrb.org, msultana@icddrb.org, and mfjohura@icddrb.org. Zillur Rahman, International Centre for Diarrhoeal Disease Research, Bangladesh (icddr,b), Infectious Disease Division, Dhaka, Bangladesh, E-mail: zillur_rahman05@yahoo.com. Indrajeet Barman, International Centre for Diarrhoeal Disease Research, Bangladesh (icddr,b), Infectious Disease Division, Dhaka, Bangladesh, E-mail: indrajeet.barman@icddrb.org. Anne Westin, Department of International Health, Johns Hopkins Bloomberg School of Public Health, Baltimore, MD, E-mail: ao582254@gmail.com. Shirajum Monira, International Centre for Diarrhoeal Disease Research, Bangladesh (icddr,b), Infectious Disease Division, Dhaka, Bangladesh, E-mail: smonira@icddrb.org. Shwapon Kumar Biswas, International Centre for Diarrhoeal Disease Research, Bangladesh (icddr,b), Infectious Disease Division, Dhaka, Bangladesh, and Department of Medicine, Rangpur Medical College Hospital, Rangpur, Bangladsh, E-mail: shwapon6@gmail.com. Munirul Alam, International Centre for Diarrheal Disease Research, Dhaka, Bangladesh, E-mail: unirul@icddrb.org.

REFERENCES

1. GBD 2016 Causes of Death Collaborators, 2017. Global, regional, and national age-sex specific mortality for 264 causes of death, 1980–2016: a systematic analysis for the Global Burden of Disease Study 2016. *Lancet 390:* 1151–1210.
2. GBD Diarrhoeal Diseases Collaborators, 2017. Estimates of global, regional, and national morbidity, mortality, and aetiologies of diarrhoeal diseases: a systematic analysis for the Global Burden of Disease Study 2015. *Lancet Infect Dis 17:* 909–948.
3. Caulfield LE, de Onis M, Blossner M, Black RE, 2004. Undernutrition as an underlying cause of child deaths associated with diarrhea, pneumonia, malaria, and measles. *Am J Clin Nutr 80:* 193–198.
4. George CM et al., 2018. Enteric infections in young children are associated with environmental enteropathy and impaired growth.*Trop Med Int Health 23:* 26–33.
5. Ruff HA, Dubiner K, 1987. Stability of individual differences in infants' manipulation and exploration of objects. *Percept Mot Skills 64:* 1095–1101.
6. Black RE et al., 2008. Maternal and child undernutrition: global and regional exposures and health consequences. *Lancet 371:* 243–260.
7. Moya J, Bearer CF, Etzel RA, 2004. Children's behavior and physiology and how it affects exposure to environmental contaminants. *Pediatrics 113 (Suppl):* 996–1006.
8. Saathoff E, Olsen A, Kvalsvig JD, Geissler PW, 2002. Geophagy and its association with geohelminth infection in rural schoolchildren from northern KwaZulu-Natal, South Africa. *Trans R Soc Trop Med Hyg 96:* 485–490.
9. Kwong LH et al., 2020. Ingestion of fecal bacteria along multiple pathways by young children in rural Bangladesh participating in a cluster-randomized trial of Water, Sanitation, and Hygiene Interventions (WASH Benefits). *Environ Sci Technol 54:* 13828–13838.
10. Julian TR et al., 2013. Fecal indicator bacteria contamination of fomites and household demand for surface disinfection products: a case study from Peru. *Am J Trop Med Hyg 89:* 869–872.
11. Pickering AJ et al., 2012. Fecal contamination and diarrheal pathogens on surfaces and in soils among Tanzanian households with and without improved sanitation. *Environ Sci Technol 46:* 5736–5743.
12. Vujcic J et al., 2014. Toys and toilets: cross-sectional study using children's toys to evaluate environmental faecal contamination in rural Bangladeshi households with different sanitation facilities and practices. *Trop Med Int Health 19:* 528–536.
13. George CM et al., 202. Child mouthing of feces and fomites and animal contact are associated with diarrhea and impaired growth among young children in the democratic republic of the congo: a prospective cohort study. *J Pediatr 228:* 110–116.
14. George CM et al., 2015. Geophagy is associated with environmental enteropathy and stunting in children in rural Bangladesh. *Am J Trop Med Hyg 92:* 1117–1124.
15. Morita T et al., 2017. Mouthing of soil contaminated objects is associated with environmental enteropathy in young children. *Trop Med Int Health 22:* 670–678.
16. Parvin T et al., 2020. Prospective cohort study of child mouthing of faeces and fomites in Dhaka, Bangladesh (CHoBI7 Program). *Trop Med Int Health 25:* 976–984.
17. Perin J et al., 2016. Geophagy is associated with growth faltering in children in rural Bangladesh. *J Pediatr 178:* 34–39, e1.
18. Alemayehu B, Ayele BT, Kloos H, Ambelu A, 2020. Individual and community-level risk factors in under-five children diarrhea among agro-ecological zones in southwestern Ethiopia. *Int J Hyg Environ Health 224:* 113447.
19. Bushen OY et al., 2004. Diarrhea and reduced levels of antiretroviral drugs: improvement with glutamine or alanyl-glutamine in a randomized controlled trial in northeast Brazil. *Nephrol Dial Transplant 38:* 1764–1770.
20. Checkley W et al., 2004. Effect of water and sanitation on childhood health in a poor Peruvian peri-urban community. *Lancet 363:* 112–118.
21. D'Souza RM, 1997. Housing and environmental factors and their effects on the health of children in the slums of Karachi, Pakistan. *J Biosoc Sci 29:* 271–281.
22. Gebru T, Taha M, Kassahun W, 2014. Risk factors of diarrhoeal disease in under-five children among health extension model and non-model families in Sheko district rural community, southwest Ethiopia: comparative cross-sectional study. *BMC Public Health 14:* 395.
23. George CM et al., 2014. Risk factors for diarrhea in children under five years of age residing in peri-urban communities in Cochabamba, Bolivia. *Am J Trop Med Hyg 91:* 1190–1196.
24. Getachew A, Tadie A, Hiwot MG, Guadu T, Haile D, Teklay GC, Gizaw Z, Alemayehu M, 2018. Environmental factors of diarrhea prevalence among under five children in rural area of North Gondar zone, Ethiopia. *Ital J Pediatr 44:* 95.
25. Ghosh S, Sengupta PG, Mondal SK, Banu MK, Gupta DN, Sircar BK, 1997. Risk behavioural practices of rural mothers as determinants of childhood diarrhoea. *J Commun Dis 29:* 7–14.
26. Kosek M et al., 2008. Epidemiology of highly endemic multiply antibiotic-resistant shigellosis in children in the Peruvian Amazon. *Pediatrics 122:* e541–e549.
27. Maponga BA, Chirundu D, Gombe NT, Tshimanga M, Shambira G, Takundwa L, 2013. Risk factors for contracting watery diarrhoea in Kadoma City, Zimbabwe, 2011: a case control study. *BMC Infect Dis 13:* 567.
28. Mulatya DM, Ochieng C, 2020.Disease burden and risk factors of diarrhoea in children under five years: evidence from Kenya's demographic health survey 2014. *Int J Infect Dis 93:* 359–366.
29. Omona S, Malinga GM, Opoke R, Openy G, Opiro R, 2020. Prevalence of diarrhoea and associated risk factors among children under five years old in Pader District, northern Uganda. *BMC Infect Dis 20:* 37.

30. Shrestha A, Six J, Dahal D, Marks S, Meierhofer R, 2020. Association of nutrition, water, sanitation and hygiene practices with children's nutritional status, intestinal parasitic infections and diarrhoea in rural Nepal: a cross-sectional study. *BMC Public Health 20:* 1241.
31. Thiam S et al., 2017. Prevalence of diarrhoea and risk factors among children under five years old in Mbour, Senegal: a cross-sectional study. *Infect Dis Poverty 6:* 109.
32. Tornheim JA, Morland KB, Landrigan PJ, Cifuentes E, 2009. Water privatization, water source, and pediatric diarrhea in Bolivia: epidemiologic analysis of a social experiment. *Int J Occup Environ Health 15:* 241–248.
33. Workie GY, Akalu TY, Baraki AG, 2019. Environmental factors affecting childhood diarrheal disease among under-five children in Jamma district, South Wello zone, Northeast Ethiopia. *BMC Infect Dis 19:* 804.
34. Luby SP et al., 2015. Microbiological contamination of drinking water associated with subsequent child diarrhea. *Am J Trop Med Hyg 93:* 904–911.
35. Ercumen A, Arnold BF, Naser AM, Unicomb L, Colford JM, Jr, Luby SP, 2017. Potential sources of bias in the use of *Escherichia coli* to measure waterborne diarrhoea risk in low-income settings.*Trop Med Int Health 22:* 2–11.
36. Adane M, Mengistie B, Kloos H, Medhin G, Mulat W, 2017. Sanitation facilities, hygienic conditions, and prevalence of acute diarrhea among under-five children in slums of Addis Ababa, Ethiopia: baseline survey of a longitudinal study. *PLoS One 12:* e0182783.
37. Wasihun AG et al., 2018. Risk factors for diarrhoea and malnutrition among children under the age of 5 years in the Tigray Region of northern Ethiopia. *PLoS One 13:* e0207743.
38. Kapwata T, Mathee A, le Roux WJ, Wright CY, 2018. Diarrhoeal disease in relation to possible household risk factors in South African villages. *Int J Environ Res Public Health 15:* 1665.
39. Baker KK, O'Reilly CE, Levine MM, Kotloff KL, Nataro JP, 2016. Sanitation and hygiene-specific risk factors for moderate-to-severe diarrhea in young children in the Global Enteric Multicenter Study, 2007–2011: case-control study. *PLoS Med 13:* e1002010.
40. George CM et al., 2016. Randomized controlled trial of hospital-based hygiene and water treatment intervention (CHoBI7) to reduce cholera. *Emerg Infect Dis 22:* 233.
41. George CM et al., 2019. Formative research for the design of a scalable water, sanitation, and hygiene mobile health program: CHoBI7 mobile health program. *BMC Public Health 19:* 1–18.
42. Thomas ED et al., 2020. Formative research to scale up a handwashing with soap and water treatment intervention for household members of diarrhea patients in health facilities in Dhaka, Bangladesh (CHoBI7 program). *BMC Public Health 20:* 1–19.
43. George CM et al., 2020. Effects of a water, sanitation, and hygiene mobile health program on diarrhea and child growth in Bangladesh: a cluster-randomized controlled trial of the cholera hospital-based intervention for 7 days (CHoBI7) mobile health program. *Clin Infect Dis* (Epub ahead of print).
44. Monira S et al., 2020. Child mouthing of soil and presence of animals in child sleeping spaces are associated with growth faltering among young children in Dhaka, Bangladesh (CHoBI7 Program). *Trop Med Int Health 25:* 1016–1023.
45. Zohura F et al., 2020. Effect of a water, sanitation and hygiene program on handwashing with soap among household members of diarrhoea patients in healthcare facilities in Bangladesh: a cluster-randomised controlled trial of the CHoBI7 mobile health program. *Trop Med Int Health 25:* 1008–1015.
46. Masud J et al., 2020. Diarrhoeal disease knowledge among diarrhoea patient housholds: findings from the randomised controlled trial of the Cholera-Hospital-Based-Intervention-for-7-days (CHoBI7) mobile health program. *Trop Med Int Health 25:* 996–1007.
47. Islam Bhuyian MS et al., 2020. Process evaluation for the delivery of a water, sanitation and hygiene mobile health program: findings from the randomised controlled trial of the CHoBI7 mobile health program. *Trop Med Int Health 25:* 985–995.
48. Biswas SK et al., 2021. Formative research for the design of a baby water, sanitation, and hygiene mobile health program in Bangladesh (CHoBI7 Mobile Health Program). *Am J Trop Med Hyg 104:* 357–371.
49. WHO, 2017. *Diarrhoeal Disease Fact Sheet*. Available at: https://www.who.int/en/news-room/fact-sheets/detail/diarrhoeal-disease. Accessed February 2020.
50. George CM et al., 2016. Sustained uptake of a hospital-based handwashing with soap and water treatment intervention (Cholera-Hospital-Based Intervention for 7 Days [CHoBI7]): a randomized controlled trial. *Am J Trop Med Hyg 94:* 428–436.
51. Islam MS et al., 2001. Microbiological analysis of tube-well water in a rural area of Bangladesh. *Appl Environ Microbiol 67:* 3328–3330.
52. WHO, 2011. *Guidelines for Drinking Water Quality*. Geneva, Switzerland: WHO.
53. Halder AK, Tronchet C, Akhter S, Bhuiya A, Johnston R, Luby SP, 2010. Observed hand cleanliness and other measures of handwashing behavior in rural Bangladesh. *BMC Public Health 10:* 545.
54. Lipsitz SR, Kim K, Zhao L, 1994. Analysis of repeated categorical data using generalized estimating equations. *Stat Med 13:* 1149–1163.
55. Knee J, Sumner T, Adriano Z, Berendes D, 2018.Risk factors for childhood enteric infection in urban Maputo, Mozambique: a cross-sectional study. *PLoS Negl Trop Dis 12:* e0006956.
56. Conan A et al., 2017. Animal-related factors associated with moderate-to-severe diarrhea in children younger than five years in western Kenya: a matched case-control study. *PLoS Negl Trop Dis 11:* e0005795.
57. Randremanana RV et al., 2016. Etiologies, risk factors and impact of severe diarrhea in the under-fives in Moramanga and Antananarivo, Madagascar. *PLoS One 11:* e0158862.
58. Black RE, Morris SS, Bryce J, 2003. Where and why are 10 million children dying every year? *Lancet 361:* 2226–2234.
59. Makoni FS, Ndamba J, Mbati PA, Manase G, 2004. Impact of waste disposal on health of a poor urban community in Zimbambwe. *East Afr Med J 81:* 422–426.
60. Moraes LR, Cancio JA, Cairncross S, Huttly S, 2003. Impact of drainage and sewerage on diarrhoea in poor urban areas in Salvador, Brazil. *Trans R Soc Trop Med Hyg 97:* 153–158.
61. Oyemade A, Omokhodion FO, Olawuyi JF, Sridhar MK, Olaseha IO, 1998. Environmental and personal hygiene practices: risk factors for diarrhoea among children of Nigerian market women. *J Diarrhoeal Dis Res 16:* 241–247.
62. Lauer JM et al., 2018. Unsafe drinking water is associated with environmental enteric dysfunction and poor growth outcomes in young children in rural southwestern Uganda. *Am J Trop Med Hyg 99:* 1606–1612.
63. Jensen PK, Jayasinghe G, van der Hoek W, Cairncross S, Dalsgaard A, 2004. Is there an association between bacteriological drinking water quality and childhood diarrhoea in developing countries? *Trop Med Int Health 9:* 1210–1215.
64. Pickering AJ et al., 2019. Effect of in-line drinking water chlorination at the point of collection on child diarrhoea in urban Bangladesh: a double-blind, cluster-randomised controlled trial. *Lancet Glob Health 7:* e1247–e1256.
65. Arnold BF et al., 2013. Optimal recall period for caregiver-reported illness in risk factor and intervention studies: a multicountry study. *Am J Epidemiol 177:* 361–370.
66. Prendergast AJ et al., 2019. Putting the "A" into WaSH: a call for integrated management of water, animals, sanitation, and hygiene. *Lancet Planet Health 3:* e336–e337.
67. Pickering AJ et al., 2019. The WASH Benefits and SHINE trials: interpretation of WASH intervention effects on linear growth and diarrhoea. *Lancet Glob Health 7:* e1139–e1146.