Pilot Intervention Study of Household Ventilation and Fine Particulate Matter Concentrations in a Low-Income Urban Area, Dhaka, Bangladesh

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Abstract. Fine particulate matter (PM_{2.5}) is a risk factor for pneumonia; ventilation may be protective. We tested behavioral and structural ventilation interventions on indoor PM_{2.5} in Dhaka, Bangladesh. We recruited 59 good ventilation (window or door in ≥ 3 walls) and 29 poor ventilation (no window, one door) homes. We monitored baseline indoor and outdoor PM_{2.5} for 48 hours. We asked all participants to increase ventilation behavior, including opening windows and doors, and operating fans. Where permitted, we installed windows in nine poor ventilation homes, then repeated PM_{2.5} monitoring. We estimated effects using linear mixed-effects models and conducted qualitative interviews regarding motivators and barriers to ventilation. Compared with poor ventilation homes, good ventilation homes were larger, their residents wealthier and less likely to use biomass fuel. In multivariable linear mixed-effects models, ventilation structures and opening a door or window were inversely associated with the number of hours PM_{2.5} concentrations exceeded 100 and 250 $\mu\text{g}/\text{m}^3$. Outdoor air pollution was positively associated with the number of hours PM_{2.5} concentrations exceeded 100 and 250 $\mu\text{g}/\text{m}^3$. Few homes accepted window installation, due to landlord refusal and fear of theft. Motivators for ventilation behavior included cooling of the home and sunlight; barriers included rain, outdoor odors or noise, theft risk, mosquito entry, and, for fan use, perceptions of wasting electricity or unavailability of electricity. We concluded that ventilation may reduce indoor PM_{2.5} concentrations but, there are barriers to increasing ventilation and, in areas with high ambient PM_{2.5} concentrations, indoor concentrations may remain above recommended levels.

INTRODUCTION

Acute lower respiratory infections (ALRIs) are the leading cause of death among children under 5 years old in Bangladesh.¹ Exposure to indoor air pollution, especially to fine particulate matter (PM_{2.5}), has been implicated as a risk factor for pneumonia and other respiratory diseases in children.^{2,3} The use of biomass cooking fuel, in particular, has often been cited as a major source of PM_{2.5}.² Other factors, such as outdoor air pollution^{4–6} and tobacco smoking,^{7,8} may contribute to indoor air pollution in Bangladesh. In Kamalapur, a low-income area in the capital city of Dhaka, the burden of pneumonia is high, at approximately 0.56 episodes per child-year in children under 2 years old,⁹ despite estimates that only 10% of the Kamalapur population use biomass fuel for cooking.¹⁰

Lack of ventilation and inadequate air flow have been identified as risk factors for transmission of respiratory pathogens in hospitals, schools, and other public buildings.^{11,12} Many health-care facilities in high-income countries have sophisticated ventilation systems to prevent transmission of infectious diseases,¹² but such technologies are typically not available in low-income areas. However, there is evidence that even simple household ventilation may decrease susceptibility to ALRI. In a recent case-control study of environmental risk factors for pneumonia in Kamalapur, those who had cross-ventilation in the home, defined as the presence of windows and/or doors in opposing walls, were 28% less likely to have pneumonia compared with those who did not have cross-ventilation in the home.¹⁰ Similarly, in a cohort study in

Kamalapur, having at least two windows in a home was associated with a 25% reduction in ALRI risk and not owning an electric fan was associated with a 50% increase in ALRI risk.¹³ Household ventilation may reduce the risk of respiratory infections directly by facilitating clearance of pathogens,^{11,12,14} indirectly by reducing particulate matter concentrations and thus pulmonary susceptibility to infection,^{4–6,15–18} or both. Particulate matter may contain pathogens, so the effects of ventilation on particulate matter may also affect pathogen clearance.¹²

In the aforementioned case-control study in Kamalapur, households with cross-ventilation (windows or doors on opposing walls) were shown to have significantly lower mean PM_{2.5} concentrations than those without cross-ventilation.¹⁵ Additional observational studies have described the effects of ventilation on the relationships between biomass fuel use,^{5,18} stove type,^{17,19} and season⁴ with indoor PM_{2.5} concentrations, but did not directly assess the effects of ventilation on PM_{2.5} concentrations.

The existing literature lacks experimental designs that directly test the impact of pragmatic interventions to increase household ventilation on indoor air pollution in low-income settings. Similarly, we have identified only one study that examines acceptability and feasibility of such ventilation interventions in a low-income setting.²⁰ This study, set in South Africa, found that improving ventilation behavior was feasible during favorable weather, but repairing ventilation structure was too costly. We hypothesized that a pragmatic intervention to increase ventilation in the household would reduce concentrations of fine PM_{2.5} in Kamalapur households, where indoor PM_{2.5} concentrations are high although few people rely on biomass fuel use. Additionally, we hypothesized that such interventions would be widely acceptable and feasible. Finally, we sought to identify motivators and barriers to adherence to a ventilation intervention in Kamalapur.

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In this pilot study, we used quantitative and qualitative methods to test an intervention to improve ventilation structure, the number of windows in a household, as well as to increase ventilation behavior, specifically, opening doors and windows and turning fans on, at no cost to the participant. We aimed to 1) describe the relationships between existing ventilation structure and behaviors and $PM_{2.5}$ concentrations, 2) determine the effect of household behavioral and structural interventions to increase ventilation on indoor $PM_{2.5}$ concentrations, and 3) describe the feasibility and acceptability of behavioral and structural ventilation interventions in Kamalapur, a low-income urban area of Dhaka, Bangladesh.

MATERIALS AND METHODS

Study population. In July and August 2011, study staff recruited participants from among the control arm of a 2009–2010 case–control study on factors associated with acute respiratory infections in children less than 5 years old in Kamalapur.¹⁰ Participants in the control arm were randomly selected from the general population undergoing syndromic surveillance, frequency matched to enrolled cases by age group.^{10,21} All data collection for the ventilation study took place during July and August 2011, the hot and rainy season in Bangladesh.

Sampling procedure. We recruited households of control children based on structural ventilation status (poor or good) as observed in the case–control study. Specifically, households were described as having poor ventilation structure if they had no windows and only one external door, or described as having good ventilation structure if they had an external window and/or door in at least three walls. We selected potential participants whose houses fit the poor ventilation and good ventilation categories based on data collected for the earlier case–control study, with the intent to enroll a 1:1 ratio of poor ventilation to good ventilation households. As this study was intended as a small-scale pilot study primarily to assess feasibility, we did not formally model a quantitative hypothesis to calculate statistical power and sample size. Based on budgetary and logistical considerations, we sought to recruit 90 participants in total.

Eligibility criteria. We sought to recruit the primary caregivers of the children who participated in the case–control study. Participants were eligible if they intended to reside in their houses for the subsequent 4 weeks, if no members of their household had respiratory illness at the time of enrollment, and if they did not cook inside their main living space. It is customary in Kamalapur for residents of several neighboring homes to share a central cooking space, adjacent to or apart from any of the living spaces. We limited our sample to those who did not cook in their main living space, since cooking is widely recognized to affect indoor air pollution.²² If one or more household members had respiratory illness at the time of the initial visit, we returned 2 weeks later and, if the illness was resolved, we attempted to recruit the household. Each eligible participant was enrolled only after written consent was obtained. All study procedures were approved by the institutional review boards at the International Center for Diarrheal Disease Research, Bangladesh (icddr,b; Dhaka, Bangladesh) and the University at Buffalo (Buffalo, NY).

Baseline data collection. Study staff interviewed consenting participants and observed household environments to

obtain information on demographic factors and factors potentially related to indoor $PM_{2.5}$ concentrations such as cooking practices, fuel use, crowding, building material of the home, and smoking inside the home. We asked all participants to name the approximate price for installation of a new window in their home and whether they considered that price to be affordable. We conducted measurements in the child's sleeping space to approximate the child's exposure to indoor air pollution. We measured the dimensions of the child's sleeping space and cooking space using a measuring tape and the distance from the stove to the child's sleeping space in steps.

We measured baseline $PM_{2.5}$ concentrations inside and outside the home for 48 consecutive hours using UCB particle monitors (Berkeley Air Monitoring Group, Berkeley, CA). We chose to use these devices due to availability and budget considerations. These devices have been validated in settings with high indoor $PM_{2.5}$ concentrations, such as Kamalapur.²³ Because children are at elevated risk of respiratory disease from high indoor $PM_{2.5}$ concentrations,^{3,24} we placed one monitor inside the home above the study child's sleeping space, 145 cm from the ground. A second monitor was placed outside, directly above the main entrance of the home. During these 48 hours of baseline $PM_{2.5}$ measurement, we asked participants to keep a log, recording the following information hourly when they were awake and at home: whether doors and windows were opened or closed, whether fans were on or off, and whether electricity was currently available in their homes. Since sunlight in a home is related to ventilation structure and ultraviolet light may prevent pathogen survival,²⁵ we measured the amount of luminance from sunlight (in lux units) at the locations of indoor and outdoor monitors. We took two measurements each at the time of placement and removal, using a digital lux meter, LX1010B.

Intervention. The intervention consisted of a behavioral component and a structural component. After baseline $PM_{2.5}$ monitoring, we implemented the behavioral component among all participants in both good and poor ventilation households: specifically, we encouraged participants to keep windows and doors open and to keep a fan on for as many hours per day as possible (Figure 1). If a participant did not have a working fan, we provided one. We chose window and door opening and fan use as behavioral targets, as they have been shown to be associated with reduced ALRI.^{13,26} We asked for these behavioral changes to continue for 1 week.

Those who lived in poor ventilation households were also eligible for the structural component of the intervention: installation of a new window in the home. We asked the participants and, where applicable, their landlords for permission to install the window. In the poor ventilation houses in which it was physically feasible to install a new window and for which we had received verbal permission from both the participant and the landlord, a local contractor installed new windows. We did not pre-specify size and location of the new windows; rather, local contractors and participants worked together to determine the best size and location of new windows, based on existing household structure. For households that received a structural intervention, the behavioral intervention was introduced immediately after installation of the new window. For homes that did not receive a structural intervention, the behavioral intervention was introduced immediately after baseline $PM_{2.5}$ monitoring.

FIGURE 1. Schematic for selection of participants and intervention, Kamalapur, Dhaka, Bangladesh.

Intervention data collection. During the week of the behavioral intervention, we monitored PM_{2.5} concentrations again for 48 hours by placing air quality monitors in the same locations as for the baseline monitoring. We did not specify the exact date of follow-up data collection to allow some flexibility in data collectors' and participants' schedules and to prevent data collection on Fridays (the Muslim holy day, when daily activities might change). During these 48 hours, we again asked participants to keep a log of whether doors and windows were opened or closed, fans were on or off, and whether electricity was available in their houses or not for each hour. We again measured the amount of sunlight at the same locations at the time of monitor placement and removal. After the week of behavioral intervention, we administered a brief end line questionnaire, querying factors associated with air pollution in the household that may have changed between the time of baseline and end line. These factors included cooking practices, fuel use, and smoking inside the house.

Qualitative data collection. After completion of quantitative data collection, we conducted qualitative in-depth interviews with participants who lived in good ventilation households, poor ventilation households who received a structural intervention, and poor ventilation households who refused a structural intervention. We selected respondents purposively from the list of participants under each of those three categories. In in-depth interviews, we asked for feedback regarding acceptability of increasing ventilation, motivators and barriers to doing so, and seasonal variation in household ventilation behavior. We recorded all in-depth interviews using a digital audio recorder and later transcribed them verbatim in Bengali.

Analysis. To analyze quantitative data, we first reported descriptive characteristics of good ventilation and poor ventilation homes. Ventilation status was characterized as 1) poor ventilation households without window installation, 2) poor ventilation households with window installation, or 3) good ventilation households. We conducted a subgroup analysis to describe any descriptive differences between poor ventilation homes that did and did not receive a structural intervention. Then, we described ventilation behavior at baseline and during intervention, as well as PM_{2.5} concentrations for all three ventilation status groups and for indoor (above child's sleeping space) and outdoor (immediately outside the home) monitors.

The lower limit of detection of the University of California, Berkeley air quality monitors is relatively high, 50 $\mu\text{g}/\text{m}^3$, which is twice the World Health Organization (WHO)-recommended 24-hour mean PM_{2.5} concentration.^{3,4,23,27-29} It is therefore difficult to accurately estimate mean PM_{2.5} concentrations using these monitors. Ezzati and others demonstrated that duration of exposure to high PM concentrations is important to acute respiratory infection risk.³⁰ Prior work in Dhaka demonstrated an association between the number of hours PM_{2.5} concentrations exceeded 100 $\mu\text{g}/\text{m}^3$ measured using the University of California, Berkeley air quality monitors and risk of ALRI among infants³ and age at first ALRI.^{3,24} Therefore, we calculated the number of hours during the 48-hour monitoring period that indoor PM_{2.5} concentrations exceeded predefined thresholds of 100 and 250 $\mu\text{g}/\text{m}^3$. We chose to use 100 and 250 $\mu\text{g}/\text{m}^3$ because they represent four and ten times the WHO standard of 25 $\mu\text{g}/\text{m}^3$, and to make our results comparable to similar studies that used the number of hours PM_{2.5} exceeded 100 and 250 $\mu\text{g}/\text{m}^3$ in highly polluted environments.^{3,4,10,24}

This study was conducted near the end of the rainy season in Bangladesh, when there are daily variations in the amount of cloud cover and, thus, outdoor sunlight. To account for the varying amounts of outdoor sunlight during our study period, we calculated the ratio of indoor to outdoor sunlight. We calculated the average ratio of indoor to outdoor sunlight for each home at baseline and at follow-up, and reported the median ratio of indoor to outdoor sunlight for the sample by intervention status.

Since we measured $PM_{2.5}$ concentrations at baseline and follow-up for each home, we assessed the effects of ventilation behavior and structure on indoor $PM_{2.5}$ concentrations using mixed-effect linear regression, accounting for repeated subjects. We tested each of the following independent variables in separate linear regression models: ventilation status, area of windows and doors in the home, number of hours that windows were open, number of hours that doors were open, number of hours that fans were on, and number of hours outdoor $PM_{2.5}$ concentrations exceed 100 and 250 $\mu g/m^3$. We calculated the number of hours that doors and windows were open by using door-hours and window-hours (one window being open for 2 hours is equivalent to two window-hours, as are two windows being open for 1 hour). Dependent variables included number of hours that indoor $PM_{2.5}$ concentrations exceeded 100 and 250 $\mu g/m^3$.

Our final models estimated the effects of behavioral and structural interventions on number of hours $PM_{2.5}$ concentration exceeded previously specified thresholds (100 and 250 $\mu g/m^3$), after adjusting for covariates and accounting for repeated measures of ventilation behavior and $PM_{2.5}$ concentrations. Covariates were chosen for inclusion in the final models if they changed the estimate of association between ventilation factors and number of hours $PM_{2.5}$ concentrations exceeded 100 and 250 $\mu g/m^3$ by at least 10% and were not strongly collinear with other covariates in the model. Categorical covariates must have been present in some poor and some good ventilation homes to be considered for inclusion in final models. Covariates tested included measures of crowding, cooking fuels, smoking in the home, physical attributes of the home and cooking space, outdoor air pollution, and wealth status. We ranked households according to wealth status using principal component analysis of household assets.³¹

To address the feasibility of structural interventions, we first described the proportion of poor ventilation households for whom both occupants and owners agreed to a new window installation and reasons for refusal for those who refused, gathered during qualitative in-depth interviews. We then reported descriptive statistics for reported estimated cost of window installation. To assess the feasibility of behavioral interventions, whether participants were able to increase ventilation behaviors, we described the reported number of hours that doors and windows were open, a fan was on, and electricity was available at baseline and during the intervention period. We compared the differences in ventilation behavior at baseline compared with the intervention period separately for all three ventilation status groups.

To analyze the qualitative data, we developed a code list according to study objectives and based on themes that emerged from the collected data. Then, we coded all the responses and performed content analysis according to the major themes, which included motivators and

barriers to practicing ventilation behavior offered during the intervention.³²

RESULTS

We recruited 29 poor ventilation and 59 good ventilation households for this study. We were unable to locate many of the potential poor ventilation participants who had taken part in the 2009–2010 case-control study because they had moved. Thus, we enrolled a 1:2 ratio of poor to good ventilation households. We were able to install new windows in 9 of the 29 poor ventilation households. All respondents were female. Compared with participants living in poor ventilation households, participants living in good ventilation households were wealthier, more educated, more likely to own their house, more likely report paying for electricity, and more likely to exclusively use improved cooking fuels (Table 1). Their houses were larger, had fewer people per sleeping room, and were all constructed of concrete, brick, or mud, whereas tin and bamboo thatch were also used in poor ventilation houses. There were no significant differences between poor and good ventilation households with respect to age of respondent, distance between stove and cooking space, and smoking inside the house. Likewise, we did not observe statistically significant differences between descriptive characteristics of respondents in poor ventilation homes that did not receive a structural intervention and those who did, possibly a function of small sample size. Those who did not receive a structural intervention were slightly younger (mean age 28.6 years) than those in homes that received a structural intervention (mean age 32.8 years, $P = 0.4$) and were more likely to have at least one concrete or brick wall (40% compared with 11%, $P = 0.2$), but the two groups did not differ in any other descriptive characteristic (results not shown).

At baseline, all participants reported high levels of ventilation behavior during the hot and rainy season. Among poor ventilation households, doors were opened for an average of more than 13 hours per day and fans were on for an average of more than 16 hours per day. Participants in good ventilation households reported that windows and doors were open and fans were on for an average of more than 18 hours per day (Table 2). At follow-up (median of 7 days after baseline), participants did not significantly increase the number of hours that their doors were opened. Among good ventilation households, participants opened their windows for an average of nearly two hours more at follow-up compared with baseline ($P = 0.1$). Fan use was significantly lower at follow-up compared with baseline among all ventilation groups, likely due to decreases in availability of electricity as reported by participants.

$PM_{2.5}$ concentrations exceeded 100 and 250 $\mu g/m^3$ for longer at follow-up compared with baseline for poor ventilation households and outdoor monitors, but these differences were not statistically significant (Table 3). At follow-up, $PM_{2.5}$ concentrations exceeded 100 and 250 $\mu g/m^3$ for the longest time among poor ventilation households with no structural intervention. During 48 hours of monitoring at baseline, $PM_{2.5}$ concentrations exceeded 100 ($P = 0.006$) and 250 $\mu g/m^3$ ($P = 0.02$) in poor ventilation homes for approximately twice as long compared with good ventilation homes.

At baseline, the median amount of sunlight in poor ventilation homes that did not receive a structural intervention was

TABLE 1

Descriptive characteristics of homes enrolled in ventilation pilot study at baseline by ventilation status,* Kamalapur, Dhaka, Bangladesh (N = 88)

	Poor ventilation (N = 29)	Good ventilation (N = 59)	P value (t test)
	Mean (SD)	Mean (SD)	
Age of respondent (years)	29.9 (9.0)	29.7 (6.8)	0.9
Number of people/sleeping room	3.8 (1.3)	3.0 (1.2)	0.003
Volume of room where child sleeps (m ³)	21.3 (6.0)	35.2 (11.3)	< 0.0001
Distance from stove to sleeping space (m)	4.7 (3.3)	4.7 (2.7)	0.9
Number of years of formal education completed by respondent	2.5 (3.0)	8.6 (3.8)	< 0.0001
	N	N (%)	P value (χ ²)
Wealth quartile			< 0.0001
Poorest	18 (64)	3 (5)	
Moderately poor	9 (32)	13 (22)	
Moderately wealthy	1 (4)	22 (37)	
Wealthiest	0 (0)	21 (36)	
House ownership			0.002
Own	2 (7)	20 (34)	
Rent	25 (86)	39 (66)	
Squatter	2 (7)	0 (0)	
Household pays for electricity	3 (10)	29 (49)	0.0004
Cooking fuel used			0.0005
Cleaner fuels only†	18 (62)	56 (95)	
Some biomass‡	9 (31)	3 (5)	
Smoking in house			0.1
At least daily	13 (45)	18 (31)	
Less than daily	9 (31)	14 (24)	
Never	7 (24)	27 (46)	
Material of house			< 0.0001
Bamboo thatch	9 (31)	0 (0)	
Tin	3 (10)	0 (0)	
Concrete/brick/mud	3 (10)	59 (100)	
Combination	14 (48)	0 (0)	

SD = standard deviation.

* Good ventilation homes have at least one door or window in each of three or four walls. Poor ventilation homes had no windows and only one door.

† Cleaner fuels include biogas, LPG, supply gas, electricity, and kerosene.

‡ Biomass fuels include dung, crop residue/grass, rice husk, leaves, wood/bamboo stick, and wood.

0.4% that of outdoor sunlight (interquartile range [IQR] 2.7%) and, at follow-up, was 0.3% that of outdoor sunlight (IQR 2.7%). The median amount of sunlight in poor ventilation households that received a structural intervention was 0.7% that of outdoor sunlight at baseline (IQR 1.5%) and was 1% of outdoor light (IQR 6.0%) at follow-up. At baseline, the median amount of sunlight in good ventilation homes was 7.7% of

outdoor sunlight (IQR 19.0%) and was 6.8% that of outdoor sunlight (IQR 17.2%) at follow-up.

Because we had a small sample size and few results were statistically significant, we report on associations with a substantial effect size (≥ 1 hour difference in time PM_{2.5} concentration exceeded threshold), as well as those that were statistically significant at $P < 0.05$. We presented bivariate and

TABLE 2

Number of hours that windows and doors were opened and fans were operated at baseline and at follow-up, by ventilation status, Kamalapur, Dhaka, Bangladesh (N = 88)

	Baseline*	Follow-up*	P value (t test)
	Mean (SD)	Mean (SD)	
Poor ventilation households with no structural intervention (N = 20)			
Hours window open per day	NA	NA	NA
Hours door open per day	15.8 (5.1)	16.4 (4.0)	0.7
Hours fan on per day	19.1 (4.0)	7.9 (1.3)	< 0.0001
Hours electricity available per day	22.2 (3.1)	8.2 (1.5)	< 0.0001
Poor ventilation households with structural intervention (N = 9) ³			
Hours window open per day	NA	13.8 (3.3)	NA
Hours door open per day	13.9 (4.4)	16.6 (1.7)	0.1
Hours fan on per day	16.8 (3.5)	8.4 (0.7)	< 0.0001
Hours electricity available per day	21.1 (3.6)	8.9 (0.9)	< 0.0001
Good ventilation households (N = 59)			
Hours window open per day	18.1 (6.7)	20.0 (9.2)	0.1
Hours door open per day	18.5 (5.1)	19.3 (3.9)	0.3
Hours fan on per day	19.6 (4.2)	7.9 (1.2)	< 0.0001
Hours electricity available per day	21.2 (2.5)	8.3 (1.2)	< 0.0001

* Follow-up occurred a median of 7 days after baseline.

TABLE 3

Summary statistics for number of hours that PM_{2.5} concentration exceeded thresholds during 48-hour monitoring periods at baseline and during intervention, Kamalapur, Dhaka, Bangladesh (N = 88)

	Baseline*	Follow-up*	P value (t test)
	Mean (SD)	Mean (SD)	
Outdoor monitors (N = 88)			
Hours PM _{2.5} > 100 µg/m ³	9.2 (9.9)	11.6 (11.9)	0.2
Hours PM _{2.5} > 250 µg/m ³	3.5 (7.3)	5.6 (10.1)	0.1
Poor ventilation households with no structural intervention (N = 20)			
Hours PM _{2.5} > 100 µg/m ³	10.5 (10.0)	15.4 (14.0)	0.2
Hours PM _{2.5} > 250 µg/m ³	5.2 (7.3)	8.8 (12.1)	0.3
Poor ventilation households with structural intervention (N = 9)			
Hours PM _{2.5} > 100 µg/m ³	9.6 (7.4)	12.9 (7.1)	0.4
Hours PM _{2.5} > 250 µg/m ³	3.0 (4.1)	5.0 (4.1)	0.3
Good ventilation households (N = 59)			
Hours PM _{2.5} > 100 µg/m ³	4.9 (5.6)	4.6 (4.9)	0.8
Hours PM _{2.5} > 250 µg/m ³	1.4 (3.2)	1.4 (2.5)	0.96

* Follow-up occurred a median of 7 days after baseline.

adjusted mixed-effects linear regression models, accounting for repeated measures. Adjusted models included variables coding for distance from stove to sleeping space, outdoor air pollution, and use of biomass cooking fuels; we examined each indicator of ventilation in separate models due to collinearity among the ventilation indicators (Table 4). Although smoking has been demonstrated to be a source of PM_{2.5} in other contexts, it was not a significant predictor of PM_{2.5} in this study. After adjustment, homes with good ventilation status had 4.4 fewer hours during which PM_{2.5} concentrations exceeded 100 µg/m³ ($P = 0.001$) and 3.0 fewer hours during which PM_{2.5} concentrations exceeded 250 µg/m³ ($P = 0.004$) compared with those with poor ventilation status that did not receive a structural intervention. Poor ventilation homes that received a structural intervention had 1.6 fewer hours during which PM_{2.5} concentrations exceeded 100 µg/m³ ($P = 0.5$) and 2.4 fewer hours during which PM_{2.5} concentrations exceeded 250 µg/m³ ($P = 0.1$) compared with homes with poor ventilation status that did not receive a structural intervention. Area of windows and doors, window-hours, and door-hours of ventilation were inversely associated with the number of hours PM_{2.5} concentrations exceeded 100 and 250 µg/m³. We did not observe an association between number of hours a fan was on and number of hours PM_{2.5} exceeded 100 or

250 µg/m³. The number of hours outdoor PM_{2.5} concentrations exceeded 100 and 250 µg/m³ was positively associated with the number of hours indoor PM_{2.5} concentrations exceeded 100 ($P = 0.06$) and 250 µg/m³ ($P = 0.1$).

We conducted in-depth interviews with 16 participants from all three ventilation status categories. Seven of eight respondents in the good ventilation household group reported that their usual practice is to open their doors and windows from morning until evening during the hot summer months whenever they are at home. They practiced these ventilation behaviors to get more sunlight or fresh air inside the room during the day. Respondents also reported seasonal variation of usual ventilation behaviors. Although most respondents reported closing their windows more often during winter due to cool or foggy weather or to prevent mosquito entry, a few ($N = 3$) reported practicing the same ventilation behaviors in winter as they do in summer to have adequate sunlight in their homes during winter. According to the respondents, since they had already been practicing these ventilation behaviors, they did not change much during the intervention period. The only added practice for the respondents from poor ventilation households ($N = 4$) who received a structural intervention was to keep the window open most of the time. These respondents also indicated their ability to open a newly installed window as

TABLE 4

Associations between ventilation structures, behaviors, and outdoor PM_{2.5} concentrations on number of hours (out of 48) indoor PM_{2.5} concentrations exceed 100 and 250 µg/m³, Kamalapur, Dhaka, Bangladesh

	Number of hours PM _{2.5} concentrations exceed 100 µg/m ³				Number of hours PM _{2.5} concentrations exceed 250 µg/m ³			
	Bivariate		Adjusted*		Bivariate		Adjusted*	
Ventilation characteristics	Estimate (SE)	P value	Estimate (SE)	P value	Estimate (SE)	P value	Estimate (SE)	P value
Poor with no structural intervention	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Poor with structural intervention	-1.9 (2.2)	0.4	-1.6 (2.1)	0.5	-3.1 (1.6)	0.06	-2.4 (1.6)	0.1
Good	-8.2 (1.4)	0.001	-4.4 (1.3)	0.001	-5.6 (1.0)	< 0.0001	-3.0 (1.0)	0.004
Area of windows and doors in house (m ²)	-1.0 (0.2)	< 0.0001	-0.7 (0.3)	0.008	-0.6 (0.2)	< 0.0001	-0.4 (0.2)	0.04
Ventilation behavior								
Window-hours of ventilation	-0.07 (0.02)	< 0.0001	-0.03 (0.01)	0.03	-0.04 (0.01)	0.0003	-0.02 (0.01)	0.08
Door-hours of ventilation	-0.1 (0.02)	< 0.0001	-0.05 (0.02)	0.007	-0.06 (0.02)	0.0002	-0.03 (0.01)	0.02
Fan-hours of ventilation†	-0.06 (0.05)	0.3	-0.06 (0.1)	0.6	-0.04 (0.04)	0.2	0.001 (0.07)	0.98
Outdoor PM _{2.5} concentration‡	0.2 (0.05)	0.0002	0.1 (0.05)	0.06	0.2 (0.05)	0.001	0.07 (0.05)	0.1

SE = standard error. Results shown from bivariate and adjusted models. All models account for repeated measures at the household level.

* Adjusted for distance from stove to sleeping space, outdoor air pollution, and use of biomass cooking fuels.

† Multivariate model adjusted for number of hours electricity was available in home, distance from stove to sleeping space, outdoor air pollution, and use of biomass cooking fuels.

‡ Multivariate model adjusted for distance from stove to sleeping space and use of biomass cooking fuels.

a motivator. They considered this new window as an alternative to a fan, especially when electricity is unavailable. Additional benefits include increased natural light and cool air in their room. One respondent who received a structural intervention stated

If we felt hot in this room, we used to go outside. Now we do not go; we do stay in this room. . . .the window is always open. . . . (we) feel cool here (in the room). . . Air comes through the window, that's why we can sit down here.

Although, during the intervention period, many respondents tried to open their doors and windows as much as possible during the day compared with their usual practices, they reported closing their doors and windows after dusk to prevent mosquito entry, block outside noise or street lights, sudden rain, and while sleeping for fear of theft or anticipation of rain at night. The majority of respondents from all three categories reported some common explanations for turning off their fans: during cooking to avoid the pungent smell of cooking smoke or heat inside the room, during evening, when sweeping the room, when children were outside or going to school and no one was available in the room, in cloudy weather, during rain, or if the temperature was relatively cool. However, the most commonly reported barriers to operating fans were sporadic power outages, perceptions of wasting electricity, and landlords requesting respondents to turn off fans. Although many participants do not report paying for electricity, they perceived that turning a fan on in an empty room is a waste of electricity. Some respondents also reported that turning on fans for a long time could make the room hotter, and leaving the fan on was believed to reduce the longevity of the fan. Only in a few cases (good ventilation households), where respondents reported not being concerned about high electricity bills or theft, were they able to practice this intervention ventilation behavior entirely.

Respondents from poor ventilation households without a window ($N = 4$) said that they did not make any change to their regular ventilation practice during intervention. One respondent in this group considered the advantage of not installing a window in her household to avoid theft, but also mentioned that it takes some time to cool her home in the absence of a window.

The four participants living in poor ventilation households with no structural intervention who participated in qualitative interviews reported that their landlords would not allow window construction. One participant reported that a window would look odd in her low ceiling one-room house with a lack of physical space. There was a general concern that a window would place households at risk for theft.

Only 40 of the 88 participants were able to estimate a price for installation of a new window; other participants reported not knowing how much window installation costs. The median price mentioned (in USD) was \$33.56, with a range of \$3.23–\$192.75 and a mode of \$12.84. Of these 40 participants, 22 (55%) believed this perceived price to be affordable. The actual price of window installation varied by the building material of the house's walls, but ranged from \$9.68 to \$15.49. Thirty-one (78%) of these 40 participants believed the quoted price to be affordable.

DISCUSSION

In this pilot study of pragmatic behavioral and structural ventilation interventions, having good household ventilation (doors or windows in at least three walls compared with no windows and one door) was associated with shorter duration of high PM_{2.5} concentrations in a home. We observed potential associations between installation of a new window in homes that previously had no window and area of doors and windows in a home with a shorter duration of high PM_{2.5} concentrations. However, likely due to our small sample size, these associations were not statistically significant. Good ventilation homes had more natural light compared with poor ventilation homes; installation of a window did not substantially increase the amount of light in a home. The amount of time doors and windows were open and outdoor PM_{2.5} concentrations had a small effect on duration of high PM_{2.5} concentrations. These results are consistent with the existing literature on structural ventilation and air quality.^{17,18} Although we did not assess health outcomes in this study, PM_{2.5} exposure is a known risk factor for childhood ALRI and other diseases.^{2,3,33–35} Because of its association with PM_{2.5}, we believe household ventilation may be beneficial to health, but the extent to which improving ventilation may improve childhood health is not clear from this study.

Households with good ventilation status had shorter durations of high PM_{2.5} concentrations compared with those with poor ventilation status at baseline and follow-up. This is likely to be at least partially due to the increased area of windows and doors. Additionally, there may be other differences between poor and good ventilation homes that may affect air quality. Compared with poor ventilation homes, good ventilation homes were larger in volume, more likely to be made of concrete, and less likely to use biomass fuel for cooking, all of which have been shown to affect air quality in other studies.^{5,6,36} We were unable to adjust for volume and building material of the home, as these factors were highly correlated with our exposures of interest and biomass fuel use.

Participants were unable to increase ventilation behavior with existing infrastructure, as they were already practicing high ventilation behavior at baseline. Additionally, concerns of theft may limit a participant's willingness to open doors and windows, particularly among the poorest households, who had lower ventilation behaviors compared with wealthier homes. This study was conducted during hot, humid summer months, when behaviors to increase household ventilation are common. Findings from our qualitative exploration suggest that many people have different ventilation behavior during the winter, and indoor air pollution levels in Bangladesh are higher during cooler, drier winter months compared with hot, humid summer months.^{4,6} In our study, outdoor PM_{2.5} was associated with indoor PM_{2.5}, with borderline statistical significance and was highly polluted. Because outdoor air was highly polluted, ventilation alone would not have been sufficient to decrease indoor air pollution to safe levels. Additionally, the effect of outdoor air pollution on indoor air pollution may be different during summer months than during winter.⁶ Indoor and outdoor PM_{2.5} concentrations were generally high for longer durations at follow-up compared with baseline, although this was more notable in poor ventilation compared with good ventilation households. It is unclear why this is the case, but it is possible that, since data collection occurred

near the end of the monsoon season, this could reflect a seasonal trend of increasing air pollution into the post-monsoon season, as previously noted.^{4,6}

We observed a small inverse association between the number of hours that a door or window was opened and duration of high PM_{2.5} concentrations, but we did not observe such an association for number of hours of fan use. Although Dasgupta and others have demonstrated a small association between fan use and indoor air quality during the cooler, dry winter season in Bangladesh,⁶ we did not observe this relationship during the hot and rainy season, when we conducted this pilot study. Fan use decreased at follow-up, likely due to reduced electricity availability. In a megacity such as Dhaka, with an unstable electricity supply, household interventions that rely on electricity are not feasible. In addition to electricity availability, perceived cost of electric bills and concerns about fan longevity were barriers to fan use. Participants were averse to wasting electricity, and fan use was perceived as wasting electricity. It is clear that fan use is not a feasible intervention for those who live in low-income areas with unreliable electricity supplies.

Installation of a new window was not widely accepted, especially by landlords of the participants. Our small sample size may have limited our ability to observe an effect of the ventilation intervention on air quality. Because few ventilation intervention studies have been conducted, there is little literature on the feasibility and acceptability of interventions to improve ventilation. We have identified only one such study from rural South Africa, in which ventilation behaviors, keeping at least two sources of ventilation (doors or windows) open while a fire was burning, were found to be acceptable and feasible, although repairing broken windows was believed to be too costly.²⁰ The main motivator for new window installation in our study was comfort. The main non-modifiable barrier to window installation was a lack of physical space in the housing structure. Those who did not receive a structural intervention were more likely to have at least one brick or concrete wall in their home compared with those who received a structural intervention. It is possible that, as brick and concrete are difficult to cut into, participants or landlords refused window installation based on building materials. We identified several potentially modifiable barriers to installing a new window, including perceived risk of theft, landlord refusal, and appearance. The windows that we installed had iron bars and shutters, which could discourage theft. Developing a variety of appropriate models for varying wall construction and effectively communicating beneficial features to residents may increase interest in window installation. Although many participants were not able to provide an estimate for the cost of a window, most of those who responded believed that the actual cost of a new window would be affordable. Further evidence is needed to understand why landlords refused window installation. Landlords' interest in improving structural ventilation could lead to better ventilation status and, therefore, more comfortable and potentially healthier living areas for their tenants.

This study has several important limitations. Envisioned as a pilot study, this study had a small sample size. Moreover, based on landlord and tenant willingness, window installation was only possible in nine homes, which may not be sufficient to fully describe the effect of windows on air pollution concentrations. We may have failed to observe statistically significant findings due to the small sample size. Additionally, there may be

fundamental differences between poor and good ventilation households. We used University of California Berkeley air quality monitors, which have a relatively high limit of detection, 50 µg/m³, which is twice the WHO-recommended 24-hour limit for PM_{2.5}.^{3,4,27,28} We were unable to detect relatively low PM_{2.5} concentrations. Thus, we may have underestimated the impact of the intervention. This study did not entail a robust behavior change strategy, and follow-up was within 7 days. This may not be long enough to sustain or observe behavior change. Future studies should focus on improving behavior change strategies and be carried out over a longer period.

CONCLUSIONS

The poorest participants in this heterogeneous community lived in the worst housing conditions, with poor ventilation, long durations of high air pollution, and little sunlight. This at least partially explains the pathway by which children in poor households may be susceptible to ALRI, although we did not examine health outcomes in this study. From this pilot study, we observed evidence that good ventilation status in a home is associated with reduced duration of high PM_{2.5} concentrations. Addition of one window in a home may reduce the duration of high PM_{2.5} concentrations, but a larger sample size is needed to verify this observation. Opening doors and windows had a small effect on duration of high PM_{2.5} concentrations. We also identified several motivators, including comfort, and barriers, including perceived risk of theft, lack of physical space, and landlord refusal, for ventilation interventions. In a future, larger study, there is a need to more clearly understand ventilation structure and behaviors and how they may affect air quality and ALRI.

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REFERENCES

1. National Institute of Population Research and Training (NIPORT), Mitra and Associates, Measure DHS ICF International, 2013. *Bangladesh Demographic and Health Survey 2011*. Dhaka,

- Bangladesh and Calverton, MD: NIPOORT, Mitra and Associates, Measure DHS ICF International.
2. Ezzati M, Saleh H, Kammen DM, 2000. The contributions of emissions and spatial microenvironments to exposure to indoor air pollution from biomass combustion in Kenya. *Environ Health Perspect* 108: 833–839.
3. Gurley ES, et al., 2013. Indoor exposure to particulate matter and the incidence of acute lower respiratory infections among children: a birth cohort study in urban Bangladesh. *Indoor Air* 23: 379–386.
4. Gurley ES, et al., 2012. Seasonal concentrations and determinants of indoor particulate matter in a low-income community in Dhaka, Bangladesh. *Environ Res* 121: 11–16.
5. Dasgupta S, Huq M, Khaliquzzaman M, Pandey K, Wheeler D, 2006. Indoor air quality for poor families: new evidence from Bangladesh. *Indoor Air* 16: 426–444.
6. Dasgupta S, Wheeler D, Huq M, Khaliquzzaman M, 2009. Improving indoor air quality for poor families: a controlled experiment in Bangladesh. *Indoor Air* 19: 22–32.
7. National Institute of Population Research and Training (NIPOORT), Mitra and Associates, Macro International, 2009. *Bangladesh Demographic and Health Survey 2007*. Dhaka, Bangladesh and Calverton, MD: National Institute of Population Research and Training, Mitra and Associates, Macro International.
8. Giovino G, et al., 2012. Tobacco use in 3 billion individuals from 16 countries: an analysis of nationally representative cross-sectional household surveys. *Lancet* 380: 668–679.
9. Brooks WA, Santosham M, Naheed A, Goswami D, Wahed MA, Diener-West M, Faruque ASG, Black RE, 2005. Effect of weekly zinc supplements on incidence of pneumonia and diarrhoea in children younger than 2 years in an urban, low-income population in Bangladesh: randomised controlled trial. *Lancet* 366: 999–1004.
10. Ram PK, et al., 2014. Household air quality risk factors associated with childhood pneumonia in urban Dhaka, Bangladesh. *Am J Trop Med Hyg* 90: 968–975.
11. Li Y, et al., 2007. Role of ventilation in airborne transmission of infectious agents in the built environment—a multidisciplinary systematic review. *Indoor Air* 17: 2–18.
12. Tang JW, Li Y, Eames I, Chan PKS, Ridgway GL, 2006. Factors involved in the aerosol transmission of infection and control of ventilation in healthcare premises. *J Hosp Infect* 64: 100–114.
13. Murray EL, Brondi L, Kleinbaum D, McGowan JE, Van Mels C, Brooks WA, Goswami D, Ryan PB, Klein M, Bridges CB, 2012. Cooking fuel type, household ventilation, and the risk of acute lower respiratory illness in urban Bangladeshi children: a longitudinal study. *Indoor Air* 16: 426–444.
14. Hoge CW, Reichler MR, Dominguez EA, Bremer JC, Mastro TD, Hendricks KA, Musher DM, Elliott JA, Facklam RR, Breiman RF, 1994. An epidemic of pneumococcal disease in an overcrowded, inadequately ventilated jail. *N Engl J Med* 331: 643–648.
15. Crabtree-Ide CR, et al., 2011. Household Factors Associated with Indoor Air Pollution in a Low-Income Urban Area in Bangladesh. American Society of Tropical Medicine and Hygiene Annual Meeting, Philadelphia, PA.
16. Dasgupta S, Huq M, Khaliquzzaman M, Pandey K, Wheeler D, 2006. Who suffers from indoor air pollution? Evidence from Bangladesh. *Health Policy Plan* 21: 444–458.
17. Clark ML, Reynolds SJ, Burch JB, Conway S, Bachand AM, Peel JL, 2010. Indoor air pollution, cookstove quality, and housing characteristics in two Honduran communities. *Environ Res* 110: 12–18.
18. Colbeck I, Nasir ZA, Ali Z, 2010. Characteristics of indoor/outdoor particulate pollution in urban and rural residential environment of Pakistan. *Indoor Air* 20: 40–51.
19. Clark ML, Peel JL, Burch JB, Nelson TL, Robinson MM, Conway S, Bachand AM, Reynolds SJ, 2009. Impact of improved cookstoves on indoor air pollution and adverse health effects among Honduran women. *Int J Environ Health Res* 19: 357–368.
20. Barnes BR, Mathee A, Krieger L, Shafritz L, Favin M, Sherburne L, 2004. Testing selected behaviors to reduce indoor air pollution exposure in young children. *Health Educ Res* 19: 543–550.
21. Brooks WA, Breiman RF, Goswami D, Hossain A, Alam K, Saha SK, Nahar K, Nasrin D, Ahmed N, El Arifeen S, 2007. Invasive pneumococcal disease burden and implications for vaccine policy in urban Bangladesh. *Am J Trop Med Hyg* 77: 795–801.
22. Devakumar DSS, Osrin D, Yadav SK, Kurmi OP, Saville NM, Shrestha B, Manandhar DS, Costello A, Ayres JG, 2014. Biomass fuel use and the exposure of children to particulate air pollution in southern Nepal. *Environ Int* 66: 79–87.
23. Chowdhury Z, Edwards RD, Johnson M, Naumoff SK, Allen T, Canuz E, Smith KR, 2007. An inexpensive light-scattering particle monitor: field validation. *J Environ Monit* 9: 1099–1106.
24. Gurley ES, Salje H, Homaira N, Ram PK, Haque R, Petri WA Jr, Bresee J, Moss WJ, Luby SP, Beye P, Azziz-Baumgartner E, 2014. Indoor exposure to particulate matter and age at first acute lower respiratory infection in a low-income urban community in Bangladesh. *Am J Epidemiol* 179: 967–973.
25. Hobday RA, Dancer SJ, 2013. Roles of sunlight and natural ventilation for controlling infection: historical and current perspectives. *J Hosp Infect* 84: 271–282.
26. Gurley ES, Homaira N, Salje H, Ram PK, Haque R, Petri W, Bresee J, Moss WJ, Breyse P, Luby SP, Azziz-Baumgartner E, 2013. Indoor exposure to particulate matter and the incidence of acute lower respiratory infections among children: a birth cohort study in urban Bangladesh. *Indoor Air* 23: 379–386.
27. Edwards R, Smith KR, Kirby B, Allen T, Litton CD, Hering S, 2006. An inexpensive dual-chamber particle monitor: laboratory characterization. *J Air Waste Manag Assoc* 56: 789–799.
28. World Health Organization, 2006. *WHO Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide*. Geneva, Switzerland: World Health Organization.
29. Berkeley Air Monitoring Group IAPT, 2008. *UCB Particle Monitor User Manual*. Berkeley, CA: School of Public Health, University of California.
30. Ezzati M, Kammen DM, 2001. Quantifying the effects of exposure to indoor air pollution from biomass combustion on acute respiratory infections in developing countries. *Environ Health Perspect* 109: 481–488.
31. Filmer D, Pritchett LH, 2001. Estimating wealth effects without expenditure data—or tears: an application to educational enrollments in states of India. *Demography* 38: 115–132.
32. Hsieh H-F, Shannon SE, 2005. Three approaches to qualitative content analysis. *Qual Health Res* 15: 1277–1288.
33. Emmelin A, Wall S, 2007. Indoor air pollution: a poverty-related cause of mortality among the children of the world. *Chest* 132: 1615–1623.
34. World Health Organization, 2014. *Burden of Disease from Household Air Pollution for 2012: Summary of Results*. Geneva, Switzerland: World Health Organization.
35. Wardlaw TM, Johansson EW, Hodge M, 2006. *Pneumonia: The Forgotten Killer of Children*. New York, NY: World Health Organization; UNICEF.
36. Bautista LE, Correa A, Baumgartner J, Breyse P, Matanoski GM, 2009. Indoor charcoal smoke and acute respiratory infections in young children in the Dominican Republic. *Am J Epidemiol* 169: 572–580.