Household Air Quality Risk Factors Associated with Childhood Pneumonia in Urban Dhaka, Bangladesh

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Abstract. To inform interventions to reduce the high burden of pneumonia in urban settings such as Kamalapur, Bangladesh, we evaluated household air quality risk factors for radiographically confirmed pneumonia in children. In 2009–2010, we recruited children < 5 years of age with pneumonia and controls from a population-based surveillance for respiratory and febrile illnesses. Piped natural gas was used by 85% of 331 case and 91% of 663 control households. Crowding, a tin roof in the living space, low socioeconomic status, and male sex of the child were risk factors for pneumonia. The living space in case households was 28% less likely than in control households to be cross-ventilated. Particulate matter concentrations were not significantly associated with pneumonia. With increasing urbanization and supply of improved cooking fuels to urban areas, the high burden of respiratory illnesses in urban populations such as Kamalapur may be reduced by decreasing crowding and improving ventilation in living spaces.

INTRODUCTION

Pneumonia is the leading cause of child mortality worldwide, accounting for an estimated 1 million deaths annually.¹ Globally, poor indoor air quality has been associated with an increased risk of pneumonia in young children,² with much of indoor air pollution in resource-limited settings attributed to solid fuel use.³ In Demographic and Health Survey data from 176 countries in year 2007,⁴ we found that, on average, urban populations were one-fourth as likely as rural populations to use solid fuels (Ram PK, unpublished observations). Despite increased access to improved fuels, the pneumonia burden remains stubbornly high in urban settings. In Kamalapur, a densely populated urban area of Dhaka, Bangladesh, where only 15% of households have reported using biomass fuels,⁵ the incidence of pneumonia has been estimated at 511 episodes per 1,000 child-years.⁶

We used a case-control design to evaluate the relationship between factors affecting household air quality and radiographically confirmed pneumonia in children < 5 years of age in the Kamalapur context of high pneumonia burden but infrequent solid fuel use. Much of the literature describing the effects of indoor air quality on respiratory illness in low-income settings has relied on proxy measures or respondent report, rather than on direct observation or measurement of particulate matter concentrations.⁷ In Kamalapur, because we anticipated that cooking fuel would play a relatively minor role in pneumonia risk compared with other environmental factors, we sought direct and objective measures that would inform us about poor quality of indoor air in the child's household environment. Specifically, we measured ventilation, building materials, and 24-hour fine particulate matter concentrations (PM_{2.5}) in cooking and sleeping areas.⁵

METHODS

This analysis uses data from a larger study that investigated household-level risk factors for both pneumonia and laboratory-confirmed influenza cases; to increase the efficiency of

evaluating risk factors for both of these respiratory outcomes, we recruited a common set of controls. In this work, we present findings from our investigation of the air quality risk factors for pneumonia; information about risk factors for influenza is forthcoming.

Participants in this study were recruited from the Kamalapur area in Dhaka, where the International Centre for Diarrheal Disease Research, Bangladesh (icddr,b) conducts active, population-based surveillance for respiratory and febrile illnesses in about 5,000 households. Kamalapur is a densely populated, low- and middle-income urban community in southeastern Dhaka; a major railway station is situated in Kamalapur and vehicular traffic is routed through the area from southeastern Bangladesh. The surveillance system has been described in previous publications.^{8,9} Briefly, children < 5 years of age with either clinical signs of respiratory illness at the time of the surveillance worker's visit or a report of multiple symptoms of respiratory illness during the preceding 7 days are referred for care at the icddr,b study clinic in Kamalapur. Parents from the surveillance area also seek care for ill children at the study clinic on their own. At the study clinic, children are evaluated by a project physician using standardized criteria for signs of pneumonia. Children with cough or difficulty breathing, age-specific tachypnea, and auscultatory evidence of crepitations are given a clinical diagnosis of pneumonia, and referred for chest radiography at the Monowara Hospital, also located within the Kamalapur community. Radiographs are subsequently interpreted by icddr,b project physicians for presence of infiltrates or lobar consolidation.

We obtained vaccination data for case and control children from the ongoing periodic demographic surveillance. Measles vaccine and a pentavalent vaccine that included diphtheria, pertussis, tetanus, *Haemophilus influenzae* type b, and Hepatitis B were available to children in Kamalapur at the time of this study; vaccines to prevent *Streptococcus pneumoniae* and influenza were not routinely available to residents of the Kamalapur area and, thus, were not queried.

Case and control recruitment. A pneumonia case was defined as clinical diagnosis of pneumonia, and radiograph findings indicative of any infiltrate or consolidation by the project physician in a child < 60 months of age presenting between March 2, 2009 and March 14, 2010. Each week, we

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listed the pneumonia cases identified during the previous week and selected a proportion of them for inclusion in the case-control study. We sought to maximize the number of cases and controls enrolled to maintain a minimum 2:1 ratio of controls to cases. Because we had a fixed number of field workers each week, the exact proportion of pneumonia cases to be enrolled varied weekly and was dependent on field-worker availability. Once the proportion of pneumonia cases to be enrolled was established, we used a random number generation function in Microsoft Excel (Microsoft Corp., Redmond, WA) to identify cases for potential recruitment. For recruitment into the case-control study, children's households were visited 3–4 weeks after the clinic visit that prompted chest radiography. This lag was implemented because of the potential for behaviors that may affect indoor air quality, such as opening of windows and doors, to be altered at the time of acute illness. At the recruitment visit, the fieldworker described the case-control study to the primary caregiver of the child with pneumonia and requested voluntary informed consent. We excluded case children if the household had previously been enrolled in the case-control study either as a case or as a control.

We recruited controls according to frequency matching by age group of cases: 0 to < 6 months, 6 to < 12 months, 12 to < 24 months, and 24 to < 60 months. Each week, we applied a random selection process to query the demographic information database for the surveillance area to identify a sufficient number of potential controls to maintain a 2:1 ratio of controls to cases. Potential controls were defined as children < 60 months of age, who had not had a clinic visit for respiratory symptoms within the preceding 6 months. This strategy led to case (and, hence, control) recruitment with similar frequency throughout the year of study. At the time of the initial visit to households of potential control children, the interviewer confirmed the absence of recent respiratory symptoms by asking whether the child had any respiratory symptoms during the preceding 4 weeks and that the household had not previously taken part in the case-control study. If the absence of respiratory symptoms was confirmed, the primary caregiver was requested to provide voluntary informed consent.

Data collection procedures. After obtaining informed consent, the field worker administered a questionnaire and observed the household environment, including the cooking and sleeping spaces. We measured concentrations of $PM_{2.5}$, using the University of California at Berkeley (UCB) particle monitor (<http://www.berkeleyair.com/products-and-services/instrument-services>). The UCB particle monitor has been validated in laboratory and household-level applications.^{3,10,11} We used a random number function in Microsoft Excel (Microsoft Corp.) to choose one-half of the case and control households for measurement of $PM_{2.5}$ concentrations; we relied on the random selection process to maintain an ~2:1 ratio of controls to cases among the subset of households with $PM_{2.5}$ measurement. In these households, we sought to measure $PM_{2.5}$ in the cooking space and the living area where the child was reported to sleep. Monitors were not placed if there was no roof, or if household members refused placement because of safety or other concerns. We used the operating procedures provided by the UCB group, and defined the limit of detection at 50 micrograms per cubic meter (mcg/m^3).¹² According to the UCB group's recommendations, we placed monitors in the cooking space ~1 meter from the stove, and ~1.5 meters above

the floor and away from windows and doors.¹³ In the living space, we placed the monitor at ~1.5 meters above the floor over the child's bed or sleeping area, and 1.5 meters horizontally away from openable doors and windows. We sought to record $PM_{2.5}$ concentration during a 24-hour period in each location. Because the data download procedure for the UCB particle monitor involves specifying the start and end times of sampling, we specified a start time immediately after the required 30 minutes zeroing time and downloaded a maximum of 24 consecutive hours of sampling, to ensure comparability of data across households.

Data analysis. We compared case and control households with respect to independent variables, including demographics and factors related to air quality. In a post-hoc decision after preliminary data analysis, we categorized households according to the number of people reported to sleep in the same room as the case child or control child based on the mean number reported for control households. Among the fuels used by at least one participating household, piped natural gas, liquefied petroleum gas, and kerosene were classified as "improved fuels."³ Wood and bamboo were classified as "unimproved fuels." We constructed a dichotomous variable to capture cross-ventilation, defined as the presence of at least one window or door in two or more opposing walls of the cooking or living space. To further explore the effects of increasing ventilation, we also developed an ordinal variable with five levels to describe ventilation: 1) only one door, 2) one window and one door or two doors in the same wall, 3) one window or door in two non-opposing walls, 4) one window or door in two opposing walls, and 5) one window or door in each of three or four walls.

Among households with particle monitor data, we retained in the analysis those households that had 24 hours of air quality monitoring to ensure comparability of monitoring periods; as noted previously, we limited data capture to 24 hours. We described the 24-hour geometric means, and the median of the 90th percentile of $PM_{2.5}$ readings. Furthermore, we compared case and control households with respect to 24-hour geometric means and medians of $PM_{2.5}$, and the number of hours that the $PM_{2.5}$ concentration exceeded 100 mcg/m^3 and 250 mcg/m^3 . Because the limit of detection of the UCB particle monitor (50 mcg/m^3) was twice as high as the World Health Organization (WHO) standard for indoor air quality (25 mcg/m^3), we could not investigate the number of hours that indoor $PM_{2.5}$ concentrations exceeded the WHO standard.¹⁴

We used logistic regression for bivariate and multivariate analyses to calculate odds ratios (ORs) and 95% confidence intervals (CIs), adjusting for age category in all analyses. In the overall data set, we used multivariate logistic regression models to further test air quality variables found to be associated with case-control status at $P < 0.10$ on bivariate analysis. Only those variables significantly associated with case-control status at the $P < 0.05$ level, after adjustment for all other variables in the model, were retained in the final multivariate analysis. We also examined potential confounding by socioeconomic status (SES). We included household assets, home ownership or rental, and respondent education in a principal component analysis and calculated factor scores based on the first component.¹⁵ Households were assigned to SES quartiles based on the distribution of principal component analysis-derived factor scores within the control group. The highest SES group was used as the referent for analyses.

TABLE 1

Associations between observed and reported risk factors and radiographically confirmed pneumonia among children < 60 months of age, Kamalapur, Dhaka, 2009–2010

Variable	Cases (<i>N</i> = 331)	Controls (<i>N</i> = 663)	Bivariate analysis* odds ratio (95% CI) <i>P</i> value	Multivariate analysis† Adjusted odds ratio (95% CI) <i>P</i> value
Demographic factors				
Age group of child				
< 6 months	16%	16%	—	—
6 to < 12 months	22%	21%	—	—
12 to < 24 months	32%	30%	—	—
24 to < 60 months	30%	33%	—	—
Male child	55%	48%	1.36 (1.04, 1.77) <i>P</i> = 0.02	1.35 (1.03–1.79) <i>P</i> = 0.03
Mean age of respondent in years ± SD	26.5 (6.5)	27.0 (6.7)	0.99 (0.97, 1.01) <i>P</i> = 0.45	—
Mean no. years education of respondent ± SD	3.7 (3.5)	5.3 (4.0)	0.90 (0.87, 0.94) <i>P</i> < 0.0001	—
Mean no. persons in household ± SD	5.2 (1.9)	5.0 (2.0)	1.05 (0.97, 1.12) <i>P</i> = 0.19	—
Mean no. children < 5 years old ± SD	1.3 (0.5)	1.3 (0.5)	1.21 (0.93, 1.57) <i>P</i> = 0.15	—
Mean no. rooms in the home (excluding the bathroom) ± SD	1.3 (0.8)	1.5 (1.1)	0.73 (0.62, 0.87) <i>P</i> = 0.0005	—
No. persons usually sleeping in case or control child's room				
Fewer than four	24%	38%	Ref	Ref
Four or more	76%	62%	1.89 (1.40, 2.54) <i>P</i> < 0.0001	1.60 (1.18–2.18) <i>P</i> = 0.003
Socioeconomic status				
Poorest (Quartile 1)	35%	25%	3.47 (2.24, 5.35) <i>P</i> < 0.0001	2.16 (1.33–3.51) <i>P</i> = 0.002
Quartile 2	30%	25%	2.92 (1.88, 4.53) <i>P</i> < 0.0001	2.07 (1.29–3.33) <i>P</i> = 0.003
Quartile 3	24%	25%	2.31 (1.47, 3.63) <i>P</i> < 0.0001	1.91 (1.20–3.05) <i>P</i> = 0.007
Wealthiest (Quartile 4)	11%	25%	1.00	1.00
Characteristics of cooking space				
Use of improved fuel	85%	91%	0.57 (0.38, 0.86) <i>P</i> = 0.006	—
Four walls present	52%	60%	0.66 (0.44, 0.99) <i>P</i> = 0.04	—
Brick or concrete walls	75%	83%	0.61 (0.44, 0.85) <i>P</i> = 0.003	—
Tin walls	6%	6%	0.98 (0.57, 1.71) <i>P</i> = 0.96	—
Roof present	92%	96%	0.49 (0.27, 0.86) <i>P</i> = 0.01	—
Tin roof	64%	55%	1.49 (1.14, 1.96) <i>P</i> = 0.004	—
Cooking space cross-ventilated‡	36%	41%	0.80 (0.60, 1.06) <i>P</i> = 0.12	—
Characteristics of living area				
Brick or concrete walls	60%	73%	0.58 (0.43, 0.76) <i>P</i> < 0.001	—
Tin walls	14%	11%	1.24 (0.84, 1.83) <i>P</i> = 0.29	—
Tin roof	78%	61%	2.33 (1.71, 3.16) <i>P</i> < 0.0001	1.54 (1.08–2.19) <i>P</i> = 0.02
Presence of working fan	98%	98%	0.88 (0.36, 2.12) <i>P</i> = 0.77	—
Living area cross-ventilated‡	41%	57%	0.53 (0.40, 0.69) <i>P</i> < 0.0001	0.72 (0.53–0.98) <i>P</i> = 0.04
Mean no. steps from stove to child's sleeping area ± SD	13 (9–19)	13 (10–19)	1.00 (0.99, 1.01) <i>P</i> = 0.89	—
At least one smoker in household	66%	58%	1.36 (1.04, 1.79) <i>P</i> = 0.03	—
Frequency of smoking in home: at least weekly	52%	42%	1.46 (1.12, 1.90) <i>P</i> = 0.006	—

* All odds ratios in bivariate analysis reflect adjustment for age group.

† All variables significantly associated with case-control status at the *P* < 0.20 level in bivariate analysis were tested in multivariate analysis. The final multivariate model included those associated with case-control status after inclusion of all other variables in the model: age group, sex of child, no. persons usually sleeping in child's room, socioeconomic quartile, tin roof in the living area, and cross-ventilation of living area.

‡ Cross-ventilation defined as one window or one door in two or more opposing walls.

CI = confidence interval.

Among households in which air quality monitoring were performed, we tested each variable describing particulate matter concentration in a separate multivariate model that included age group and all variables shown to be associated with pneumonia in the overall study population (Table 1). No two particulate matter concentration variables were simultaneously included in the same model.

RESULTS

Of 551 children identified with radiographically confirmed pneumonia during March 2009 to March 2010 through routine surveillance, we randomly selected 369 (67%) for inclusion in the case-control study of whom, 8 (2%) refused, and 12 (3%) were deemed ineligible. Consent was provided by caregivers of 349 pneumonia case-children; among these 18 (5%) later withdrew. Among 1,303 potential control children, 578 (44%) were deemed ineligible; 569 of these were ineligible because they had moved away from the residence listed in the demo-

graphic surveillance database. Caregivers of 716 (99%) of the remaining 725 potential controls provided consent; during data collection, 53 (7%) respondents withdrew. Thus, data were available from 331 radiographically confirmed pneumonia case children and 663 control children frequency matched by age group. The mean age of primary caregiver respondents was similar among cases and controls, but case respondents had significantly fewer years of education than controls in the bivariate analysis (Table 1). Case children were 1.36 times more likely to be boys, compared with control children (OR = 1.36, 95% CI = 1.04–1.77). Frequencies of measles vaccination were nearly identical among case (83%) and control (82%) children (*P* = 0.67); 12% of case children and 14% of control children were reported to have received the pentavalent vaccine (*P* = 0.21).

The number of persons living within the household was similar in the two groups (Table 1). The majority of households in both groups had only one room in the living area of the household, although cases had fewer rooms in the household on average. There was a higher mean number of

TABLE 2

Relationship between degree of ventilation in living area and odds of radiographically confirmed pneumonia among children < 60 months of age, Kamalapur, Dhaka, 2009–2010

Variable	Cases (N = 331)	Controls (N = 663)	Odds ratio (95% CI)*
Only one door	29%	16%	1.00
One window and one door or two doors in the same wall	18%	15%	0.63 (0.41, 0.99) <i>P</i> = 0.61
One window or door in two non-opposing walls	13%	12%	0.76 (0.47, 1.2) <i>P</i> = 0.51
One window or door in two opposing walls	26%	29%	0.57 (0.38, 0.86) <i>P</i> = 0.12
One window or door in each of three or four walls	15%	27%	0.56 (0.34, 0.95) <i>P</i> = 0.24

*The multivariate model included age group, socioeconomic status (SES) quartile, sex of child, ≥ 4 persons usually sleeping in child's room, and tin roof in the living area. Adjusted *P* value for trend was 0.07.

CI = confidence interval.

persons in the room where the child slept in case households (mean 4.5 persons [SD 1.3]), compared with control households (mean 4.1 persons [SD 1.2]). Case households were 1.89 times more likely than control households to be crowded (4 or more persons in the sleeping room) and 3.47 times as likely to be in the poorest SES quartile as in the wealthiest.

Compared with caregivers of controls (58%), caregivers of cases (66%) more frequently reported that at least one smoker lived in the household and that smoking happens at least weekly in the home (52% cases, 42% controls) (Table 1). Only 2 case (0.6%) and 10 control (2%) households located their stoves in their living areas; all others located their stoves in designated cooking spaces outside the living area.

Most case (85%) and control (91%) households used improved fuels (Table 1). Among those using improved fuels, all but one case household and all but two control households reported using piped natural gas. Case households were 39% less likely to have solely brick or concrete walls in the cooking space than control households. Cases' cooking spaces were less likely than controls' to have four walls or a roof. Interviewers observed only one door and no windows in the cooking space of 37% of case households and 35% of control households. The frequency of cross-ventilation, defined as the presence of at least one window or door in opposing walls, was similar in the cooking spaces of case (36%) versus control (41%) households.

Having solely concrete or brick walls was less common in case households' main living spaces than in control households

(Table 1). Roofs made of tin, as opposed to other types of materials, were 2.3 times as likely to be observed in living areas of case households as in control households. Tin was the material of all four walls in only 12% of living spaces, a finding not associated with pneumonia case status; almost all of the households with four walls made of tin were in the lower two socioeconomic strata. Cross-ventilation of case children's sleeping spaces was nearly 50% less common than of sleeping spaces of control children. Almost all households in each group (98%) had a working fan; we did not inquire about fan use practices.

Cross-ventilation and observation of a tin roof in the living space were associated with SES. Compared with households in the highest SES quartile, households in the lowest SES quartile were one-eighth as likely to have a cross-ventilated living space ($P < 0.0001$), and five times as likely to have a tin roof ($P < 0.0001$). We evaluated but did not find statistical evidence of multicollinearity between SES and either cross-ventilation or presence of a tin roof in the living space, and thus, we included all of these variables in our multivariate models.

In multivariate analysis, several risk factors were independently and significantly associated with pneumonia case status after adjustment for age group and SES quartiles (Table 1). Case children were 35% more likely than control children to be male, and their households were 60% more likely to be crowded. Compared with those of control children, living spaces of case children were 54% more likely to be covered with tin roofs, and 28% less likely to be cross-ventilated.

TABLE 3

Analysis of risk factors for radiographically confirmed pneumonia among children < 60 months of age, stratified by crowding, Kamalapur, Dhaka, 2009–2010

Variable	Overall	Crowded households (≥ 4 persons sleeping in same room as child) N = 665*	Less crowded households (< 4 persons sleeping in same room as child) N = 329†
Age group of child			
< 6 months	Ref	Ref	Ref
6 to < 12 months	1.04 (0.66, 1.63)	1.20 (0.71, 2.03)	0.67 (0.27, 1.66)
12 to < 24 months	1.14 (0.75, 1.74)	1.28 (0.78, 2.10)	0.79 (0.34, 1.81)
24 to < 60 months	0.97 (0.63, 1.48)	1.03 (0.63, 1.69)	0.71 (0.30, 1.65)
Sex	1.35 (1.03, 1.79)	1.21 (0.87, 1.67)	2.00 (1.16, 3.45)
SES			
Quartile 1 (poorest)	2.16 (1.33, 3.51)	1.61 (0.91, 2.86)	5.04 (1.93, 13.20)
Quartile 2	2.07 (1.29, 3.33)	1.87 (1.07, 3.27)	2.13 (0.83, 5.49)
Quartile 3	1.91 (1.20, 3.05)	1.60 (0.91, 2.83)	2.89 (1.22, 6.87)
Quartile 4 (wealthiest)	Ref	Ref	Ref
Cross-ventilated living space‡	0.72 (0.53, 0.98)	0.58 (0.40, 0.83)	1.40 (0.77, 2.55)
Tin roof in living space	1.54 (1.08, 2.19)	1.31 (0.86, 2.0)	2.41 (1.22, 4.80)
Crowding (≥ 4 persons sleeping in same room as index child)	1.60 (1.18, 2.18)	n/a	n/a

P value for interaction between crowding and cross-ventilated living space was 0.13. *P* values for terms evaluating interaction between crowding and each of the other variables of interest (child sex, socioeconomic status [SES], and tin roof in the living space) all exceeded 0.20.

*251 cases, 414 controls.

†80 cases, 249 controls.

‡Cross-ventilation defined as one window or one door in two or more opposing walls.

TABLE 4

Bivariate and multivariate analysis of fine particulate matter (PM_{2.5}) concentrations in cooking spaces of households of children with and without pneumonia, Kamalapur, Dhaka, Bangladesh, 2009–2010

Cooking space	Cases (<i>N</i> = 97)	Controls (<i>N</i> = 215)	Bivariate analysis odds ratio* (95% CI), <i>P</i> †	Multivariate analysis odds ratio‡ (95% CI), <i>P</i>
Median of 24-hour geometric mean PM _{2.5} (mcg/m ³) (IQR)	76.4 (64.4–90.6)	69.7 (61.1–87.7)	1.00 (0.998–1.003), <i>P</i> = 0.84	1.00 (0.996, 1.002), <i>P</i> = 0.68
Median of 90th percentile of PM _{2.5} (mcg/m ³) readings (IQR)	162.9 (96.1–266.8)	135.8 (92.7–234.2)	1.00 (1.00–1.00), <i>P</i> = 0.39	1.00 (1.00, 1.00), <i>P</i> = 0.88
Median number of hours PM _{2.5} > 100 mcg/m ³ (IQR)	4.5 (2.3–7.4)	3.9 (2.1–6.8)	1.04 (0.98–1.10), <i>P</i> = 0.22	1.02 (0.95, 1.08), <i>P</i> = 0.65
PM _{2.5} > 100 mcg/m ³ for 4 hours or more	60%	48%	1.64 (1.0, 2.69), <i>P</i> = 0.05	1.28 (0.75, 2.20), <i>P</i> = 0.37
Duration PM _{2.5} > 100 mcg/m ³				
Less than 4 hours	40%	52%	1.00 (p for trend = 0.14)	1.00 (p for trend = 0.67)
4 to < 6 hours	27%	18%	1.96 (1.04, 3.67), <i>P</i> = 0.14	1.41 (0.72, 2.77), <i>P</i> = 0.43
6 to < 8 hours	11%	13%	1.14 (0.52, 2.51), <i>P</i> = 0.48	0.97 (0.42, 2.27), <i>P</i> = 0.54
> 8 hours	22%	17%	1.71 (0.88, 3.30), <i>P</i> = 0.40	1.36 (0.67, 2.74), <i>P</i> = 0.55
Median number of hours PM _{2.5} > 250 mcg/m ³ (IQR)	1.3 (0.7–2.5)	1.0 (0.4–2.2)	1.06 (0.98–1.15), <i>P</i> = 0.03	1.02 (0.93, 1.11), <i>P</i> = 0.73
PM _{2.5} > 250 mcg/m ³ for 1 hour or more	63%	50%	1.70 (1.03, 2.81), <i>P</i> = 0.04	1.28 (0.74, 2.23), <i>P</i> = 0.38
Duration PM _{2.5} > 250 mcg/m ³				
< 1 hours	37%	50%	1.00 (p for trend = 0.17)	1.00 (p for trend = 0.85)
1 to < 2 hours	29%	23%	1.72 (0.94, 3.17), <i>P</i> = 0.49	1.31 (0.68, 2.54), <i>P</i> = 0.69
2 to < 3 hours	14%	12%	1.62 (0.76, 3.46), <i>P</i> = 0.74	1.28 (0.56, 2.92), <i>P</i> = 0.82
> 3 hours	20%	15%	1.74 (0.88, 3.47), <i>P</i> = 0.52	1.23 (0.59, 2.59), <i>P</i> = 0.92

*All odds ratios in bivariate analysis reflect adjustment for age group.

†*P* values were calculated using unconditional logistic regression for categorical variables.

‡Each particulate matter indicator was tested in a separate multivariate model that include age group and all variables shown to be associated with pneumonia case status in the overall study (Table 1): male sex, socioeconomic status (SES), crowding, cross-ventilation, and tin roof in living space. No two particulate matter variables were tested simultaneously in the same model.

CI = confidence interval; IQR = interquartile range.

Cases were about twice as likely as controls to be in each of the poorest three SES quartiles, rather than in the wealthiest.

On further analysis, we sought to understand whether there was a relationship between degree of ventilation and pneumonia case status (Table 2). Although the point estimates suggest decreasing odds of pneumonia with increasing ventilation, CIs for those point estimates for each of the ventilation categories were largely overlapping.

We performed stratified analysis to evaluate interaction between crowding and several of the other risk factors independently associated with pneumonia (Table 3). Cross-ventilation of the living space was inversely associated with pneumonia among crowded households (OR_{adj} = 0.58, 95%

CI = 0.40–0.83), but not in households that reported fewer than four persons sleeping in the case- or control child's room (OR_{adj} = 1.40, 95% CI = 0.77–2.55). A term describing the interaction between crowding (four or more persons in the sleeping room) and cross-ventilation into a multivariate model containing all of the risk factors independently associated with pneumonia was not statistically significant (*P* = 0.13). Confidence intervals were largely overlapping between the two crowding strata for each of the other variables of interest (male sex of the child, SES quartile, and presence of a tin roof in the living space).

Fine particulate matter was measured for a 24-hour period in the cooking spaces of 97 (29%) case and 215 (32%) control

TABLE 5

Bivariate and multivariate analysis of fine particulate matter (PM_{2.5}) concentrations in living spaces of households of children with and without radiographically confirmed pneumonia, Kamalapur, Dhaka, Bangladesh, 2009–2010

Living space	Cases (<i>N</i> = 168)	Controls (<i>N</i> = 317)	Bivariate analysis odds ratio* (95% CI), <i>P</i> †	Multivariate analysis odds ratio‡ (95% CI), <i>P</i> ‡
Median of 24-hour geometric mean PM _{2.5} (mcg/m ³) (IQR)	70 (61–93)	68 (59–90)	1.00 (0.98–1.00), <i>P</i> = 0.86	1.00 (0.99, 1.00), <i>P</i> = 0.35
Median of 90th percentile of PM _{2.5} readings	142 (96–271)	126 (88–268)	1.00 (0.999–1.00), <i>P</i> = 0.41	1.00 (0.99, 1.00), <i>P</i> = 0.26
Median number of hours PM _{2.5} > 100 mcg/m ³ (IQR)	4.2 (2.1–7.6)	3.7 (1.8–7.4)	1.02 (0.97–1.06), <i>P</i> = 0.44	0.99 (0.94, 1.04), <i>P</i> = 0.62
PM _{2.5} > 100 mcg/m ³ for 2 hours or more	78%	72%	1.41 (0.91, 2.19), <i>P</i> = 0.13	1.17 (0.73, 1.88), <i>P</i> = 0.51
Duration PM _{2.5} > 100 mcg/m ³				
Less than 2 hours	22%	28%	1.00 (p for trend = 0.31)	1.00 (p for trend = 0.75)
2 to < 4 hours	26%	26%	1.29 (0.76, 2.19), <i>P</i> = 0.97	1.22 (0.69, 2.15), <i>P</i> = 0.62
4 to < 8 hours	30%	23%	1.67 (0.98, 2.84), <i>P</i> = 0.11	1.28 (0.73, 2.26), <i>P</i> = 0.43
> 8 hours	23%	22%	1.30 (0.75, 2.25), <i>P</i> = 0.98	1.01 (0.56, 1.81), <i>P</i> = 0.55
Median number of hours PM _{2.5} > 250 mcg/m ³ (IQR)	1.0 (0.3–2.8)	0.7 (0.1–2.5)	1.02 (0.95–1.09), <i>P</i> = 0.64	0.98 (0.91, 1.05), <i>P</i> = 0.58
PM _{2.5} > 250 mcg/m ³ for 30 minutes or more	67%	56%	1.65 (1.12, 2.45), <i>P</i> = 0.01	1.31 (0.86, 1.99), <i>P</i> = 0.21
Duration PM _{2.5} > 250 mcg/m ³				
< 30 minutes	33%	44%	1.00 (p for trend = 0.054)	1.00 (p for trend) <i>P</i> = 0.44
30 to < 60 minutes	16%	14%	1.60 (0.90, 2.84), <i>P</i> = 0.77	1.46 (0.80, 2.68), <i>P</i> = 0.51
60 to < 120 minutes	17%	11%	2.12 (1.18, 3.80), <i>P</i> = 0.10	1.55 (0.83, 2.89), <i>P</i> = 0.36
> 120 minutes	34%	31%	1.51 (0.96, 2.38), <i>P</i> = 0.98	1.15 (0.71, 1.87), <i>P</i> = 0.55

*All odds ratios in bivariate analysis reflect adjustment for age group.

†*P* values were calculated using unconditional logistic regression for categorical variables.

‡Each particulate matter indicator was tested in a separate multivariate model that includes age group and all variables shown to be associated with pneumonia case status in the overall study (Table 1): male sex, SES, crowding, cross-ventilation and tin roof in living space. No two particulate matter variables were tested simultaneously in the same model.

CI = confidence interval; IQR = interquartile range.

households, and in the living spaces of 168 (51%) case and 317 (48%) control households. From further analyses, we excluded data from several households that had air quality monitors placed, but for fewer than 24 hours: five households with fewer than 24 hours of PM data from the cooking space, and three households with fewer than 24 hours of PM data from the living space.

The median of the 24-hour geometric mean PM_{2.5} in the cooking space was high among both case (76.4 mcg/m³) and control (69.7 mcg/m³) households (Table 4), with similarly high geometric means in the living space (Table 5). In general, particulate matter exposures were higher in cooking and living spaces of case households. In bivariate analysis, cooking spaces of case households were 1.64 times as likely as those of control households to have PM_{2.5} exceeding 100 mcg/m³ for 4 or more hours. Similarly, cooking spaces of case households were 1.70 times as likely as those of control households to have PM_{2.5} exceeding 250 mcg/m³ for 1 or more hours; living spaces of case households were 1.65 times as likely as those of control households to have PM_{2.5} exceeding 250 mcg/m³ for 30 or more minutes. There was no significant relationship between increasing duration of hours that PM_{2.5} exceeded 100 mcg/m³ or 250 mcg/m³ in either location and pneumonia case status. None of the PM_{2.5} measures were significantly associated with pneumonia in multivariate analysis.

DISCUSSION

Interventions to reduce environmentally mediated pneumonia in resource-limited settings have largely focused on improved stoves and fuel (www.cleancookstoves.org). Our data suggest that, in the context of a densely populated urban area with widespread access to improved cooking fuels, the high pneumonia prevalence could be reduced by interventions to increase ventilation and decrease crowding in homes. As the world becomes increasingly urbanized and the supply of improved cooking fuels to residents of urban areas improves, the high burden of respiratory illnesses attributable to poor indoor air quality in urban populations may be reduced by improving ventilation and decreasing crowding. Particulate matter concentrations in both cooking and living spaces of case and control children exceeded the WHO guidelines for indoor particulate matter exposure (24 hour mean of 25 mcg/m³), reflecting poor ambient air quality, a widespread concern in the world's low-income megacities.¹⁴

Our findings of a 60% increase in the odds of pneumonia among children living in crowded households are consistent with those of Cardoso and colleagues, who used the same cut-off of > 4 persons per room and described a 2.5-fold increase in the odds of all-cause respiratory infections among young children.¹⁶ Various other definitions of crowding have been associated with infectious respiratory outcomes, including the number of children sleeping in the same room as the index child (respiratory syncytial virus infection)¹⁷; person density or the number of people living in a household divided by the number of rooms in the home (influenza-like illness)¹⁸; and small living area (nasopharyngeal carriage of *Haemophilus influenzae* type B and *S. pneumoniae*).¹⁹

Crowding was particularly a risk factor for pneumonia in households that were not cross-ventilated, which is consistent with data from Hoge and colleagues,²⁰ who showed that the

rates of *S. pneumoniae* incidence were highest in prison cell environments that were both crowded and poorly ventilated, compared with prison cells that did not share both of these risk factors. Crowding may be addressed in the long term by increasing the space allocated to households with large numbers of people, and reducing household size; by reducing the total fertility rate of women of child-bearing age, Bangladesh has made substantial strides in reducing household size. Efforts to increase the ventilation especially of the homes occupied by crowded households may also reduce their children's risk of pneumonia.

Cross-ventilation of the living space likely decreases a child's risk of respiratory infection through several mechanisms. By enhancing natural air flow, cross-ventilation may facilitate microbe clearance from the household environment, thereby directly decreasing a child's risk of exposure to respiratory pathogens. By promoting air exchange, cross-ventilation can also lead to reduced particulate matter concentrations indoors, which is expected to decrease the risk of lung injury²¹ and, hence, the susceptibility to respiratory pathogens. In a secondary analysis of data from the control arm of this case-control study, we have identified a significant inverse association between increasing levels of ventilation in the living space and the number of hours during which indoor PM_{2.5} concentrations exceed 100 mcg/m³ (Crabtree-Ide C, personal communication). Because our findings did not show a relationship between indoor PM_{2.5} concentrations and pneumonia, it is possible that cross-ventilation affects pathogen clearance directly in the Kamalapur context. Cross-ventilation may also be a proxy for sunlight exposure, which directly reduces the survival of pathogens on surfaces.²²

In their systematic review of the role of ventilation on transmission of respiratory pathogens in indoor environments, Li and others²³ concluded that there is sufficient evidence to implicate ventilation factors in the airborne transmission of respiratory pathogens but found little information on the minimal requirements for adequate ventilation in home settings. Whereas our relatively crude measure of ventilation was based on the number of walls with ventilation structures (windows or doors) present, other ventilation measures shown to be associated with either indoor particulate matter concentrations or respiratory outcomes in observational studies have included the presence of ventilation grates,⁵ opening of kitchen windows after cooking,²⁴ the number of windows and doors open to ambient air,²⁵ and the number of walls with eave space.²⁶ These observational studies offer suggestions of locally acceptable options to increase ventilation. In addition, the use of electric fans may increase ventilation in some settings. Although there is nearly universal fan ownership in Kamalapur, inconsistent electricity supply may hamper fan use.²⁷ Much of the experimental work on increasing ventilation in low-income settings has focused on ventilation of cookstoves. However, we find no experimental studies set in low-income communities investigating the impact of increasing ventilation in living spaces by these or other measures. Experimental studies are needed to investigate the impact of increasing living area ventilation, either through structural or behavioral changes or both, on indoor air quality, particularly in crowded urban areas.

In our multivariate analysis, case households were significantly more likely than control households to have tin roofs in the living space, even after adjusting for SES. Because

particulate matter deposits more efficiently on rough and porous surfaces (such as brick) than on smooth surfaces,²⁸ in an environment with smooth surfaces such as tin, particulate matter can stay suspended in the air as opposed to being deposited on the wall and thereby removed from air circulation.²⁹ Further research in low-income communities could evaluate the impact of roof and wall material on air flow, pathogen clearance, and particulate matter concentrations, and identify and test low-cost options that will decrease the circulation of air pollutants and the transmission of airborne pathogens.

In the Kamalapur area, particulate matter concentrations in cooking and sleeping spaces exceeded WHO guidelines for indoor air quality severalfold in both case and control households. Because biofuel use for cooking is relatively uncommon in Kamalapur, and 24-hour median PM concentrations are relatively similar in case and control households, high indoor PM concentrations are likely attributable to ambient air pollution. A study of ambient air pollution between 2002 and 2007, several years before this study, found PM_{2.5} concentrations exceeding the WHO standard in all six sites in Dhaka city; average PM_{2.5} concentrations in the site closest to Kamalapur (Lalbag) was 99.0 mcg/m³.³⁰ Possible sources of ambient air pollutants in the Kamalapur surveillance community include vehicular traffic, diesel engines³¹ on trains at the major railway station in Kamalapur, and the hundreds of brick kilns located in peri-urban Dhaka.³² Although PM_{2.5} concentrations in Kamalapur homes are certainly lower than in communities where biofuel is the dominant cooking fuel used,³³ our findings suggest that Kamalapur residents, young and old, are at risk for numerous cardiovascular and respiratory health effects likely associated with high levels of particulate matter.

Our sample size was insufficient to establish precise PM_{2.5} dose-response relationships with pneumonia case status. We selected a subset of participating households for the PM_{2.5} monitoring because of logistical considerations, which may limit generalizability. Moreover, the UCB particle monitors may not have detected small but clinically meaningful differences in PM_{2.5} concentrations. Although it would have potentially been useful to estimate the number of hours that the PM_{2.5} concentration exceeded 25 mcg/m³, the WHO 24-hour guideline for air quality, we were unable to do so because the lower limit of detection of the monitors is 50 mcg/m³. The median of the 24-hour geometric mean could be an overestimation of actual PM concentrations, given the high lower limit of detection. However, we also report a number of measures that overcame the relatively high lower limit of detection by examining exposures to very high concentrations of PM_{2.5}: number of hours PM_{2.5} exceeds 100 mcg/m³ and 250 mcg/m³. Therefore, this study contributes to the relatively sparse literature on meaningful thresholds of PM_{2.5} for disease risk.³⁴

The exact proportion of pneumonia cases enrolled, and thus controls, varied weekly based on the fixed size of the field team. We did not have surge capacity to increase enrollment during seasons with relatively high pneumonia identification. Therefore, the distribution of etiologies of pneumonia among cases enrolled in this study is not necessarily representative of the distribution of etiologies of all pediatric pneumonia occurring in Kamalapur. Because we tested a number of potential explanatory variables, some of the associations we detected could have been a result of chance. However, there is biologic plausibility for the relationship between each variable associated with pneumonia in multivariate modeling. We

chose to collect data for this study several weeks after the pneumonia episode in case children. Although this approach risks the possibility of reverse causality, in that the illness may have led to prolonged alterations in behavior, we did so purposefully to allow for any acute illness-related behaviors to revert to more typical behaviors.

In a densely crowded community in which one in two children experiences an episode of pneumonia each year, we have identified crowding as a particularly strong risk factor, which may be addressed in part by improving ventilation of the living areas. Our work spurs a number of questions about the measurement of and, more importantly, the efficacy and feasibility of improving ventilation to decrease respiratory infection risk. Low-technology, low-cost solutions to optimize pathogen clearance, and air exchange in the living and cooking environments of low-income urban communities that experience high pneumonia burden could significantly reduce childhood pneumonia and the huge number of deaths associated with it.

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