

ORIGINAL ARTICLE

A Longitudinal Analysis of the Efficacy of Environmental Interventions on Asthma-Related Quality of Life and Symptoms Among Children in Urban Public Housing

J. E. CLOUGHERTY,^{1,*} J. I. LEVY,¹ H. P. HYNES,² AND J. D. SPENGLER¹

¹Harvard School of Public Health, Department of Environmental Health, Boston, Massachusetts, USA

²Boston University School of Public Health, Department of Environmental Health, Boston, Massachusetts, USA

In an environmental intervention study in public housing, we examined monthly Juniper Paediatric Asthma Quality of Life (QOL) Questionnaires for 51 children. Longitudinal analysis and spline models were used to identify time periods with significant improvements in QOL to inform judgments about causality. We found significant improvements in QOL, with moderate improvements before environmental interventions, increased rates of improvement immediately after, and reduced rates more than 5 months post-intervention. Effect modification analyses identified high-risk subpopulations and emphasized the importance of environmental, social, and economic conditions. Our results demonstrate the value of longitudinal techniques in evaluating the benefits of environmental interventions for asthma.

Keywords childhood asthma, quality of life, symptoms, environmental interventions, indoor air

INTRODUCTION

Severe asthma disproportionately affects minority children in lower-income urban communities in the U.S. where complex environmental and social exposures may play a role in the etiology and exacerbation of a highly multifactorial disease. Asthma currently accounts for approximately 14.7 million missed school days and 11.8 million missed workdays, 1.9 million emergency department visits, and 196,000 pediatric hospital admission per year (1). The dramatic increase in asthma prevalence over the past two decades (2) and the disproportionate impact of severe asthma on inner-city children (3) indicate that genetics alone cannot be responsible for asthma etiology.

A number of environmental, economic, and social factors have been related to asthma exacerbation and may also affect baseline immune function and responsiveness to environmental triggers. Environmental exposures include allergens such as pollen (4), pets, dust mites, cockroach and rodent antigen (3), ambient air pollution including vehicle exhaust (5), household size, crowding and exposure to viral illness, environmental tobacco smoke (ETS) (6), and weather (7). Cockroach and mouse antigen, more prevalent in low-income urban housing, can act as triggers for asthma and other atopic disease (8), and pesticides, used to combat infestation, may induce immune dysregulation (9, 10) and allergic disease. Socioeconomic factors including poverty (both individual and neighborhood level), poor nutrition and housing stock, access to healthcare and pharmacies, and regimen compliance can influence asthma patterns. In addition, sociobehavioral and

indoor environmental factors including anxiety, exercise, and household smoking habits may play a role, and psychological stress (11, 12) and exposure to violence have been shown to directly alter immune function and inflammation (13–15). The immune effects of social and psychological stressors may contribute to increased susceptibility within the same neighborhoods where physical environmental exposures may be elevated. The marked geographic and social patterning of asthma severity closely mirrors the distribution of a number of these social and environmental exposures and may result from multiplicative effects among them.

A few recent studies have explored the efficacy of allergen-reducing environmental interventions to alleviate childhood asthma, and most have found some reduction in symptoms (16, 17). One study of preventative interventions (HEPA vacuuming, dust mite covers, carpet removal, and chemical dust mite control) found reduced symptoms at one year (18), although one meta-analysis found no effect of dust mite control on symptoms (19). The National Cooperative Inner-City Asthma Study (NCICAS) found long-term reductions in reported symptoms and symptom-days, disruption of caretaker's plans, lost sleep for child and caregiver, and missed school days with behavioral interventions to reduce exposures to ETS, cockroach, mouse, mold, and pets (20). Some prior work examined varying symptom improvement rates with interventions; NCICAS identified higher improvement rates during the first 2 months after initiating home interventions. This study relied on 2-week reports of symptoms, unplanned doctors' visits, and other endpoints, and detected greater improvements in the intervention group, during both the intervention and follow-up year. In contrast, our study uses formal longitudinal analysis and dense temporal data collection to examine trends in quality of life and symptom improvement and to understand intervention efficacy without a control group.

*Corresponding author: Jane E. Clougherty, Harvard School of Public Health, Department of Environmental Health, Landmark Center, Room 404-West, P.O. Box 15677, Boston, MA 02215; E-mail: jcloughe@hsph.harvard.edu

Few studies have examined whether in-home environmental interventions may differentially benefit some asthmatic individuals. NCICAS indicated several economic and social factors that may interfere with asthma management and thereby modify intervention efficacy, including limited asthma problem-solving skills, multiple asthma managers, child and adult adjustment problems, and higher life stress (11). However, NCICAS did not explicitly explore effect modification in intervention compliance or efficacy by social, medical, economic, or environmental factors.

In general, intervention studies have not yet identified the most effective environmental interventions for asthma, largely because indoor interventions tend to be bundled (i.e., integrated pest management includes intensive cleaning and incorporates aspects of education and support). Further, most studies have focused on direct exposure reductions from interventions but have not explicitly considered context, as we have done in this multifactorial investigation. Finally, few studies used longitudinal approaches to investigate time trends in health improvements around interventions, and no previous studies, to our knowledge, have explored effect modification of housing interventions for asthma in detail.

The Boston Healthy Public Housing Initiative (HPHI), a collaborative community-based participatory research study, examined whether environmental interventions may be effectively introduced into this setting to alleviate symptoms of pre-existing childhood asthma. Specifically, HPHI investigates whether in-home environmental interventions (including replacement of mattresses, industrial cleaning, and integrated pest management) can reduce asthma exacerbation among children 4 to 17 years of age living in Boston public housing and what factors may modify the efficacy of interventions.

This paper examines the efficacy of a set of targeted in-home environmental interventions, using dense longitudinal data collection and statistical methods to capture time trends in respiratory symptom experience. Additionally, we examine key factors in the social, physical, and medical environment that may modify the efficacy of the interventions, potentially providing insight about both causality and means of more effectively allocating intervention resources, from both a cost and health perspective, for optimal environmental improvement and asthma alleviation.

MATERIALS AND METHODS

Between April 2002 and January 2003, 78 asthmatic children between 4 and 17 years of age were recruited from three public housing developments in Boston. Of those, 58 children in 44 households remained in the study to receive environmental interventions, and 51 were retained through exit questionnaires in August 2003. This analysis examines data from 520 Juniper Paediatric Asthma Quality of Life Questionnaires (PAQLQ) from 51 participants, with 3 months or more data capture per child before intervention, and 5 to 9 months per child post-intervention. Recruiting efforts and enrollment criteria are detailed elsewhere (21).

Given rolling recruitment and the inherent seasonality of asthma, we chose to implement interventions in two phases. During fall 2002, 13 households in one development (Franklin Hill) received four environmental interventions:

- *Replacing the child's mattress* with a microfiber mattress to prevent dust mite migration.
- *Industrial cleaning* to remove accumulated in-home allergens, and using caulking and expandable spray foam in cracks to reduce pest entry.
- *Integrated pest management (IPM)* to reduce infestation with minimal pesticide application. IPM visits included (1) initial assessment and trap placement, (2) recovery and counting of traps, (3) minimal, targeted pesticide treatment using bubbletraps and gels, and (4) additional treatments as necessary.
- *In-home education about IPM.* IPM relies on participant cleaning behaviors. Residents were trained in basic pest and pesticide concepts and measures to minimize available food, water, and shelter for pests. Storage bins, covered garbage cans, mops, and brooms were provided. Residents were encouraged to submit work orders to the Boston Housing Authority for holes in walls, torn window screens, and other repairs to reduce pest entry.

During spring 2003, the remaining 31 households from 3 developments received similar interventions. Radiators were cleaned in all homes, although industrial cleaning was more intensive in homes with visible signs of roach infestation. A limited asthma education/case management effort was provided to all participants throughout the study, wherein a Community Health Nurse created asthma action plans with the families and provided peak flow meters. The nurse facilitated some linkages with health care providers for children in acute distress before environmental interventions and evaluated medications monthly to assess changes in respiratory health and adherence to medication regimens. Community Health Advocates (CHAs), members of the developments or surrounding neighborhoods who were trained in basic asthma advocacy and interviewing techniques, provided ongoing support and some asthma education. This limited case management approach was designed to ensure that all children had access to roughly similar baseline health care, enabling us to better isolate the influence of environmental interventions.

Measures

Standardized health outcomes questionnaires were administered monthly by the same CHA matched with particular families, starting at intake and continuing through the post-intervention periods. Questionnaires were directly administered to older children, and caretakers responded for children under 8 years of age. Questionnaires included PAQLQ for both child and caregiver (22), questions on symptom frequency that would allow for asthma severity classification according to National Heart, Lung, and Blood Institute (NHLBI) guidelines, unplanned ED/clinic visits, missed school/work days, and medication use changes. Here, we focus on the child's PAQLQ results, which provided the greatest variability in responses and broad representation of impacts of asthma on the children's lives.

The PAQLQ is a 23-item questionnaire that evaluates asthma quality of life in three domains: Symptoms ($n = 10$), Activity Limitation ($n = 5$), and Emotional Function ($n = 8$) (23). The score for each domain is the average of all the items within it, and the symptom and activity limitation subscales are reverse-scored. Scores range from 1 to 7, with 7 as the

optimal score for any item or domain. A Total PAQLQ score is calculated as the mean score across all three domains, and this total is used here as the key longitudinal outcome. In addition, we repeat all significant results for the Total PAQLQ score for the Symptom domain.

The PAQLQ is validated as both an evaluative (within-subject variation) and discriminative (between-subject variation) instrument. The evaluative properties of the instrument, of most interest to our study, have been validated with paired *t* tests of the sensitivity of the PAQLQ instrument to detect asthma changes due to treatment and natural fluctuations in asthma over time, such as seasonality ($p < 0.001$), and to differentiate these groups from those who remained stable over time ($p < 0.0001$). Intraclass correlations (ICC) also held among groups who remained stable over time (ICC = 0.95) (22). The scale has been validated for childhood populations in several countries (24) and used to examine effects of poverty, social support, age (25), obesity (26), and medication changes (27) on asthma QOL, as well as the effect of QOL and emotional function on emergency department visits, school absenteeism, and doctors' visits. An improvement of 0.5 points on this scale, maintaining a constant medication regimen, is shown to be clinically significant (22).

With the exception of environmental sampling covariates and allergy status, all effect modifiers were drawn from enrollment questionnaires and are summarized elsewhere (21). This questionnaire, administered to the primary caretaker, included questions about symptom frequency, self-reported allergies, perceived indoor environmental exposures, and social stress indicators for the caregiver: the four-item perceived stress scale (PSS) (28), self-reported fear of violence, and the My Child's ETV scale (29). Environmental sampling for cockroach antigens, pesticides, and nitrogen dioxide (NO₂) was performed in each home before and after environmental interventions. Allergy testing was performed once using the prick puncture method. Methods and results for environmental sampling are detailed elsewhere (30, 31).

Analytic Methods

Mixed models in SAS version 9.1 were used to examine PAQLQ changes over time and compare improvements in multiple time intervals (pre-intervention, up to 5 months post-intervention, greater than 5 months post-intervention). Knot points at intervention and 5 months post-intervention were selected by AIC fit.

The longitudinal model to examine overall improvements over the course of the study is:

$$Y_{ij} = \beta_0 + \beta_1 * \text{Time}_j + e_{ij} \quad (1)$$

The general longitudinal model to examine outcomes in multiple periods is:

$$Y_{ij} = \beta_0 + \beta_1 * \text{Time}_j + \beta_2 * \text{Post} * \text{Time}_j + \beta_3 * (\text{GT5_MonthsPost})_j * \text{Time}_j + e_{ij} \quad (2)$$

The general longitudinal model to examine effect modification is:

$$Y_{ij} = \beta_0 + \beta_1 * \text{Group}_i + \beta_2 * \text{Time}_j + \beta_3 * \text{Group}_i * \text{Time}_j + e_{ij} \quad (3)$$

Where Y_{ij} is total PAQLQ score (continuous, where i = housing unit and j = time), Group is binary for each effect modifier except housing development, which is categorical. Time is continuous, centered around the date of initial home intervention (intensive cleaning); group differences in the intercept indicate differences at time of intervention. Post is binary, indicating whether each measurement occurs before or after intervention, and GT5_Months is binary, indicating whether the measure occurred more than 5 months after the initial intervention date. Errors are assumed normally distributed. Reported results reflect the random intercept model only, with random slopes by household for exposure correlation within seven sibling pairs in our study. Models were repeated with random slopes to confirm directionality of results, although sample size limits significance. Also due to power limitations, the effect modification model in Equation 3 excludes knot points, although again we evaluate the sensitivity of our findings to inclusion of these knot points.

To evaluate effect modification, or whether interventions were more beneficial for some children than others, providing some insight towards causality, we considered the following potential modifiers individually:

- **Demographic variables:** child's age, sex, race/ethnicity, housing development
- **Individual health risk factors:** allergies to cockroach and dust mite antigen, NHLBI asthma severity classification at enrollment, overweight, admitted to Neonatal Intensive Care Unit (NICU) at birth, respirator at birth, under 5 pounds birthweight, eczema
- **Social factors:** perceived stress, fear of violence, restricted outdoor play due to parental fear of violence, social capital
- **Medical care indicators:** having a doctor to call other than the emergency department (ED), properly medicated at study intake
- **Environmental factors:** season of intervention, time spent around smokers, smokers living in home, kitchen NO₂ concentrations, measured cockroach antigen reductions (kitchen Bla g 1 and Bla g 2), pesticide reductions (diazinon, chlorpyrifos, permethrin, cyfluthrin, cypermethrin, and esfenvalerate).

Reductions in kitchen concentrations of Bla g 1, Bla g 2, and six pesticide analytes were dichotomized at the median to indicate relative reductions in the highest-concentration area of the home. Reductions were calculated by comparing pre-intervention and average post-intervention concentrations. Homes were dichotomized at median kitchen NO₂ concentrations during heating season (median = 51 ppb). Medication adequacy at baseline was assessed by physician review of reported prescriptions and asthma severity, as determined by symptom frequency and spirometry.

Effect modifiers were explored individually. In each case, the cohort was dichotomized by the modifier, and, due to sample size considerations, slopes were initially assumed constant throughout intervention. We examined effects by group (indicating overall difference at time of intervention) and a group-by-time interaction term (indicating differing average improvement rates). Statistically significant modifiers were then examined against the PAQLQ Symptom subscale to assess objective health improvement. Lastly, relative

TABLE 1.—Baseline demographic characteristics of asthmatic children in the environmental intervention cohort.

	West Broadway	Franklin Hill	Washington Beech	Total
Number of children	21	23	7	51
Age: Percentage age 8 or older	67%	74%	86%	73%
Sex: % Female	57%	48%	43%	51%
Race/Ethnicity (%)*				
Hispanic	81%	57%	86%	71%
African-American	14%	43%	14%	27%
Overweight	52%	70%	71%	57%
Positive allergy test: Cockroach	52%	69%	50%	58%
Dust mite	67%	62%	33%	60%
(Derf 1 or Der p 1)				

*Hispanic status and race were asked separately—total may be greater than 100%.

improvement between the groups during each time period (pre-, early post-, late post-intervention) was compared for each significant effect modifier, although power was limited in this analysis. For this analysis, Equation 2 was applied separately to outcomes in each time period. Lastly, Equation 1 was applied separately to each effect modifier group to examine differences in slopes between time periods, within groups.

RESULTS

A majority of the children were eight years or older (73%); and most were Hispanic (71%); 57% were overweight at intake (BMI greater than 95th percentile by age). There was a very high prevalence of allergies in all three developments; over 80% were allergic to one or more allergens, and approximately 60% had positive skin prick tests to cockroach or dust mite. Demographic characteristics by development are detailed in Table 1 and in our enrollment analysis (21).

At enrollment, the mean Total PAQLQ score was 4.9 (SD = 1.4), and the Symptom, Activity Limitation, and Emotional Function subscale means were 4.7 (SD = 1.5), 4.5 (SD = 1.5), and 5.3 (SD = 1.4), respectively, across all developments (Table 2). Activity limitation scores were slightly lower than for other domains, and scores in West Broadway were slightly lower than other developments (note: lower symptom scores indicate more severe symptoms and lower quality of life). A wide range of scores were indicated: from 1.4 to 7 in Total PAQLQ.

Overall, the participants showed significant improvements in PAQLQ over the course of study in models without knot points. The overall improvement rate across all participants and periods was 0.06 points per month ($p < 0.0001$). Improvements were comparable across the three PAQLQ domains.

In models with knot points at intervention and 5 months post-intervention, we find significant improvement rates

TABLE 2.—Mean and standard deviation for PAQLQ domains at the start of the study, by development.

	Symptoms	Activity Limitation	Emotional Function	Total
West Broadway	4.29 (1.65)	4.21 (1.81)	4.89 (1.62)	4.48 (1.58)
Franklin Hill	5.09 (1.24)	4.75 (1.29)	5.51 (1.26)	5.17 (1.17)
Washington Beech	4.59 (1.67)	4.51 (1.21)	5.70 (1.03)	4.95 (1.12)
Total	4.69 (1.50)	4.50 (1.52)	5.28 (1.41)	4.86 (1.36)

TABLE 3.—Longitudinal analysis of PAQLQ scores with knot points placed at the date of intervention and five months post-intervention.

	Estimate
Intercept	5.14 ($p < .001$)
Slope pre-Intervention	0.09 ($p = .07$)
Slope 0–5 months after intervention	0.16 ($p = .39$)
Slope 5 to 9 months after intervention	0.04 ($p = .001$)

Note: Slopes reported are actual slopes for each section of the curve, p -values are reported for the difference between each subsequent slope.

before interventions. Average improvement rates increase in the 5 months following intervention, although this change in slope is not statistically significant (Table 3). More than 5 months after interventions, improvements continue but at a significantly lesser rate. In only the first 5 months after intervention, children showed average improvements of 0.80 points, greater than the 0.5-point improvement determined to be clinically significant on the Juniper scale. Over the 13 months of follow-up in this spline analysis, with period-specific improvement rates, the overall predicted improvement is 1.32 points.

Although the spline analysis provides some insight about the relative influence of indoor environmental interventions versus other factors (i.e., participation effect, social support, or case management), an evaluation of effect modification may address this issue in greater detail. Within our longitudinal model without knot points (Equation 2), we found that, at the point of intervention, boys had PAQLQ scores that were 0.64 points higher on average than girls but made comparatively less improvement (Table 4). Significantly less improvement was also seen for overweight children, those whose caretakers reported high fear of violence in their communities, and children spending more time around smokers. Children allergic to cockroach also made less improvement ($p = 0.06$). Factors that indicated significantly lower PAQLQ at intervention included higher perceived stress by the caregiver, residence at Washington Beech, and age younger than 8 years. This effect of age may be confounded because parents

TABLE 4.—Statistically significant effect modification results for 51 children in longitudinal analysis without knot points.

	Difference in intercept (at intervention)	Difference in overall slope
Demographics:		
Sex (male) (n = 25 male/26 female)	0.639*	−0.057**
Development		
West Broadway (n = 21, reference)		
Franklin Hill (n = 23)	0.070	0.033
Washington Beech (n = 7)	−0.886**	−0.003
Age less than 8 years (yes = 14, no = 37)	−0.826*	−0.007
Individual Risk Factors:		
Positive roach allergy skin prick test (yes = 23, no = 17)	−0.388	−0.045*
Overweight (yes = 29, no = 22)	−0.082	−0.050**
Social Factors:		
High perceived stress (yes = 24, no = 26)	−0.920**	−0.014
Fear of violence (yes = 23, no = 26)	0.173	−0.047**
Environmental Factors:		
Time spent around smokers (yes = 24, no = 24)	0.316	−0.062**
Pesticides: Cyfluthrin (yes = 18, no = 14)	0.415	−0.053*

*Significant: $p < 0.1$

**Highly significant: $p < .05$.

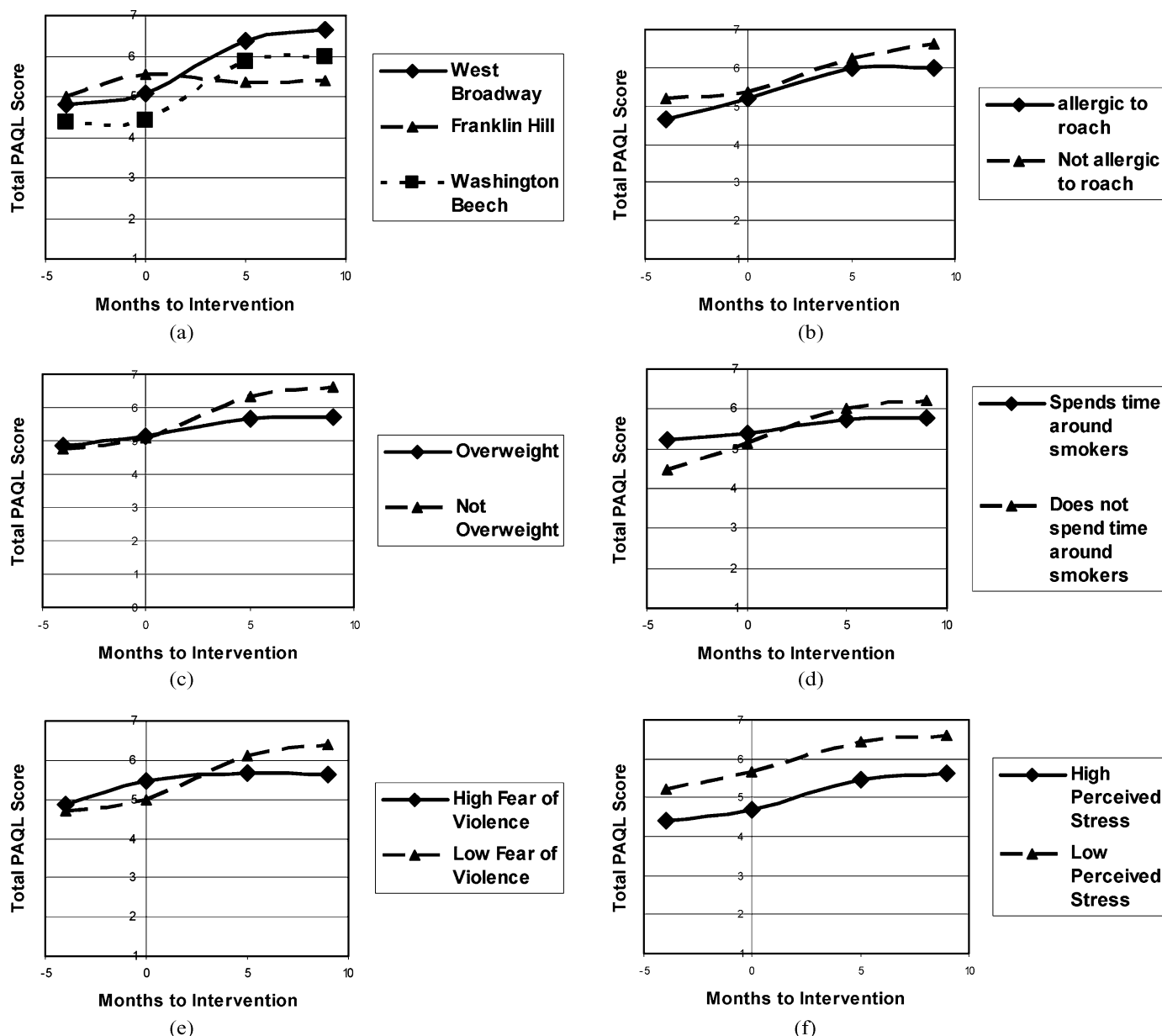


FIGURE 1.—Longitudinal spline model results for effect modifiers shown to be significant under non-spline analysis.

answered questionnaires for children younger than 8 years of age.

The largest overall between-groups difference at intervention was that children of families reporting higher levels of perceived stress had PAQLQ scores that were 0.92 points lower at intervention ($p < 0.01$) and symptom scores that were 0.94 points lower, on average ($p < 0.01$).

We explored additional analyses to better understand differences in improvement rates across time periods for different groups, although our statistical power was limited for these assessments. First, we conducted a two-groups spline analysis, applying Equation 2 by group. Our findings generally corroborated the effect modification analyses in Table 4, with evidence that overweight children, those who spent time around smokers, and those with a high fear of violence had the most notable attenuation of benefits post-

intervention (Figure 1 A–F), although none of the differences in slope, including those for housing development, were statistically significant. Alternatively, we can apply Equation 3 within each of the defined time intervals to capture effect modification in a model with no constraints on intercepts. In this model, the only statistically significant modifier was perceived stress; children in higher-stress families made less improvement during both the early-post and late-post periods. However, the limited number of observations per child per time interval impairs interpretability of this finding.

No effect modification was seen for any medical care indicators, including access to medical care (having a doctor to call other than the ED), or pre-existing medical condition (eczema, low birthweight, being in NICU at birth, properly medicated). No effect modification was found by cockroach reductions, NO_2 , or symptom severity. The only significant

TABLE 5.—Reduction in kitchen cockroach antigen levels, by cockroach allergy status.

	High Bla g 1: Yes	No	Total
Roach allergy:			
Yes	8	11	19
No	5	9	14
Total	13	20	33
	High Bla g 2: Yes	No	Total
Roach allergy:			
Yes	9	13	22
No	4	10	14
Total	13	23	36

OR (High Bla g 2) = 1.12, Spearman correlation coefficient = 0.13 ($p = 0.46$).

High Bla g 1 and High Bla g 2 refer to above-median reductions in kitchen cockroach allergen concentrations.

pesticide result was a near-significant inverse association of PAQLQ improvement and cyfluthrin reduction.

Models producing significant results were repeated against the Symptom subscale, arguably the most objective domain of the PAQLQ, to establish objective health improvements. Symptom results were comparable to those for Total PAQLQ; comparable improvement rates were shown in each phase, and all effect modifiers remained significant and in the expected direction.

Because children *not* allergic to cockroach made more improvement, contrary to expectations, we examined whether these homes may have been cleaner on enrollment because of the child's known allergy status, leading to lesser allergen reduction with interventions. Table 5 presents the dichotomous cockroach antigen reduction by cockroach allergy but indicates no differential reductions. We also examined time trends in health improvements for Bla g 1 and Bla g 2 allergen reductions in the kitchen, air, and bed, by allergy status, and found no significant differences in PAQLQ improvements.

DISCUSSION

Our results clearly indicate significant improvements in overall asthma-related quality of life and symptoms over the course of study. Moreover, our spline model analysis indicates that some health benefits occurred before environmental interventions. The rate of improvement increased in the 5 months subsequent to interventions, although this effect was not statistically significant. Additional improvements were seen in later months, at a significantly lower rate. Parsing through these time periods and effect modification results, we gain some insight towards potential causal mechanisms underlying health improvements.

Significant improvements before intervention are unlikely to be attributable to changes in access to health care or other medical management efforts. A separate pre-post analysis (32) demonstrated that most health care factors did not change between enrollment and study completion, including the prevalence of asthma action plans, medication adequacy, and access to health insurance and primary care physicians. Families were provided with peak flow meters during the pre-intervention period, but this is unlikely to explain the magnitude of benefits.

Pre-intervention benefits may be due to researcher/Hawthorne effect or may indicate benefits of informal case

management, education, or support provided by Community Health Advocates. Of note, because medication regimens did not change significantly during the study, the magnitude of PAQLQ improvement in our cohort may be considered clinically meaningful.

The highest improvement rates, and greatest absolute PAQLQ gain, occurred in the 5 months following intervention, indicating some direct health benefit of environmental interventions. Time trends in cockroach allergen concentrations showed significant reductions in Bla g 1 and Bla g 2, with troughs 5 to 6 months post-intervention and gradual increases in later months (30). This trend corresponds to that in PAQLQ scores and provides further support for the influence of environmental interventions. In addition, the late-stage slowing of improvement is not surprising, as children are nearing the maximal value of 7 points on this scale, and we expect some diminishing marginal return. In addition, environmental benefits of some interventions (i.e., intensive cleaning) may deteriorate at later stages.

Although our overall longitudinal analysis indicates stronger health improvements following environmental interventions, effect modification results suggest other potential causal mechanisms. In particular, results indicate no effect modification by the magnitude of in-home allergen reductions. The only moderately significant effect was reduced PAQLQ improvement among children allergic to cockroach. This lack of effect modification by allergy status or allergen reduction may be due, in part, to power considerations; because our study did not exclude non-allergic participants, we may be unable to detect an improvement occurring only in participants who are both allergic *and* achieve significant in-home allergen reductions. It is also possible that families aware of a child's positive allergy status may have cleaner homes before intervention, such that the marginal environmental benefit of interventions was lesser. We found no evidence that homes of allergic children achieved lesser allergen reduction with interventions. However, these tables (Table 5) indicate that only a small fraction of our cohort had both allergies to cockroach and high allergen reductions (24% for Bla g 1, 25% for Bla g 2), resulting in limited power to detect this effect. In general, given limited knowledge about threshold levels or shape of the cockroach allergen dose-response function, and given significant variability between sampling sessions, it is challenging to construct meaningful dichotomous exposure indicators for such analysis. Our pre-post analysis of respiratory symptoms (32) found that the number of allergens with large concentration reductions was a more robust predictor of improvements in some respiratory outcomes than many covariates representing cockroach allergens alone, indicating either ancillary benefits of industrial cleaning or greater statistical stability for this covariate; this term was not significant in this longitudinal analysis.

Other significant effect modifiers were more directly interpretable and correspond with findings reported elsewhere. In our study, male participants reported higher PAQLQ scores at intervention, but made less improvement, as was also indicated in our pre/post analysis of symptoms in this cohort. One Swedish study also found higher PAQLQ overall in boys (33). To our knowledge, there is no prior evidence on gender differences in PAQLQ improvements. Our finding may indicate regression towards the mean, better intervention compliance

among girls, or better mentoring/role-modeling by the mostly female CHAs.

Overweight children made less improvement in our study, as did children of families reporting greater fear of violence, and spending more time around smokers. Each has shown independent associations with asthma exacerbation (34–36), and it is possible that eliminating a few environmental risk factors through our interventions may be less influential where other risk factors are present.

The lower PAQLQ scores at intake and lesser improvement among children from higher-stress families may indicate that exacerbation thresholds were lower in this subpopulation, or may reflect diminished responsiveness to environmental improvements among those with elevated exposure to other risk factors. This result is in keeping with findings elsewhere of increased susceptibility and compromised immune function with stress. Chronic stress is associated with airway obstruction and wheeze initiated through neuroendocrine and immune processes (37), activation of hypothalamic-pituitary-adrenal (HPA) axis, and disturbed HPA regulation (15) and an excess of glucocorticoids and catecholamines, which can cause hyperactivation of immune mediators and increased inflammation (14). Among asthmatic adolescents, socioeconomic status, life stress, and beliefs about control over one's health have been associated with higher levels of Th-2 cytokines (IL-5) and cytokines associated with Th-1 response (IFN- γ), and marginally lower morning cortisol, indicating that SES, stress, and health beliefs may partly explain the association between SES and asthma (13). The Home Allergen Study demonstrated that caregiver perceived stress was positively associated with wheezing before 6 months of age ($p = 0.049$), due in part to behavioral factors, such as less vigilant home cleaning (12). A difference in home cleaning behaviors would be corrected by our intervention in the short term, but such behavioral differences could contribute to later-stage allergen levels and health outcomes.

Using PSS scores from our enrollment questionnaire to examine effect modification, we were able to avoid the cyclicality that challenges much research on stress and health. By dichotomizing families by perceived stress at enrollment, we compare relative improvement, such that stress acts as a pre-existing condition and modifier. Were we to use PSS scores from later in the study, we would be unable to establish this directionality, as poor or worsening health over time is certainly a key stressor; we would then expect stress scores to respond to the child's health status, at the same time as the child's health may be affected by family stress.

Limitations

Although our analyses provide some useful insight about the efficacy, and differential efficacy, of in-home environmental interventions, there are a number of limitations. First, it is clearly an analytic limitation that our study lacks a control group. However, from a community-based participatory research (CBPR) perspective, our ability to analyze health outcomes using longitudinal methods without a control group was regarded as a strength because community partners were extremely uncomfortable providing environmental interventions to only some participants. Thus, we rely on longitudinal analysis, allowing individuals to act as their own controls, and

designed our study to collect data with dense temporal resolution. As such, we can more closely observe temporal trends in PAQLQ improvements and their relationship to environmental interventions and can better understand intervention efficacy over multiple periods.

Second, as in most intensive intervention studies, our sample size was limited by cost and logistical considerations. Due to resultant power considerations, we could not employ a random slopes approach in our longitudinal models, and our statistical power in models for spline analysis and effect modification is limited. Our lack of significant results for medical care access and individual health risk modifiers may be due to our relatively small datasets that are unbalanced for some modifiers.

Additionally, our results from three public housing developments are not necessarily generalizable to other developments, nor to non-public housing populations. Children in the West Broadway development, for instance, made more improvement during our study. However, it is difficult to interpret that result—our developments are demographically different, located in very different communities, and building conditions vary; in particular, roofing and ventilation systems in West Broadway buildings have been upgraded in recent years. Moreover, our community-based design involved hiring local community members for data collection, and accordingly, CHA staff varied by development, providing slightly different support and education. Lastly, all West Broadway participants joined during the second recruitment period and received springtime interventions—although we found no significant effect by intervention season, it is challenging to distinguish its effect from the development effect. Similarly, because interventions in each home were performed within a short period of time, we are not able to directly differentiate the health benefits of specific interventions.

Some effect modification results may be spurious, as we evaluated a large number of effect modifiers in a relatively small cohort. However, exploring multiple effect modifiers is in keeping with our multifactorial design and reflects the nature of CBPR and intervention studies. In such studies, sample size is often limited by resources and logistical considerations, use of a control group may be considered, and attrition rates can be high. The inverse association of reductions in cyfluthrin exposure and intervention efficacy, for example, may be a spurious result, as we tested six different pesticides and nearly 20 effect modifiers. Moreover, cyfluthrin was generally used in Hispanic households with significant roach infestation, so this may indicate a number of other social and environmental factors. The nature of our study, however, in its attempt to characterize the multi-faceted nature of urban childhood asthma, necessitates a wide-ranging analysis to understand causality in the association between environmental interventions and health outcomes, and we can view these analyses as generating key hypotheses for future studies.

Strengths

Despite these limitations, our analysis makes some important contributions to the literature on environmental interventions for asthma. First, to our knowledge, this is the first attempt to use longitudinal methods with dense data collection

for an asthma intervention study without a control group. The longitudinal approach has four key advantages in this setting: (1) it maximizes the power of a small sample size, to which intensive intervention studies are normally limited by cost and logistical considerations; (2) it allows for the identification of critical time points, to better understand lags in health effects and causality in intervention studies; (3) by allowing each participant to serve as their own control, individual confounders are eliminated; and (4) it is more robust to incomplete and uneven data than are traditional pre/post comparisons. In particular, in a community-based research setting, small sample size, lack of control populations, differential attrition, and missing data are often common problems, and this analytical design can provide robust findings despite these limitations. It is clear from our results that, were a simple pre/post analysis used, results would vary greatly depending on when the post measurement was taken, as rates of improvement vary greatly in the few months leading up to and following interventions. Our approach, which employs a multi-step examination of temporality and effect modification, provides stronger evidence on causality in intervention studies than does traditional pre/post analysis, by more accurately identifying trends in improvement around intervention, and providing some evidence suggesting improvement pathways through effect modification.

Additionally, our longitudinal approach is appropriate to the analysis of QOL data in general, as individual self-report is subject to reporting bias and because subjective baselines for measures of QOL can vary greatly. As such, QOL data can be difficult to interpret and to compare across individuals—it does, however, provide a robust indication of the broad range of impact of a multifactorial disease on a child's life and serves nicely to capture and quantify within-individual changes over time.

In general, our results indicate that environmental interventions may benefit asthmatic children in public housing. While it remains unclear the degree to which benefits are attributable to environmental or social aspects of intervention, evidence suggests that both may contribute. The significant improvement in quality of life and symptoms *before environmental interventions* is an important indication that providing some level of education and support to caretakers. The act of intervening in response to their child's health status, appears to have created strong benefits aside from the physical nature of the interventions themselves. Social and environmental aspects of interventions may act in tandem to create significant health benefits in our study. Our results emphasize the multifaceted nature of asthma and need for coordinated interventions, as individual health characteristics, other environmental factors, and social factors may modify the efficacy of environmental interventions. The analytic challenges of distinguishing the effects of individual versus development characteristics, temporal clustering in interventions, and lack of a control group are very much the reality of community-based research. Producing rigorous community-based research requires the development of methodologically sophisticated methods to isolate confounders that are not isolated in the real world. In doing so, we can more explicitly tease out causal factors to better understand multifactorial diseases such as asthma and develop more effective, targeted interventions.

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ABBREVIATIONS

AIC = Akaike's Information Criteria;
 Bla g 1, Bla g 2 = cockroach antigens;
 BMI = body mass index;
 CHAs = community health advocates;
Derf 1, *Der p* 1 = dust mite antigens;
 ED = emergency department (emergency room);
 ETS = environmental tobacco smoke;
 FVC = forced vital capacity;
 HPA = hypothalamic pituitary adrenal axis;
 HPHI = Healthy Public Housing Initiative;
 IL-5 = interleukin-5;
 IFN- γ = interferon-gamma;
 IPM = integrated pest management;
 NCICAS = National Cooperative Inner-City Asthma Study;
 NHLBI = National Heart, Lung, and Blood Institute;
 NICU = Neonatal Intensive Care Unit;
 NO₂ = nitrogen dioxide;
 PAQLQ = Juniper Paediatric Asthma Quality of Life Questionnaire;
 PPB = parts per billion;
 PSS = Perceived Stress Scale;
 SES = socioeconomic status;
 Th-1, Th-2 = T-helper lymphocytes;
 QOL = quality of life

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