Health Benefits of Green Public Housing: Associations With Asthma Morbidity and Building-Related Symptoms

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Objectives. We examined associations of several health outcomes with green and conventional low-income housing, where the prevalence of morbidities and environmental pollutants is elevated.

Methods. We used questionnaires and a visual inspection to compare sick building syndrome (SBS) symptoms and asthma-related morbidity among residents in multifamily units in Boston, Massachusetts, between March 2012 and May 2013. Follow-up was approximately 1 year later.

Results. Adults living in green units reported 1.35 (95% confidence interval [CI] = 0.66, 2.05) fewer SBS symptoms than those living in conventional (control) homes ($P < .001$). Furthermore, asthmatic children living in green homes experienced substantially lower risk of asthma symptoms (odds ratio [OR] = 0.34; 95% CI = 0.12, 1.00), asthma attacks (OR = 0.31; 95% CI = 0.11, 0.88), hospital visits (OR = 0.24; 95% CI = 0.06, 0.88), and asthma-related school absences (OR = 0.21; 95% CI = 0.06, 0.74) than children living in conventional public housing.

Conclusions. Participants living in green homes had improved health outcomes, which remained consistent over the study period. Green housing may provide a significant value in resource-poor settings where green construction or renovation could simultaneously reduce harmful indoor exposures, promote resident health, and reduce operational costs. (*Am J Public Health.* 2015;105: 2482–2489. doi:10.2105/AJPH.2015.302793)

Numerous studies have demonstrated associations between environmental risks present in the home environment and adverse resident health outcomes.[1–4] Most notably, the indoor environment has been implicated in the development and exacerbation of asthma.[5,6] Lanphear et al.[7] estimate that 39.2% of doctor-diagnosed asthma among US children is attributable to residential risk factors. Reducing exposure to indoor environmental risks is especially important among vulnerable populations, such as racial/ethnic minorities, recent immigrants, and those living in poverty, where the prevalence of asthma can be 2 to 4 times as great as in the general population[8,9] and residential environmental exposures may be elevated.[10]

Home-based environmental interventions have been shown to improve health for children diagnosed with asthma.[11–15] These approaches have included a combination of resident education and strategies to reduce in-home exposures to allergens and other environmental triggers. Environmental components have included implementation of integrated pest management to reduce allergens and pesticide usage,[16,17] HEPA filter installation to reduce airborne particles,[18] and home improvements targeting mold and moisture problems.[19] Other approaches have successfully reduced indoor environmental exposures in low-income populations, including weatherization[20] and interventions to reduce gas stove emissions.[21]

Another health problem associated with poor indoor environmental quality is an increase in a host of nonspecific symptoms, collectively labeled sick building syndrome (SBS).[4,22] SBS emerged as improved construction methods and insulation aimed at increasing building energy efficiency dramatically reduced the amount of air exchanged between indoor and outdoor environments. Construction with the aims of increasing energy efficiency and using environmentally friendly materials—now widely defined as green construction—has the potential to both improve resident health and decrease housing costs, but adequate ventilation standards must be maintained. Current green building guidelines aim to avoid health problems by incorporating environmental quality and health goals into construction[23] and renovation[24] practices. Studies examining self-reported improvements in asthma,[25,26] general SBS symptoms,[27–29] and mental health[30] of people moving into new and rehabilitated green buildings found positive outcomes associated with these transitions. These findings are consistent with exposure assessments that measured lower levels of several key pollutants, including particles, nitrogen dioxide, volatile organic compounds, and allergens in green buildings.[28,29,31]

Studying the effects of housing on health is complicated because the home environment encompasses a diverse profile of exposures driven by interrelated factors, such as building design, housing policies, and resident behaviors.[32] Many of these drivers of exposure are also associated with socioeconomic status (e.g., age of building, location near pollution sources, high occupant density),[10,33] creating a high potential for confounding.

In 2010, the Boston (Massachusetts) Housing Authority began redeveloping 2 housing sites according to green standards; the project received Leadership in Energy and Environmental Design platinum and gold certifications from the US Green Building Council.[34] At one of the sites, half of the units were redeveloped and the other half remained conventional public housing stock. These within-development design and construction differences, combined with the similarities between residents in housing developments across Boston Housing Authority facilities (as a result of uniform housing eligibility criteria), afforded a unique opportunity to isolate the effects of housing on health while minimizing bias from unmeasured socioeconomic effects and spatial differences in ambient pollution.

Green design incorporates many attributes that could reduce environmental exposures and improve health, such as the removal of pollution sources and the addition of exhaust ventilation. Coupled with smoke-free policies and better pest control practices, these approaches are expected to improve respiratory health among public housing residents. We compared indoor environmental conditions and key health outcomes between residents living in green and conventional low-income multifamily housing and explored how these trends varied over time. In addition, we examined the relative impact of individual environmental indicators to understand how the combination of development policies, building characteristics, and participant behaviors contributes to overall indoor environmental quality and health.

METHODS

Research staff completed surveys and visual home inspections with residents of public housing developments operated by the Boston Housing Authority. We conducted baseline home visits between March 2012 and May 2013. We recruited participants from 3 developments: Old Colony (green and conventional), Washington Beech (green), and Ruth Lillian Barkley (conventional). Old Colony completed construction of 116 new green units in the fall of 2011. At the time of the study, more than 600 units at Old Colony remained conventional (control) units within the same 20-acre site. Washington Beech, 6 miles away, was completely redeveloped as green housing in 2010. We used Barkley, located within 5 miles of both Old Colony and Washington Beech, as a second control site (a map of the developments is shown in Figure A, available as a supplement to the online version of this article at http://www.ajph.org). The conventional buildings at Barkley were similar in building age and design to the conventional buildings at Old Colony. We thus had 2 green groups and 2 conventional groups in our analysis.

Residents moving into green apartments received an educational booklet, which provided some informal education on maintaining their green property. All of the properties (green and conventional) used integrated pest management practices, and beginning in October 2012, the Boston Housing Authority prohibited smoking throughout all its properties. Details of the building characteristics of each group can be found in Table A (available as a supplement to the online version of this article at http://www.ajph.org).

We randomly selected a subset of 600 addresses from all units at each development with the goal of recruiting 200 participants, distributed proportionally to the number of units in each housing group, to obtain a representative sample. From previous work in Boston public housing, we anticipated a 33% participation rate. We further randomized addresses to be recruited during heating or nonheating season. We defined heating season to be consistent with the Massachusetts housing code, which requires that residential property owners (including housing authorities) provide adequate heating between September 15 and June 15 of each year. Participants were eligible if they were aged 18 years or older and spoke English, Spanish, Mandarin Chinese, or Cantonese. If more than 1 person in the apartment matched the selection criteria, field staff interviewed the first available, eligible respondent.

Approximately 1 year after the initial visit, we administered the same questionnaire and visual inspection of the residential unit with each participant. Most participants remained in their original green or conventional apartments, with the exception of 18 participants, who moved from conventional to green homes, as described elsewhere in greater detail.[29]

Measures

To understand whether specific environmental characteristics were associated with the observed differences in health outcomes, we used questionnaire and inspection data to create 6 environmental exposure indicators to denote poor environmental quality in a previous study of the indoor environment and self-reported health[35]:

- Inadequate ventilation—our inspection found no bathroom fan or vent, a bathroom fan with inadequate suction, no kitchen fan, or a kitchen fan that did not work or recirculated air.
- Chemical exposure—residents reported using pesticides (spray, powders, or foggers) or spray air fresheners more than a few times a month.
- Mold—residents reported seeing or treating mold, or we saw mold during our inspection of the unit.
- Secondhand smoke—residents reported any smoking activity in the home or no smoking activity in the home but the respondent was a current smoker.
- Pests—residents reported seeing cockroaches, ants, or mice at least a few times a month or rats or bedbugs at least a few times a year.
- Combustion byproducts—the unit had a gas stove but no mechanical exhaust to the exterior (i.e., no kitchen fan, kitchen fan did not work, or kitchen fan was recirculating air), or the gas stove was used to heat the apartment.

To represent the cumulative indoor exposure profile, we also created an environmental index as the sum of all 6 individual binary indicators.

Participants reported whether they experienced any of 14 common SBS symptoms (dizziness, headaches, nausea, coughing, tired more than usual, nosebleeds, breathing problems, blurred vision, wheezing, sneezing attacks, inner ear infection, skin rashes, burning or itching eyes, and sore or dry throat) in their home in the past month.[36] We also used an ordinal measure of self-reported health (1 = excellent, 2 = very good, 3 = good, 4 = fair, 5 = poor), which has been shown to be associated with morbidity in adults.[37]

Participants reported whether a doctor or health care professional had ever diagnosed them with asthma. Participants with a positive response answered additional questions to characterize asthma morbidity: whether they experienced asthma symptoms in the previous month and whether they had an asthma attack or visited the hospital for asthma in the previous 12 months. We also asked whether a child in the respondents' home had asthma. We repeated the same asthma questions for children; in addition, parents reported whether asthmatic children had taken any asthma medication to prevent an asthma attack in the past month or missed school in the past 12 months as a result of asthma.

Statistical Analysis

We compared demographics at baseline between control and green homes with Fisher exact tests. We compared differences in the prevalence of negative environmental indicators with univariate linear mixed-effects models with random intercepts for individual participants to control for correlation within a home from year to year. We tested the effect of living in a green home and assessed changes from the baseline to follow-up visit in the SBS symptoms summary score and self-reported health scale with multivariate linear mixed-effects models with random intercepts for each participant. The adult and children's asthma health outcomes were binary (yes or no) responses, and we constructed multivariate, generalized marginal models to test the effects of green housing and year. We assumed that the distribution was binomial and specified the link in PROC GENMOD to be logistic. We accounted for within-respondent associations with an unstructured pairwise log odds ratio pattern. We also adjusted all multivariate health models for season.

To further explore the temporal effects of living in a green home, we used the respondents' reported move-in date to calculate a continuous variable for the amount of time residents had lived in their apartment and built a model for the SBS symptoms score that included this longer variable for residential tenure. We used the SBS symptoms score because this was the most sensitive health outcome and was measured among all participants. We also explored whether there was effect modification in time living in the apartment by housing type by including an interaction term between tenure and housing type.

To investigate the specific environmental factors that drove the observed health outcomes, we conducted a manual forward selection model-building process with the 6 negative environmental indicators. We maintained indicators with a cutoff of $\alpha = 0.05$. We performed this process to predict the SBS symptoms score, because this was the most sensitive and robust measure. We performed the same steps with a generalized marginal model to predict children's asthma attacks, because this was a sensitive asthma outcome with great public health importance.

To compare the relative effect of individual environmental indicators with the overall effect of living in green housing, we compared the effect estimates of living in a green home from models adjusted only for season to the green housing effect estimates from models also adjusted for the remaining environmental predictors. In all tests, we considered $\alpha = 0.05$ statistically significant. We performed all analyses with SAS version 9.4 (SAS Institute Inc, Cary, NC).

RESULTS

We performed 423 home visits with 235 unique participants in 3 Boston public housing developments; 188 residents (80%) participated in 2 visits over the successive years. Details of the sampling design may be found in Figure B (available as a supplement to the online version of this article at http://www.ajph.org).

Baseline participant demographics are summarized in Table 1. The population was predominantly female (77%) and ranged in age from 18 to 84 years (median = 49 years). The majority of participants identified themselves as Hispanic or Latino (57%). For participants born outside the United States (63%), the most common country of origin was the Dominican Republic (24% of total cohort). The prevalence of current smokers (21%) and adult asthmatics (21%) was higher than the background prevalence of smoking and asthma in the United States (19.3%[38] and 8.4%,[39] respectively). We observed no significant differences in demographics between participants living in green or conventional (control) units.

Environmental and Health Outcomes

The distribution of negative environmental indicators between green and conventional homes is summarized in Table 2. Green homes had a lower percentage of every negative indicator. Chemical use was the most prevalent (63% of visits) and did not differ statistically by housing type ($P = .384$). None of the green homes had a combustion byproducts score because of the shift from gas to electric stoves in both green developments. Overall, control homes had a mean of 3.6 (SD = 1.3) negative environmental indicators; green homes scored 1.3 (SD = 1.8; $P < .001$).

The mean summary score of SBS symptoms and the self-reported health score for green and conventional homes and across visits are detailed in Table 3. Over the 2 visits, participants in conventional homes experienced a mean of 4.2 symptoms and those in green homes, 2.9 symptoms ($P < .001$). Green home participants had marginally better self-reported health than did control participants ($P = .082$).

Fifty unique adults reported having asthma, and 38 asthmatic adults participated in 2 visits (88 visits in total). Self-reported occurrences of any asthma symptoms in the past month, an asthma attack, a hospital visit, or an overnight hospital visit in the past year are detailed in Table 3. The odd ratios (ORs) of adults in green rather than conventional housing reporting asthma symptoms in the past month were 0.61 (95% confidence interval [CI] = 0.24, 1.51); an asthma attack, 0.46 (95% CI = 0.17, 1.2); an asthma-related hospital visit, 0.98 (95% CI = 0.35, 2.67); or an asthma-related overnight hospital visit, 0.40 (95% CI = 0.08, 1.91). However, these differences were not statistically significant.

The sample included 44 unique children with asthma, with 30 children participating in 2 visits (74 visits in total). The adult-reported children's asthma exacerbations are detailed in Table 3. Children's asthma exacerbations were also all lower in the green than the conventional homes. In models adjusted for season, children in green homes were less likely than those in conventional homes to experience asthma symptoms in the past month (OR = 0.34; 95% CI = 0.12, 1.00), an asthma attack (OR = 0.31; 95% CI = 0.11, 0.88), an asthma-related hospital visit (OR = 0.24; 95% CI = 0.06, 0.88), or missed school days in the past year (OR = 0.21; 95% CI = 0.06, 0.74).

We observed no statistically significant difference from the first visit to the second visit for any health outcome (Table 3). However, models that included time since moving into the apartment revealed a marginal ($P = .061$) increase of 0.065 (95% CI = –0.003, 0.133) symptoms per year living in the apartment. We found no significant difference in this effect between green and conventional homes ($P = .395$).

TABLE 1—Baseline Demographics of Residents of Green and Conventional Public Housing: Boston, MA, 2012–2014

Characteristic	Total Participants (n = 235), No. (%)	Conventional Unit Residents (n = 135), No. (%)	Green Unit Residents (n = 100), No. (%)	P
Age, y				.144
< 45	98 (42)	56 (41)	42 (42)	
45–55	48 (21)	34 (25)	14 (14)	
55–65	48 (21)	23 (17)	25 (25)	
> 65	40 (17)	22 (16)	18 (18)	
Self-reported BMI				.789
Normal (< 25 kg/m2)	57 (29)	34 (30)	23 (28)	
Overweight (25–29.9 kg/m2)	66 (34)	36 (32)	30 (37)	
Obese (> 30 kg/m2)	72 (37)	38 (43)	29 (35)	
Gender				.152
Female	180 (77)	108 (80)	72 (72)	
Male	55 (23)	27 (20)	28 (28)	
Language				.309
English	118 (51)	66 (49)	52 (53)	
Spanish	112 (48)	65 (49)	47 (48)	
Chinese	3 (1)	3 (2)	0 (0)	
Race/ethnicity				.251
Hispanic	133 (57)	72 (53)	61 (61)	
Non-Hispanic Black	50 (21)	35 (26)	15 (15)	
Non-Hispanic White	26 (11)	14 (10)	12 (12)	
Asian	26 (11)	14 (10)	12 (12)	
Country of origin				.614
United States	87 (37)	47 (35)	40 (40)	
Dominican Republic	56 (24)	18 (14)	16 (16)	
Puerto Rico	34 (15)	36 (27)	20 (20)	
Other Latin America	15 (7)	7 (5)	8 (8)	
Other	41 (18)	25 (19)	16 (16)	
Highest level of education				.091
< high school	117 (51)	62 (47)	55 (57)	
High school/GED	58 (25)	39 (29)	19 (20)	
Some college	28 (12)	13 (10)	15 (15)	
Completed college	27 (12)	19 (14)	8 (8)	
Employed				.497
Yes	89 (38)	54 (40)	35 (35)	
No	146 (62)	81 (60)	65 (65)	
Current smoker				.521
Yes	50 (21)	31 (23)	19 (19)	
No	185 (79)	104 (77)	81 (81)	
Self-reported asthma				.872
Yes	50 (21)	28 (21)	22 (22)	
No	185 (79)	105 (79)	78 (78)	
Parent-reported child with asthma				.833
Yes	39 (16)	23 (17)	16 (16)	
No	196 (83)	112 (83)	84 (84)	

Note. BMI = body mass index; GED = general equivalency diploma. Fisher exact tests used to test for differences.

Multivariate Environmental Indicator Models

The effect estimates and ORs of environmental variables in 3 models predicting the SBS symptoms score and children's asthma attacks are detailed in Table 4. The forward selection process to elucidate environmental predictors of SBS symptoms yielded a model that retained the mold indicator ($P=.023$) and pest indicator ($P<.001$; model 2). When we introduced the variable for living in a green unit into the model, the effect estimate of pests remained significant but mold did not ($P=.117$; model 3). In the model adjusted only for season (model 1), the effect of green relative to conventional housing was attenuated from 1.35 fewer symptoms (95% CI = 2.05, 0.66) to 0.83 fewer symptoms (95% CI = 1.60, 0.07) when the model included environmental parameters (model 3).

The pest indicator was the only variable maintained in the forward selection process for children's asthma attacks ($P<.001$; model 2). When we reintroduced the variable for living in a green home into the model, the effect of green housing was not a significant predictor of having an attack ($P=.968$; model 3).

DISCUSSION

We used questionnaires and visual inspections to compare indoor environmental conditions and key health outcomes among 235 residents in green and conventional (control) apartments over 2 years (423 visits). Significantly fewer green homes had indicators of inadequate ventilation, mold, secondhand smoke, pests, and combustion byproducts. Adult respondents living in green units reported fewer SBS symptoms than those living in conventional homes. Furthermore, asthmatic children living in green homes were less likely to experience asthma symptoms, an asthma attack, a hospital visit, or asthma-related missed school days.

These results are consistent with recent studies finding that residents in newly constructed[25,27,30] or renovated[26,28] green homes have improved health relative to residents of conventional housing. Our findings strengthen this evidence by capturing a sample size large enough to study rare events (such as children's asthma attacks and

TABLE 2—Distribution of 6 Environmental Indicators and Summary Score by Green and Conventional Public Housing: Boston, MA, 2012–2014

Indicator	Total Home Visits (n = 423), No. (%) or Mean ±SD	Visits to Conventional Units (n = 222), No. (%) or Mean ±SD	Visits to Green Units (n = 201), No. (%) or Mean ±SD	P
Inadequate ventilation	253 (60)	198 (89)	55 (27)	< .001
Chemical exposure	267 (63)	144 (65)	123 (61)	.384
Mold	75 (18)	68 (31)	7 (4)	< .001
Secondhand smoke	106 (25)	68 (31)	38 (19)	.011
Pests	167 (40)	128 (58)	39 (20)	< .001
Combustion byproducts	178 (42)	178 (82)	0 (0)	. . .
Summary score	2.5 ±1.5	3.6 ±1.3	1.3 ±0.8	< .001

Note. Longitudinal, marginal models used to test differences in environmental indices. Linear mixed-effects model used to test difference in summary score.

hospital visits) and showing that these effects were consistent from 1 year to the next over a variable length of residency.

Asthma is the most common chronic childhood disease, and the prevalence of childhood asthma is increasing in the United States.[8] It is estimated that asthma costs $56 billion in health care and societal costs in this country,[40] and improvements in housing, such as those we observed, could greatly reduce some of these costs. Reductions in asthma morbidity were statistically significant for children—but not adults—living in green homes, reflecting children's higher asthma morbidity[41] and possibly increased sensitivity to environmental exposures in the home. These results could also represent differences in activity patterns or the relative contribution of home environments to daily exposure profiles. However, we hypothesize that with a larger sample size, improvements in adult asthma morbidity would also be seen.

We identified the indicator variables for mold and pests as significant environmental predictors of SBS symptoms. Although exposure to combustion byproducts, secondhand smoke, and chemicals have important implications for health,[42–44] these exposures are more likely associated with latent health outcomes such as cancer or cardiovascular disease. In addition, even though none of the remaining 4 environmental indicators were significant predictors of SBS symptoms in our data, the addition of both the ventilation and combustion byproduct indicators in these models greatly increased the residual effect of living in a green building. This is a result of the correlation between inadequate ventilation (a component of the combustion byproducts indicator) and the presence of pests ($r = 0.23$) and mold ($r = 0.25$), highlighting how characteristics of building design may drive several environmental exposures. Because we designed our analysis to minimize the use of collinear terms and elucidate the most significant predictors (by using a forward selection model-building process), we presented a final model that only includes mold and pests.

TABLE 3—Distribution of Health Outcomes in Total, by Public Housing Type, and by Home Visit: Boston, MA, 2012–2014

		Visit 1		Visit 2		P	
Variable	Total Visits (n = 423), No. (%) or Mean ±SD	Conventional Units (n = 135), No. (%) or Mean ±SD	Green Units (n = 100), No. (%) or Mean ±SD	Conventional Units (n = 87), No. (%) or Mean ±SD	Green Units (n = 101), No. (%) or Mean ±SD	Green Units	Visits
SBS symptoms summary score	3.6 ±3.3	4.1 ±3.6	2.9 ±3.2	4.2 ±3.3	2.9 ±2.8	< .001	.952
Self-reported health	3.2 ±1.2	3.2 ±1.2	3.0 ±1.2	3.3 ±1.1	3.1 ±1.1	.082	.15
Adults with asthma	88	28	22	17	21		
Asthma symptoms	64 (73)	21 (75)	14 (63)	15 (88)	14 (70)	.285	.239
Asthma attack	49 (56)	16 (57)	10 (45)	12 (71)	11 (55)	.114	.445
Hospital visit	23 (26)	7 (25)	7 (32)	4 (24)	5 (25)	.971	.600
Overnight hospital visit	11 (13)	5 (18)	2 (9)	3 (18)	1 (5)	.252	. . .
Children with asthma	74	27	17	21	9		
Asthma symptoms	29 (39)	14 (52)	4 (24)	9 (43)	2 (22)	.051	.541
Asthma medication use	40 (54)	17 (63)	7 (41)	13 (62)	3 (33)	.161	.787
Asthma attack	30 (41)	14 (52)	3 (18)	10 (48)	3 (33)	.028	.833
Hospital visit	20 (27)	8 (30)	1 (6)	9 (43)	2 (22)	.031	.15
Overnight hospital visit	7 (9)	5 (19)	2 (12)	0 (0)	0 (0)	.735	. . .
Missed school	22 (30)	10 (37)	0 (0)	9 (43)	3 (33)	.015	.145

Note. SBS = sick building syndrome. *P* values represent the test of the effect of green housing and home visit in multivariate linear mixed-effects models (SBS symptoms summary score and self-reported health) and generalized marginal models (all binary asthma outcomes). All models also adjusted for season.

TABLE 4—Models Predicting Sick Building Syndrome Symptoms Score and Asthma Attacks in Children With Asthma in Green and Conventional Public Housing: Boston, MA, 2012–2014

Model	SBS Symptoms Summary Score		Children's Asthma Attack	
	Effect Estimate (95% CI)	P	OR (95% CI)	P
1: green housing	−1.35 (-2.05, −0.66)	<.001	0.30 (0.11, 0.84)	.023
2				
Mold	0.92 (0.13, 1.70)	.023	1.00 (Ref)	
Pests	1.19 (0.58, 1.81)	<.001	6.63 (2.21, 19.87)	<.001
3				
Green housing	−0.83 (−1.60, −0.07)	.033	1.02 (0.31, 3.37)	.968
Mold	0.65 (−0.15, 1.46)	.117	1.00 (Ref)	
Pests	0.97 (0.32, 1.62)	.004	6.74 (2.00, 22.70)	.002

Note. CI = confidence interval; OR = odds ratio; SBS = sick building syndrome. Model 1 shows the effect of green housing in primary models adjusted only for season. Model 2 illustrates the effects of the environmental indices maintained in a forward selection procedure. Model 3 represents model 2 with the reintroduction of a variable for living in a green home.

Interestingly, after we controlled for exposure to mold and pests, 60% of the unadjusted effect of living in a green home remained. We were not able to measure specific environmental pollutants for our entire study population; however, results from pollutant monitoring in a subset of participants at Old Colony showed reductions in multiple indoor air pollutants that could further explain the remaining health improvements.[29] It is also likely that synergistic effects of green construction, healthy home policies, and resident education resulted in the observed improvements in SBS symptoms, for example, from the combination of improvements in indoor air quality, thermal comfort, lighting, noise, and sleep quality.

The forward selection model-building process for children's asthma attacks only retained the pest exposure indicator, and this is consistent with a strong body of evidence linking pest exposure to asthma exacerbations.[6] Exposure to poor ventilation, secondhand smoke, mold, and combustion byproducts have also been shown to trigger asthma events.[1,45] Most likely, our sample size was not large enough to identify these relationships.

The observed reduction in children's asthma attacks attributable to the reduction of pests in green homes is an important finding. Reduction in pest exposure can be a benefit of green design and renovation and a great example of how improvements in indoor environmental quality are controlled by multiple levels of housing intervention. Specifically, tightening of the building envelope coupled with mechanical ventilation reduces moisture and prevents pest access, both of which reduce the likelihood of pest infestation.[46,47] Furthermore, the implementation of integrated pest management at the development policy level enhances pest reduction where improved construction methods aren't sufficient.[17] It should be noted, however, that 20% of green homes still reported indications of pest exposure. Further work should investigate whether the management and maintenance of green buildings requires additional considerations in the design of integrated pest management programs.

Limitations

The predominantly case–control design may have allowed for unmeasured confounders that could explain the observed differences in health outcomes. However, we greatly minimized the potential for unmeasured confounding by comparing similar populations in Boston public housing, approximately half of whom resided within a 3-block radius in a single housing development (90 visits to green units and 150 to conventional units at Old Colony).

Although it is important to evaluate how the effects of housing on health change over time, our longitudinal findings were limited. We did not see a change in health outcomes from 1 year to the next, but it is possible that a 1-year time frame is not clinically relevant for some household exposures. However, in the separate model that incorporated the amount of time living in the study apartment, we saw a suggestive trend that the health of residents of both green and conventional units worsened over length of housing tenure ($P = .061$). Residency in the conventional apartments ranged from 6 months to 37 years and in the green units from 8 months to 4 years, and this trending effect of residency length may have been driven by the extreme environmental exposures in conventional buildings. However, we did not observe modification of the effect of tenure by building status, suggesting that the association between health outcomes and housing tenure among green and control participants was comparable. Increasing SBS symptoms over time could be a result of exposure to deteriorating environmental conditions as a building ages or the increased cumulative effect of housing-related exposures.

The relationship between time living in an apartment and health could be confounded by the participant's age; however, we did not find a significant relationship between age and the SBS symptoms score ($P = .436$), and including a linear term for age did not change any of the effect estimates in this model. This measure could also be subject to selection bias by participants lost at follow-up. However, participants who did not complete a second visit ($n = 47$) were not differentially distributed at baseline between green and conventional homes, nor did they report differences in the SBS symptoms score, adult asthma attacks, or children's asthma attacks.

We were also limited in interpreting the results of self-reported health outcomes. Participants could not be blinded to their building type, and it is possible that residents were exposed to information about green buildings and improved health that influenced their responses. However, we used objective questions on SBS symptoms and asthma exacerbation that have been used in previous studies.[36,48] Furthermore, research has shown a high degree of agreement between health care claims with self-reported or caregiver-reported health care utilization and asthma exacerbations.[49,50]

We compared new, green construction to conventional buildings constructed 70 years earlier and were thus limited in our ability to distinguish between the relevance of green and new building characteristics in shaping our findings. Our study cannot provide evidence on the specific attributes of new housing that may maximize the benefit–cost trade-offs for energy, materials, labor, and occupant health. In some cases, interventions focused on eliminating the most significant environmental exposures, rather than on achieving a green standard, could provide the most significant benefits to occupant health.

Many argue that multicomponent interventions are necessary to comprehensively improve indoor air quality and resident health.[51,52] Consequently, our aim was not to identify the individual, causal mechanisms of improved environmental conditions and health, but rather, to study the cumulative effects of a multicomponent intervention combining changes in building design, policies, and resident education geared toward energy-efficient and healthy indoor spaces.

Conclusions

We observed significantly improved outcomes in several key health indicators among low-income residents of multifamily public housing who lived in green rather than conventional buildings. Specifically, we found significant reductions in asthma morbidity among children living in green homes.

Although green buildings are often considered a luxury suitable for middle- or high-income communities, in resource-poor settings, green construction or renovation may represent a significant value, with the potential to simultaneously reduce harmful indoor exposures, promote resident health, and reduce operational costs. ■

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Contributors

M. D. Colton performed the analysis, with help from J. G. C. Laurent and P. MacNaughton, and was primary author of the article. G. Adamkiewicz designed the study with help from M. D. Colton, J. G. C. Laurent, and J. Spengler. M. Bennett-Fripp coordinated data collection with help from M. D. Colton and J. Kane.

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Human Participant Protection

All participants gave informed consent and received compensation for their participation, in accordance with the Harvard T. H. Chan School of Public Health institutional review board.

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