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Housing and allergens: A pooled analysis of nine US studies ☆

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ABSTRACT

Background: Housing conditions can contribute to allergen exposures that are linked to asthma, but little is known about which of those conditions are most likely to predict high levels of allergens in settled house dust.

Methods: We pooled allergen, housing condition, occupant behavior, demographic, and other data from nine asthma studies (n=950 homes in 6 US cities). Dust mite (Der f 1 or Der p 1), cockroach (Bla g 1 or Bla g 2), mouse (Mus m 1), cat (Fel d 1) and dog (Can f 1) allergens were measured in settled dust from kitchens or bedrooms, and concentrations were categorized according to previously published asthma symptom thresholds. We calculated odds ratios (OR) using logistic regression to identify those housing conditions and occupant behaviors that were associated with clinically significant allergen levels, after adjusting for numerous confounding variables.

Results: The adjusted results show that high cockroach allergen was associated with cracks or holes in walls (OR=2.1), high dust mite allergen was associated with mold odor (OR=2.5), housing built before 1951 (OR=2.1), and single-family home with slab on grade (OR=1.9); and mouse allergen was associated with rodent control or signs of rodents (OR=3.62) and inversely associated with presence of a cat (OR=0.20). Water leaks and below average housekeeping had unadjusted high odds ratios for high cockroach allergen.

Conclusion: We have identified a number of housing conditions that are consistently associated with increased allergen dust concentrations. This study indicates that screening for housing-based asthma triggers should include presence of cats, dogs, cockroaches, or rodents; water leaks; mold or mold odor; holes or cracks in walls; and below average housekeeping. Single family houses that have basements or crawl spaces or are built before 1951are also important predictors for increased allergens in housing.

1. Introduction

Asthma is a common and complex chronic disease that affects both children and adults (Johnson et al., 2002). It typically manifests itself by variable airflow obstruction, bronchial hyperresponsiveness, and airway inflammation. Twelve-month prevalence of self-reported asthma increased 74% from 1980 to 1996 across the United States (Mannino et al., 1998; Mannino et al., 2002), but there has been no discernable change in asthma attack estimates since 1997 or in current asthma prevalence from 2001 to 2004 (Moorman et al., 2007). In 1996, the estimated number of persons with current asthma was 14.6 million (55.2 cases per 1000). In 1997, the National Center for Health Statistics changed their questionnaire so data before and after 1997 is not comparable. In 1997, 25.7 million (96.6 cases per 1000) persons reported a physician diagnosis of asthma in their lifetime. That rate has increased 8% to 104.7 cases per 1000 in 2004 (American Lung Association, 2006). In short, asthma remains a widespread condition.

Housing-related exposures are associated with the exacerbation of asthma (Institute of Medicine, 2000). While a large body of evidence demonstrates that housing-related exposures can trigger asthma symptoms, there continues to be no standardized home

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assessment tools to identify and measure those hazards. Home allergen sampling is expensive and not practical or advisable on a wide scale. Interventions to improve housing are essential to improve and maintain children's health (Breysse et al., 2004). Eliminating housing risk factors associated with allergens and asthma is likely to greatly reduce hospitalization rates, emergency and clinic visits, costs, school absences, and health and functioning of children and adolescents (Lanphear et al., 2001a, b).

This study identifies evidence-based housing factors that should be assessed as a screening method to improve assessment of indoor asthma triggers and thus clinical management. We pooled nine childhood asthma studies from across the US to determine if the increased size of the cohort would increase the ability to detect those housing conditions and occupant behaviors most strongly associated with exposure to asthma-related allergens. Our goal is to help improve standardized methods of assessment of housing-related asthma triggers

2. Methods

2.1. Description of the nine studies

The studies were selected because they had extensive housing data and almost all had children with doctor-diagnosed asthma as an enrollment requirement. We believed this would increase the likelihood of identifying those housing conditions linked to high allergen levels, due the high-risk nature of the study population. The nine participating institutions and studies are listed in Table 1.

For each study, we examined study protocols, conducted investigator interviews, and reviewed data collection forms and publications (Clougherty et al., 2006; Eggleston et al., 2005; Kercsmar et al., 2006; Krieger et al., 2005; Levy et al., 2004; Takaro et al., 2004, Acosta et al., 2008). Six of the studies were randomized controlled trials; two were non-randomized controlled studies, and one was a birth cohort study. We pooled the baseline, pre-intervention data from each of the studies for this analysis, because our intent was to identify housing characteristics prior to remediation that could serve as a screening method to predict high allergen levels linked to asthma. Most of the studies recruited children of elementary to high school age and physician-diagnosed asthma was a requirement for enrollment into all but the Columbia Birth Cohort and Cleveland Composite studies. Most studies recruited children and homes from inner city, low-income urban areas. Sample sizes for each study ranged from 30 to 326 children (Table 1).

Due to the types of planned interventions, dwellings in several studies had to meet specific requirements, such as having evidence of mold/moisture problems or cockroach infestation. For example, cockroach infestation was an eligibility requirement for homes in the Columbia University Integrated Pest Management (IPM) study, since the purpose was to test the efficacy of pest control treatments. Both Cleveland studies were designed to reduce mold and moisture problems in housing, so homes in these studies had to have evidence of water damage or mold growth to be enrolled.

2.2. Assessment of housing conditions and occupant behavior

The studies shared many common visual assessment data elements, such as building type, year of construction, type of heating/cooling systems, visible evidence of pests, evidence of pets, and the presence of excess moisture/mold/water damage. Questionnaires included items to assess occupant behaviors, such as pest control measures undertaken by residents, household cleaning and smoking. The pooled analysis included all variables that were present in at least 4 of the nine studies. Studies collected information on similar variables with different methods. For example, some used a categorical yes/no variable to indicate the presence of a certain housing characteristic while others used continuous variables. To pool data, we transformed some variables. For example, those studies that assessed asthma symptom days over 4 weeks were transformed so that the period was standardized to a 2-week period.

2.3. Assessment of allergen exposure

All nine studies included collection of settled dust samples using vacuum methods followed by allergen analyzes using standard enzyme-linked immunosorbent assays (ELISA). Most collected samples from bedroom floors and assayed for dust mite and cockroach allergens. However, there was variation in type of

Table 1
Study descriptions.

Name of study	Organization	Type of study	Sample size	Homes included in this study	Eligibility	Selected outcome measures
Boston	Boston Public Health Commission	Randomized controlled trial	267 children in 183 homes	91	0–17 years; Phys. diag. asthma	Asthma symptoms, medications, health care use
Harvard	Boston Public Housing Authority	Non-randomized intervention study	79 children in 61 homes	49	4–17 years; phys. diag. asthma	Asthma symptoms
Cleveland Composite	Case Western Reserve/ Cuyahoga County	Observational-no randomization	67 children/ homes	50	Infants; evidence of risk of reduced respiratory health; water damage/mold growth	Asthma symptoms and respiratory health; health care use
Cleveland Asthma	Case Western Reserve/ Cuyahoga County	Randomized controlled trial	62 children/ homes	51	2–17 years; phys. diag. asthma; housing has water damage/mold growth	Asthma symptoms, health care use
Cincinnati	Cincinnati Children's Hospital	Randomized controlled trial	225 children/ homes	187	6–12 years; phys. diag. asthma; ≥ 5 cigarettes/day	Asthma symptoms, health care use
Columbia IPM	Columbia University	Randomized controlled trial	30 children/ homes	29	5–18 years; phys. diag. asthma; housing has cockroaches	SPT, IgE, asthma symptoms, health care use
Columbia BC	Columbia University	Birth cohort	274 children/ homes	217	Puerto Rican child born to mother with inhalant allergy and/or asthma. Child not intubated at birth	n/a
Hopkins	Johns Hopkins	Randomized controlled trial	100 children/ homes	89	6–12 years; Phys-diag asthma	Asthma symptoms, health care use, FEV_1
Seattle	Seattle Public Health	Randomized controlled trial	326 children/ homes	187	4–12 years; phys. diag. asthma;	Asthma symptoms, health care use, FEV_1

Table 2
Home evaluation methods.

Name of study	Home evaluation		Settled dust samples			
	Visual assessment/ inspection checklist	Resident interview	Allergen vacuum method	Kitchen	Child's bedroom selected samples	Allergen analysis
Boston	Yes	Yes	Mighty Mite; filter not specified	No	Floor: two 1 m^2 integrated samples	50 μg sieved dust (425 μm screen). Dust shipped to lab on ice. Dust stored at −20 °C. Extract stored at −20 °C. ELISA
Harvard	Yes	Yes	Mighty Mite w/filter	Floor	Bedding	100 mg sieved dust (425 μm screen). Dust stored at −20 °C. Extract stored at −20 °C. ELISA
Cleveland Composite	Yes	Yes	Mighty Mite w/Hysurf insert	No	Floor: adjacent to and beneath child's bed	200 mg sieved dust (300 μm screen) Dust shipped to lab at ambient temp. Dust stored at 4 °C. Extract stored at −20 °C. ELISA
Cleveland Asthma	Yes	Yes	Mighty Mite w/Hysurf insert	No	Floor: adjacent to and beneath child's bed	200 mg sieved dust (300 μm screen). Dust shipped to lab at ambient temp. Dust stored at 4 °C. Extract stored at −20 °C. ELISA
Cincinnati	Yes	No	HVS-3 (dirt devil vacuum+cyclone	No	Floor: center of room in high traffic area	60 mg sieved dust (350 μm screen). Dust not shipped. Dust stored at −20 °C. Extract stored at −20 °C. ELISA
Columbia IPM	Yes	Yes	Mighty Mite w/filter	Floor, (4 min)	Bedding: pillows, upper half of bed	No sieving. Dust not shipped. Dust stored at −20 °C. Extract stored at −20 °C. ELISA
Columbia BC	No	Yes	Mighty Mite w/filter	No	Mother's bed: bedding: pillows, upper half of bed	No sieving. Dust not shipped. Dust stored at −20 °C. Extract stored at −20 °C. ELISA
Hopkins	Yes	Yes	Redivac w/ unwoven fabric sleeve	Entire floor	Floor: bedding: mattress and bedding (combined w/floor)	100 mg sieved dust (300 μm sieve size). Dust not shipped. Dust stored at −30 to −20 °C. Extract stored at −30 °C. ELISA
Seattle	Yes	Yes	HVS-4	No	Floor: 4 × 0.25 m^2 areas	100 mg sieved dust (150 μm sieve size). Dust shipped to lab on ice. Dust stored at 4 °C. Extract stored at −20 °C. ELISA

Table 3
Allergens in child's bedroom and kitchen.

Study	Child's bedroom					Kitchen
	Dust mite	Cockroach	Dog	Cat	Mouse	Mouse
Boston	Der f 1 Der p 1	Bla g 1 Bla g 2	Can f 1	Fel d 1	MUP	-
Harvard	Der f 1 Der p 1	Bla g 1 Bla g 2	Can f 1	Fel d 1	MUP	Mus m 1
Cleveland Composite[a]	Der f 1 Der p 1	Bla g 1	-	-	Mus m 1	-
Cleveland Asthma	Der f 1 Der p 1	Bla g 1	-	-	Mus m 1	-
Cincinnati	Der f 1	Bla g 1	Can f 1	Fel d 1	-	-
Columbia IPM	Der f 1	Bla g 1 Bla g 2	-	-	MUP	MUP
Columbia BC[b]	Der f 1 Der p 1	Bla g 2	-	Fel d 1	MUP	-
Hopkins	Der f 1 Der p 1	Bla g 1	Can f 1	Fel d 1	Mus m 1	Mus m 1
Seattle	Der p 1	-	-	Fel d 1	-	-

[a] Bedroom of a sibling of the infant index child or the parent's room if no siblings.
[b] Mother's bedroom was sampled.

Table 4
Asthma symptom thresholds for sensitized children.

Allergen	Asthma symptom threshold
Dust mite allergen (Der f 1 and Der p 1) in the bedroom	10 μg/g (Platts-Mills et al., 1995; Kuehr et al., 1994)
Cockroach allergen (Bla g 1) in the bedroom	8 Units/g (Rosenstreich et al., 1997)
Cat allergen (Fel d 1) in the bedroom	8 μg/g (Ingram et al.,1995; Gelber et al., 1993)
Dog allergen (Can f 1) in the bedroom	10 μg/g (Ingram et al.,1995)
Mouse allergen (Mus m 1) in the kitchen	1.6 μg/g [a] (Phipatanakul et al., 2000)

[a] No symptom threshold is available so the allergic sensitization threshold was used.

vacuum collection used, other rooms sampled, location of samples in bedroom, area of floor sampled, dust-sieving methods and additional allergens sampled (Tables 2 and 3).

All of the studies provided allergen results in dust concentration units (e.g., micrograms Der f 1 per gram of sieved dust), and four sites also reported results in allergen-loading units (e.g., micrograms Der f 1 per square meter of floor sampled). Loading reflects both the concentration of the allergen in dust and the weight of dust (and therefore allergen) present on the sampled surface. However, loading is more dependent on the efficiency of dust collection, which is affected by factors such as type of vacuum nozzle, type of vacuum, flow rate, accuracy and precision of measurement of the surface area, uniformity of contact between the sampling inlet and the surface area, the amount of time taken to sample a specific area, and the type of flooring and/or floor covering. On the other hand, dust concentration results are more commonly reported and are not dependent on the size of the area sampled. In addition, allergen thresholds above which sensitization and/or symptom exacerbation occur are expressed in units of concentration, not loading (Table 4).

If an allergen concentration was at or above the asthma symptom threshold for that allergen, we classified the allergen as "high." If both Der f 1 and Der p 1

were analyzed in a room sample, then we used only the highest result. Similarly, if both Bla g 1 and Bla g 2 were analyzed in a room sample, then we used only the highest result (Pollart et al., 1991) in order to maximize the likelihood of identifying housing risk factors.

In some cases, different allergen units were reported. Harvard reported Can f 1 and Fel d 1 results in Units/g while the other sites reported results in μg/g. We transformed Units/g into μg/g by using documented conversion equations (available at www.inbio.com/pdf_files/EL-CF1.pdf and www.inbio.com/pdf_files/EL-FD1.pdf). The conversion equation used for Can f 1 was 1 U=0.001 μg. The conversion for Fel d 1 was 1 U=4 μg. For mouse allergen, the conversion for MUP to Mus m 1 used in this analysis was: Mus m 1=0.67 MUP (Chew et al., 2003, 2005).

Within a home, we selected the kitchen sample for mouse allergens and the bedroom for cockroach allergens because these rooms have the strongest relationships to asthma symptoms for the respective allergens (Eggleston et al., 1998; Phipatanakul et al., 2000). If there was no kitchen sample, we used the bedroom sample instead, because the allergen concentrations in the two rooms were highly correlated. To estimate kitchen floor dust allergen concentrations when no kitchen sample was available, we used a regression equation from the Columbia IPM study ($\log(\text{Mus m 1 in kitchen}) = 1.31 + 1.16 \times \log(\text{Mus m 1 in bedroom})$, $r=0.67$, $p<0.001$. Similarly, we used Hopkins data, where bedroom samples included both floors and bedding, to develop a regression equation for those studies that did not have both samples ($\log(\text{Mus m 1 in kitchen}) = 1.08 + 0.85 \times \log(\text{Mus m 1 in bedroom})$, $r=0.66$, $p<0.001$.

2.4. Site specific analysis of predictors of high allergen levels

For each allergen and corresponding possible predictor and study site, we developed bivariate logistic models to predict the odds that the allergen concentration was above the respective symptom threshold. If a predictor was associated with an allergen at the significance level of $p<0.10$ at two or more sites and if it was associated with the allergen at $p<0.10$ in the multivariate model described below, then it was determined to indicate high allergen levels. We used a p-value slightly above the traditional level of $p<0.05$, because we were interested in predictors that could be used for screening houses that if found to be positive could undergo a more in-depth assessment.

2.5. Multivariate cross-site pooled analysis of predictors of high allergen levels

We developed multivariate multi-site logistic models to examine the associations between predictors and high levels of bedroom dust mite, bedroom cockroach, kitchen mouse, bedroom cat and bedroom dog allergens (Table 4). We included housing characteristic, questionnaire and visual assessment variables in the multivariate models. Because not all predictors were collected in all sites, we created dummy variables to represent missing values so that homes would not be excluded unnecessarily. We used the following stepwise procedures to construct the models:

Step 1: Determine which variables were potentially significant predictors of high or low allergen concentration in separate logistic models for each predictor. Those variables that had a p-value ≥ 0.2 were dropped from further analysis.

Step 2: We then developed multivariate models that included all variables from Step 1, plus the following variables: site, type of building, and season. We included these three variables to help control for unmeasured influences and climate.

Step 3: All variables that had a p-value >0.1 were removed from further analysis. We chose a p-value <0.1 as significant to help ensure that important housing conditions were not dropped from the final models due to marginal statistical significance and because we were interested in identifying those housing conditions that could be used to screen for high allergen levels.

The logistic model fitting procedure can fail to converge when all the outcomes in one of the levels of a predictor variable in a model are the same, leading to quasi-separation. For example, in the dust mite model, all homes in the Hopkins site had low levels of dust mite allergen concentrations (i.e., below the published symptom threshold). In the cockroach model, all the Cincinnati homes had low cockroach concentrations. Although we considered using the uniform prior model method for the zero proportions, we decided to eliminate the Cincinnati and Hopkins homes from the cockroach and mite models, respectively. We used the deviance and Pearson's chi-square to examine the goodness of fit of the models. We also examined regression diagnostics to affirm that regression coefficients were not overly affected by multicollinearity or influential observations.

3. Results

We present both bivariate (Table 5) and multivariate (Table 6) model results in order to improve the ability to identify risk factors that may be associated with allergens in any given housing unit as a screening tool.

3.1. Bivariate results

Results of bivariate analysis showed that season, age and type of building (e.g., single or multi-family and rental), income, race, housekeeping score, holes and cracks, type of flooring, pets, roaches and rodents, mold and moisture, air conditioning, basement, vaporizer and dehumidifier use, exhaust ventilation and type of heating were all significant predictors of high allergen levels (Table 5).

3.2. Multivariate model results

The odds ratios for the multivariate models show that several housing characteristics are associated with allergen levels (Table 6), after controlling for confounding variables. The Der f 1/Der p 1 (dust mite) model included 851 homes and 98 (12%) had mite allergen concentrations above the symptom threshold. Buildings that were constructed before 1951, absence of a basement in a single family home, and homes with a mold odor were associated with high odds of high mite allergen levels. Because the housing variables in the model (mold odor and basement) could have different effects in pre-1951 homes than in post-1951 homes, we examined the possible interaction with housing age. The interactions were non-significant and the directionality of the effects was the same for pre- and post-1951 homes.

The Mus m 1 (mouse) model included 569 homes and 150 (26%) had allergen levels above the symptom threshold. No cats living in the home was associated with higher odds of high mouse allergen levels. Visible signs of rodents or recent rodent control were associated with higher odds of high mouse allergen levels. The odds of high mouse allergen levels in the home were lower in the summer and fall than in spring and winter.

The Bla g 1/Bla g 2 (cockroach) model included 569 homes and 97 (17%) had allergen levels above the symptom threshold. Holes or cracks in the walls and visible signs of roaches or recent roach control were all associated with higher odds of high allergen levels. If the floor was included in the bedroom allergen sample, rooms with at least 50% of the floor carpeted had lower odds of high allergen levels than rooms with no carpet or less than 50% carpeted.

The Fel d 1 (cat allergen) model included 785 homes and 112 (14%) had allergen concentrations above the symptom threshold. Not surprisingly, the odds of a high cat allergen concentration for a home with a cat were higher than that of a home without a cat. The Can f 1 (dog allergen) model included 381 homes and 63 (17%) had allergen concentrations above the symptom threshold. Similarly, the odds of a high dog allergen concentration for a home with a dog were higher than that of a home without a dog.

Furthermore, the results show that combining housing predictors improved the ability to predict allergens (sensitivity), but at the same time reduced the ability to discern particular items (specificity) (Table 7), as expected. Readers may choose to utilize this table to help identify the best candidates for a screening tool by identifying combinations of assessment questions that maximize sensitivity and specificity. For example, to identify high levels of cockroach allergen, "signs of cockroaches" and "poor housekeeping" or "presence of carpeting" and "water leaks" maximize the performance characteristics. Because of the direct relationship of cockroaches to their allergen, a combination that includes "signs of cockroaches" would be preferred.

Table 5
Bivariate odds ratios (95% confidence intervals).

Predictor	Boston	Cincinnati	Clevel and asthma	Cleveland composite	Columbia BC	Columbia IPM	Harvard	Hopkins	Seattle	All
Cockroach allergen (Bla)										
Holes or cracks in walls	0.53 (0.05,5.26)					15.8* (1.57,158)	3.97* (0.75,21.0)	1.82 (0.71,4.67)		3.24** (1.70,6.17)
Evidence of Leaks			2.97 (0.39, > 999)	2.00 (0.21,19.0)			0.63 (0.16,2.41)	2.74** (1.09,6.86)		2.51** (1.43,4.41)
Roach control or visible signs of roaches	11.6 (1.40, > 999)**	NA	1.65 (0.26,10.4)	26.0 [f](3.30,205)	9.95 (1.69, > 999)[f]	NA	3.08 (0.34,28.1)	4.24[f] (1.70,10.6)		5.11[f] (3.02,8.65)
Roach control	6.88[f] (0.67,71.0)				5.50[f] (1.26,24.0)	0.64 (0.05, > 999)	1.00 (0.18,7.15)			3.95[f] (1.63,9.60)
Visible signs of roaches	18.6 (2.23, > 999)[f]		1.65 (0.26,10.4)	26.0[f](3.30,205)	14.4 (2.46, > 999)[f]	0.26 (0.01, > 999)	4.30 (0.48,38.4)	4.24[f] (1.70,10.6)		5.94[f] (3.50,10.1)
Housekeeping [a]	0.94 (0.09,9.46)		1.76 (0.57,5.38)	1.86 (0.59,5.90)		4.82[f] (1.09,21.3)	1.78 (0.72,4.39)	4.22[f] (1.86,9.56)		3.05[f] (2.07,4.50)
Income (in 10,000s)			0.56* (0.28,1.12)		0.71[f] (0.54,0.95)	0.68 (0.15,3.00)	0.09 (0.00,4.05)	0.77 (0.45,1.32)		0.64[f] (0.52,0.78)
Bedroom Floor no Carpet [b]	2.29 (0.23,23.0)				2.92** (0.66,12.9)	0.40 (0.03,5.55)		4.40** (1.65,11.8)		3.56** (2.05,6.16)
Bedroom Floor Carpet < 50%[b]	2.83 (< 0.01,110)				1.26 (< 0.01,16.8)	2.00 (0.05,78.2)		16.0** (1.57,164)		2.48** (0.87,7.05)
Bedroom Floor Hard Surface [b]			2.9 (0.51,16.6)	2.1 (0.33,13.7)						4.43** (1.49,13.2)
Dog allergen										
Dog in home	184 (14.8,11411)**	77.3** (17.6,339)					51.3 (3.95, > 999)**	44.4** (7.96,247)		72.2** (29.1,179)
Dust mite (Der)										
Multi-Family [c]	0.21 (0.03,1.35)	0.51 (0.14,1.88)	0.53 (0.06,4.97)	0.10 (0.01,1.50)	NA	NA	NA		0.71 (0.32,1.59)	0.24** (0.13,0.42)
Single-Family–w/ Basement [c]	0.33 (0.027,2.78)	0.56 (0.16,1.98)	1	0.12 (0.01,1.26)					0.42 (0.11,1.60)	0.54** (0.29,0.99)
Constructed before 1951	NA	1.23 (0.53,2.86)	0.90 (0.30,2.90)	3.23 (1.64,6.60)**			0.51 (0.05,5.32)		2.45* (0.99,6.06)	1.77** (1.05,2.98)
Mold odor in home	4.87** (0.99,23.9)						0.50 (0.04,5.99)		2.54* (1.03,6.25)	1.17 (0.59,2.32)
Cat allergen										
Cat in home	180 (26.1, > 999)**	69.7** (21.0,231)			61.3** (19.6,192)		> 100**	23.5** (4.59,120)	4.83** (1.90,12.3)	26.4** (16.2,43.0)
Mouse Allergen										
Cat in home	0.14**(0.02,1.14)		1.89 (< 0.01,19.6)	1.50 (< 0.01,15.3)	0.18** (0.02,1.35)	0.42 (< 0.01,5.65)	1.91 (< 0.01,28.1)	0.16** (0.06,0.45)		0.41** (0.22,0.79)
Rodent control	7.00* (1.86,26.4)				6.55** (2.72,15.8)	5.25* (0.86,32.0)	11.0** (1.78,68.0)			6.86** (3.77,12.5)
Rodent control or visible signs of rodents	2.18* (0.84,5.67)		1.68 (0.14,20.3)	13.7** (1.07,175)	8.18** (3.04,22.0)	8.67** (0.89,84.8)	8.33** (1.56,44.6)	2.19 (0.79,6.04)		3.39** (2.29,5.03)
Visible signs of rodents	0.7 (0.24, 2.03		1.68 (0.14, 20.3)	13.7** (1.07, 175)	4.19** (1.90, 9.26)	11.4** (1.17, 110)	8.00* 1.41, 45.2)	2.19 (0.79, 6.04)		2.56** (1.74, 3.76
Fall [d]	0.57 (0.19,1.76)		1.22 (0.03, > 999)	1.36 (0.08,23.6)	0.84** (0.24,2.95)	1.07 (0.15,7.82)	18.0** (1.48,219)	0.31* (0.08,1.27)		1.03** (0.60,1.79)
Spring [d]	0.53 (0.15,1.78)			3.17 (0.17,58.7)	1.52** (0.57,4.01)	1.56 (0.24,9.91)	9.60** (0.95,96.9)	1.56* (0.36,6.80)		1.43** (0.88,2.34)
Summer [d]	0.30 (0.07,1.37)		1.73 (0.13, > 999)	2.5 (< 0.01,97.5)	0.36** (0.11,1.23)		12.0** (0.53,273)	0.42* (0.11,1.57)		0.59** (0.33,1.06)

[a] Odds for one unit increment in housekeeping where 1=above average, 2=average, 3=below average.
[b] Odds ratios are compared to floors with more than 50% carpet.
[c] Compared to single-family homes with no basement.
[d] Compared to winter.
* p-value < 0.05.
** $0.05 \leq p$-value < 0.10.

4. Discussion

4.1. Identification of key home assessment elements

Based on these results, we identified those visual observations and interview questions that are associated with high allergen dust concentrations and should therefore be included in a home screening assessment to identify high allergen risk. The results show that a limited number of housing variables are associated with high allergen levels in multiple jurisdictions with different housing styles and climates. The adjusted results show that high cockroach allergen was associated with cracks or holes

Table 6
Multi-variate odds ratios (95% confidence intervals).

Parameter	Level	Cat	Dog	Dust mite	Mouse	Cockroach
Intercept		0.04* (0.02,0.08)	0.02* (0.00,0.05)	0.04* (0.01,0.22)	0.17* (0.11, 0.27)	0.03* (0.01, 0.12)
Season	Fall	–	–	–	0.89 (0.58,1.36)	–
	Spring	–	–	–	1.60* (1.11,2.30)	–
	Summer	–	–	–	0.66** (0.42,1.03)	–
	Winter	–	–	–	1.00	–
Site	Boston	2.94* (1.27,6.81)	2.01 (0.49,8.26)	1.45 (0.27,7.75)	1.40 (0.81,2.41)	0.11* (0.03, 0.52)
	Cincinnati	1.09 (0.53,2.25)	0.86 (0.31,2.35)	1.50 (0.55,4.10)	–	–
	Cleveland Asthma	–	–	1.36 (0.42,4.42)	0.26* (0.09,0.75)	1.45 (0.30, 6.98)
	Cleveland Comp	–	–	3.00* (1.01,8.90)	0.28* (0.10,0.82)	2.15 (0.46,10.18)
	Columbia BC	1.06 (0.51,2.24)	–	0.09* (0.02,0.34)	0.54* (0.33,0.90)	0.82 (0.21, 3.19)
	Columbia IPM	–	–	0.21 (0.03,1.53)	1.80 (0.83,3.89)	1.10 (0.30, 4.06)
	Harvard	3.04 (0.66,14.0)	2.53 (0.30,21.43)	1.50 (0.34,6.69)	0.64 (0.18,2.25)	1.38 (0.45, 4.19)
	Hopkins	0.62 (0.25,1.54)	1.00	–	1.00	1.00
	Seattle	1.00	–	1.00	–	–
Basement			–		–	–
	Not single family	–	–	0.67 (0.39,1.12)	–	–
	Single family with basement	–	–	0.57* (0.31,1.04)	–	–
	Single family without basement	–	–	1.00	–	–
Building constructed before 1951		–	–		–	–
	No	–	–	1.0	–	–
	Yes	–	–	1.65** (0.94,2.90)	–	–
Mold odor in home		–	–		–	–
	No	–	–	1.00	–	–
	Yes	–	–	2.48* (1.14,5.42)	–	–
Cat lives in home		–	–	–		–
	No	1.00	–	–	0.20* (0.08, 0.46)	–
	Yes	31.20* (18.5,52.7)	–	–	1.00	–
Dog Lives in Home	No	–	1.00	–	–	–
	Yes	–	98.6* (34.2,284)	–	–	–
Holes or cracks in walls		–	–	–	–	
	No	–	–	–	–	1.00
	Yes	–	–	–	–	2.05** (0.93,4.51)
Rodent control or visible signs of rodents		–	–	–		–
	No	–	–	–	1.00	–
	Yes	–	–	–	3.62* (2.17,6.03)	–
Roach control or visible signs of roaches		–	–	–	–	
	No	–	–	–	–	1.00
	Yes	–	–	–	–	6.45* (3.19,13.1)
BR Floor surface type (if sampled)		–	–	–	–	
	Carpet < 50%	–	–	–	–	5.58* (1.00,31.07)
	Carpet > 50%	–	–	–	–	1.00
	Hard surface or carpet < 50%	–	–	–	–	3.18** (0.83,12.16)
	No carpet	–	–	–	–	3.94* (1.43,10.88)

** p-value < 0.05.
* $0.05 \leq p$-value < 0.10.

in walls (OR=2.05), high dust mite allergen was associated with mold odor (OR=2.48), housing built before 1951 (OR=1.65), and single-family home with slab on grade (OR=1.9); and low mouse allergen was associated with presence of a cat (OR=0.20). Water leaks and below average housekeeping had unadjusted high odds ratios for high cockroach allergen (OR=2.51 and 3.1, respectively).

There are advantages and disadvantages to including all these variables in a housing screening protocol. The advantages include a better ability to identify those conditions that are most predictive and are most likely to require remediation or additional investigation. The more variables assessed, the greater the likelihood of detecting risk factors. On the other hand, the main disadvantage to including so many items is the burden on the inspector and the occupant and also the number of homes that can be assessed. The results of this paper will help guide those who are inspecting houses for asthma triggers. While local housing conditions vary considerably from one jurisdiction to another, the fact that pooling nine studies resulted in focused inspectable items will help to inform efforts to standardize housing inspection protocols, which in turn will help to focus intervention resources.

In this pooled analysis, the larger number of houses and children in the combined dataset increased the statistical power of the analyzes and enabled an analysis of a diverse set of jurisdictions with different climates and housing stock. For example, the

Table 7
Sensitivity and specificity of housing inspection elements.

Allergen	Sensitivity (%)	Specificity (%)	Percent with condition (%)	*p*-value
To identify cockroach allergen above 8 U/g (bedroom floor)				
1. Are there signs of cockroaches (e.g., droppings, live or dead roaches) (inspection)	80	60	45	<0.001
2. Is less than 50% of the bedroom carpeted? (inspection)	77	51	52	<0.001
3. Are there cracks or holes in walls? (inspection)	72	55	51	<0.001
4. Is there evidence of water leaks or damage? (inspection)	55	67	36	0.002
5. Is the housekeeping of the unit below average? (inspection)	46	88	16	<0.001
6. Questions 1 and 5 combined (i.e., yes to any)	82	68	38	<0.001
7. Questions 2 and 4 combined	89	56	50	<0.001
8. Questions 1, 4 and 5 combined	88	51	54	<0.001
9. Questions 1, 2 and 5 combined	89	50	54	<0.001
To identify house dust mite allergen above 10 μg/g (bedroom floor)				
1. Was home built before 1951? (record review)	54	60	42	0.033
2. Is this a single-family home w/o a basement (inspection)	23	92	10	<0.001
3. Both questions combined	64	49	53	0.063
To Identify mouse allergen above 1.6 μg/g (kitchen floor)				
1. Are there signs of rodents (e.g., droppings, live or dead mice) (inspection)	85	56	53	<0.001
Or has resident used rodent control? (question)				
To identify dog allergen above 10 μg/g (bedroom floor)				
1. Is a dog present in home? (question)	90	88	25	<0.001
To identify cat allergen above 8 μg/g (bedroom floor)				
1. Is a cat present in home? (question)	71	92	17	<0.001

Baltimore and New York City sites had row homes and large multi-family structures, respectively, unlike the other cities.

The absence of cats is associated with higher mouse allergen, but most dwellings (83%) in the pooled analysis did not have cats. The absence of cats, when combined with visible signs of rodents and use of rodent control, displayed a sensitivity of 100% but a specificity of only 5%. The absence of cats did not prove to be useful in identifying homes with high mouse allergen. This study also observed the expected relationship between the presence of cats (and dogs) in the home and presence of high cat (and dog) allergen levels, respectively. For children who are allergic to cats, the presence of cats at the home is a strong risk factor.

4.2. Comparison to other studies

This study offers results that are similar to findings from the National Survey of Lead and Allergens in Housing (NSLAH) (Vojta et al., 2002). The NSLAH and our pooled analysis had approximately the same number of housing units, but NSLAH was representative of all US housing, while our study was focused on low-income higher risk units. Our pooled cohort also included children with asthma, which could mean that these houses were more likely to have high allergen levels, or, conversely, that these households were more likely to have attempted to remove allergens as a protective measure. A finding that common housing inspection items in both NSLAH and our pooled analysis predicted allergen levels means that such items are important in both average and high-risk housing. Like NSLAH, our modeling showed associations between high cockroach allergen levels and the presence of roaches; moisture (water leaks); and the housekeeping and income of the residents (Cohn et al., 2005).

Our finding that bedrooms with more than 50% carpeting had lower cockroach allergen dust concentrations is also similar to NSLAH, which reported an adjusted odds ratio of 3.55 for non-carpeted wall-to-wall carpeting. Although the carpeting effect in NSLAH was not significant at $p=0.05$, the 95% confidence interval reported (0.83–15.19) suggests that it approached significance. German cockroaches tend to stay close to the food and water sources in the kitchen and bathroom and are less likely to be found in other rooms (Ogg et al., 2006). In short, the presence of wall-to-wall carpet or large area rugs may reduce tracking cockroach allergens into the bedroom or other rooms from the kitchen and bathrooms, where cockroach allergens are more prevalent.

On the other hand, because the total dust weight on bedroom floors is higher on carpeted floors than uncarpeted floors (Elliott et al., 2007), the concentration of allergens may be "diluted" but the loading (mass per unit surface area) may be higher on carpeted floors. Because our study focused on low-income high-risk units, it is possible that carpets in our study's houses were more deteriorated and contained more dust allergen than carpets in more average houses. The ability of carpets to bind dust particles, yet also act as a sink with high levels, requires further investigation.

The association between holes and cracks in walls and cockroach allergen is similar to another recent study (Peters et al., 2007) and supports a central element of integrated pest management, which is that holes and cracks must be sealed to reduce cockroach and mouse problems. As expected, an association was observed between high mouse allergen levels in the kitchen >1.6 μg/g and the presence of rodents. The absence of a cat in the home was significantly associated with higher mouse allergen levels, consistent with earlier studies (Chew et al., 2003; Cohn et al., 2004; Matsui et al., 2005). Mouse allergens were also higher in homes tested in winter or spring. The higher levels may be related to the increased presence of mice indoors during colder months. Both cockroach and mouse allergen and the use of roach or rodent control were related to higher allergen levels. This suggests that adequate cleaning must be done after pest removal/reduction to reduce allergens in the dwelling and that pest control alone may be inadequate.

Our pooled analysis showed that older homes, single-family homes and homes with mold odor are more likely to have elevated levels of dust mites, which was also found in NSLAH (Arbes et al., 2003). The association of dust mites with older homes is plausible, because such homes are more likely to have higher moisture levels and are less likely to have air conditioning.

The results also support prior findings that homes without basements or homes built on concrete slabs are more likely to have higher dust mite allergen levels (Munir et al., 1995; Garrett et al., 1998). Houses with insulation or a room or garage below the living room have approximately half the dust mite concentration in those carpeted rooms than carpeted rooms without such factors (Wickens et al., 2001).

A British study found that mechanical humidity reduction (use of a dehumidifier) was unsuccessful in reducing dust mite allergen levels in that climate (Fletcher et al., 1996). This is similar to our finding that there was no relationship between the use of dehumidification (or humidification) and dust mite allergen levels. Air conditioning was significantly related to reduced dust mite allergen in one study (Cleveland Asthma; $p=0.04$) but was not significant at any of the other sites in the pooled analysis. Air conditioning can be used for cooling in areas with lower humidity levels, so it is reasonable that it is not consistently related to dust mite allergen. Likewise, the use of dehumidifiers, like pest control, may indicate a previously damp home, where dust mite levels may be higher (Cho et al., 2006). In short, the use of dehumidification equipment does not appear to be a good predictor for reduced allergen concentration.

When considering moisture-related housing conditions (visible mold, mold odor, and evidence of leaks), we considered using a composite variable. However, the data show that for the studies in the pooled analysis, the composite variable performed no better than the individual ones. Cockroach allergen was more likely to be associated with leaks, while dust mite allergen was more likely associated with mold odor. This distinction is consistent with prior reports showing that German cockroaches are attracted to standing water, while mites absorb water from damp environments where the air has a higher relative humidity (and mold may be a marker for higher humidity (Institute of Medicine, 2004; Arbes et al., 2003). This suggests that visible mold, mold odor and evidence of leaks should probably all be considered in a housing screening protocol.

4.3. Limitations

Some of the variables were collected using different protocols and metrics, which could introduce bias or additional variability, making it more difficult to identify significant associations. For example, differences in flow rates and sample collection efficiencies are likely to yield differences in the quantities of dust collected, as well as different particle size distributions. Variability in particle sizes collected may mean that the biologically relevant fraction of settled dust may be under-sampled or over-sampled, which could result in exposure misclassification for studies of allergy and asthma. The magnitude of these effects remains unknown and should be investigated as the field moves toward improved standardization. While the regression equations used to predict missing values for some of the homes could also introduce bias, such equations are still the best estimate available.

One limitation of this study is that we could only use concentration (not loading), because that was the constant unit of measure across all studies. This may be particularly important for carpeted floors. Other studies found that carpeting increases the concentration of dust mite allergen (Arlian et al., 1992; van Strien et al., 2004; Meijer et al., 1995; Perry et al., 2006). Our pooled analysis did not find a relationship between carpeting and dust mite allergen. As has been shown in other studies, geography and climate can be overriding factors that could have precluded our ability to see such associations (Arlian et al., 1992; Ingram et al., 1995; van Strien et al., 2004). Other studies have found that dust mite allergen concentrations are low in inner city homes. (Breysse et al., 2005; Cho et al., 2008; Simons et al., 2007; Turyk et al., 2006). Furthermore, our studies did not include representation from the southern region of the country, where the dust mite factor may differ.

Although mold odor was strongly correlated with mite allergen levels in Seattle and Boston, the majority of the units in Baltimore had mold odor, even though there were no high dust mite levels in those study units. The findings suggest that musty smells from humid dwellings are related to mite levels, while mold odor in the absence of high humidity may not be a good indicator of mite problems. The fact that our pooled cohort did not have any studies from the Southern region, which tends to have higher humidity levels, is an important limitation.

The nine cohorts included in this pooled analysis were not a representative sample of homes of US children with asthma. Furthermore, the cross-sectional, observational design of the studies pooled for this analysis limits our ability to draw causal inferences. Except for the Columbia and Cleveland composite cohorts, the studies did not include homes of non-asthmatic children. It is possible that families with and without asthmatic children behave differently, but we could not assess this prospect.

Although it is important to control for heterogeneity in study sites by including a site effect in pooled analysis models, this may result in over-controlling and could mask a true association between allergen concentrations and housing characteristics.

4.4. Needs for further research

Due to the limitations described above, further research is needed to determine which specific housing factors directly and indirectly affect a standardized measure of asthma severity; this requires improved standardization of asthma severity assessment. Further studies are also needed to determine if asthma morbidity is better correlated with concentration or loading of allergens. The finding that dust lead loading was more highly correlated with children's blood lead level than was dust lead concentration played an important role in standardizing housing lead hazard assessment methods (Lanphear et al., 1995), and could conceivably do the same for the asthma field. More standardized methods of measuring allergens in dust (specific vacuum methods, room locations and laboratory analysis) are also needed. Finally, further investigation on whether carpets are beneficial or not is needed.

5. Conclusions

The home environment has important risk factors that should be assessed in the treatment of asthmatic children, especially for low-income high-risk populations. The presence of pets (cats or dogs) or pests (cockroaches or rodents); water leaks (including visible mold and mold odor); holes or cracks in walls; age of dwelling; use of pest control; presence of basement; and housekeeping are all related to allergen levels. Except for age of dwelling, each of these risk factors provides opportunities for remediation that can be expected to improve asthma status in children.

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References

Acosta, L.M., Acevedo-Garcia, D, Perzanowski, M.S., Mellins, R., Rosenfeld, L, Cortes, D., Gelman, A., Fagan, J.K., Bracero, L., Correa, J.C., Reardon, A.M., Chew, G.L., 2008. The New York City Puerto Rican asthma study: study design, methods and baseline results. Journal of Asthma 45 (1), 51–57.

American Lung Association, 2006. In: Trends in Asthma Morbidity and Mortality. American Lung Association.

Arbes, S.J., Cohn, R.D., Ming, Y., Muilenberg, M.L., Burge, H.A., Friedman, W., Zeldin, D.C., 2003. House dust mite allergen in US beds: results from the first National Survey of Lead and Allergens in Housing. Journal of Allergy and Clinical Immunology 111, 408–414.

Arlian, L.G., Bernstein, D., Bernstein, I.L., Friedman, S., Grant, A., Lieberman, P., Lopez, M., Metzger, J., Platts-Mills, T.A.E., Schatz, M., Spector, S., Wasserman, S., Zeiger, R.S., 1992. Prevalence of dust mites in the homes of people with asthma living in eight different geographic areas of the United States. Journal of Allergy and Clinical Immunology 90, 292–300.

Breysse, P., Farr, N., Galke, W., Lanphear, B., Morley, R., Begofsky, L., 2004. The relationship between housing and health: children at risk. Environmental Health Perspectives 12, 1583–1588.

Breysse, PN, Buckley, TJ, Williams, D, Beck, CM, Jo, SJ, Merriman, B, Kanchanaraksa, S, Swartz, LJ, Callahan, KA, Butz, AM, Rand, CS, Diette, GB, Krishnan, JA, Moseley, AM, Curtin-Brosnan, J, Durkin, NB, Eggleston, PA.., 2005. Indoor exposures to air pollutants and allergens in homes of asthmatic children in inner-city Baltimore. Environmental Research 98, 167–176.

Chew, G.L., Correa, J.C., Perzanowski, M.S., 2005. Mouse and cockroach allergens in the dust and air in northeastern United Stated inner city public high schools. Indoor Air 15, 228–234.

Chew, G.L., Perzanowski, M.S., Miller, R.L., Correa, J.C., Hoepner, L.A., Jusino, C.M., Becker, M.G., Kinney, P.L., 2003. Distribution and determinants of mouse allergen exposure in low-income New York City apartments. Environmental Health Perspectives 111, 1348–1351.

Cho, S.H., Reponen, T., Bernstein, D.I., Olds, R., Levin, L., Liu, X., Wilson, K., Lemasters, G., 2006. The effect of home characteristics on dust antigen concentrations and loads in homes. Science of the Total Environment 371, 31–43.

Cho, SJ, Ramachandran, G, Grengs, J, Ryan, AD, Eberly, LE, Adgate, JL., 2008. Longitudinal Evaluation of Allergen and culturable fungal concentrations in inner-city households. Journal of Occupational and Environmental Hygiene 5, 107–118.

Clougherty, J.E., Levy, J.I., Hynes, H.P., Spengler, J.D., 2006. A longitudinal analysis of the efficacy of environmental interventions on asthma-related quality of life and symptoms among children in urban public housing. Journal of Asthma 43, 335–343.

Cohn, R.D., Arbes, S.J., Jaramillo, R., Reid, L.H., Zeldin, D.C., 2005. National prevalence and exposure risk for cockroach allergen in US households. Environmental Health Perspectives 114, 522–526.

Cohn, R.D., Arbes, S.J., Yin, M., Jaramillo, R., Zeldin, D.C., 2004. National prevalence and exposure risk for mouse allergen in US households. Journal of Allergy and Clinical Immunology 113, 1167–1171.

Eggleston, P.A., Butz, A., Rand, C., Curtin-Brosnan, J., Kanchanaraksa, S., Swartz, L., Breysse, P., Buckley, T., Diette, G., Merriman, B., Krishnan, J.A., 2005. Home environmental intervention in inner-city asthma: a randomized controlled clinical trial. Annals of Allergy, Asthma and Immunology 95, 518–524.

Eggleston, P.A., Rosenstreich, D., Lynn, H., Gergen, P., Baker, D., Kattan, M., Mortimer, K.M., Mitchell, H., Ownby, D., Slavin, R., Malveaux, F., 1998. Relationship of indoor allergen exposure to skin test sensitivity in inner-city children with asthma. Journal of Allergy and Clinical Immunology 102, 563–570.

Elliott, L., Arbes, S.J., Harvey, E.S., Lee, R.C., Salo, P.M., Cohn, R.D., London, S.J., Zeldin, D.C., 2007. Dust weight and asthma prevalence in the National Survey of Lead and Allergens in Housing (NSLAH). Environmental Health Perspectives 115, 215–220.

Fletcher, A.M., Pickering, C.A., Custovic, A., Simpson, J., Kennaugh, J., Woodcock, A., 1996. Reduction in humidity as a method of controlling mites and mite allergens: the use of mechanical ventilation in British domestic dwellings. Clinical and Experimental Allergy 26, 1051–1056.

Garrett, M.H., Hooper, B.M., Hooper, M.A., 1998. Indoor environmental factors associated with house-dust-mite allergen (Der p 1) levels in south-eastern Australian houses. Allergy 53, 1060–1065.

Gelber, L.E., Seltzer, L.H., Bouzoukis, J.K., Pollart, S.M., Chapman, M.D., Platts-Mills, T.A., 1993. Sensitization and exposure to indoor allergens (dust mite, cat, and cockroach) as factors for asthma among patients presenting to hospital. American Review of Respiratory Disease 147, 573–578.

Ingram, J.M., Sporik, R., Rose, G., Honsinger, R., Chapman, M.D., Platts-Mills, T.A.E., 1995. Quantitative assessment of exposure to dog (Can f 1) and cat (Fel d 1) allergens: relationship to sensitization and asthma among children living in Los Alamos, New Mexico. Journal of Allergy and Clinical Immunology 96, 449–456.

Institute of Medicine, 2000. In: Clearing the Air: Asthma and Indoor Air Exposures. National Academy Press, Washington, DC.

Institute of Medicine, 2004. In: Damp Indoor Spaces and Health. National Academies Press, Washington, DC.

Johnson, C.C., Ownby, D.R., Zoratti, E.M., Alford, S.H., Williams, L.K., Joseph, C.L.M., 2002. Environmental epidemiology of pediatric asthma and allergy. Epidemiology Review 24, 154–175.

Kercsmar, C.M., Dearborn, D.G., Schluchter, M., Xue, L., Kirchner, H.L., Sobolewski, J., Greenberg, S.J., Vesper, S.J., Allan, T., 2006. Reduction in asthma morbidity in children as a result of home remediation aimed at moisture sources. Environmental Health Perspectives 114, 1574–1580.

Krieger, J.W., Takaro, T.K., Song, L., Weaver, M.., 2005. The Seattle-King County Health Homes Project: a randomized, controlled trial of a community health worker intervention to decrease exposure to indoor asthma triggers. American Journal of Public Health 95, 652–659.

Kuehr, J., Frischer, T., Meinert, R., Barth, R., Forster, J., Schraub, S., Urbanek, R., Karmaus, W., 1994. Mite allergen exposure is a risk for the incidence of specific sensitization. Journal of Allergy and Clinical Immunology 94, 44–52.

Lanphear, BP, Emond, E, Weitzman, M, Jacobs, DE, Tanner, M, Winter, N, Yakir, B, Eberly, S.A, 1995. Side-by-side comparison of dust collection methods for sampling lead-contaminated house dust. Environmental Research 68, 114–123.

Lanphear, B.P., Aligne, C., Auinger, P., Byrd, R., Weitzman, M., 2001a. Residential exposures associated with asthma in U.S. children. Pediatrics 107, 505–511.

Lanphear, B.P., Kahn, R.S., Berger, O., Auinger, P., Bortnick, S., Naahas, R., 2001b. Contribution of residential exposures to asthma in US children and adolescents. Pediatrics 107, e98.

Levy, J.I., Welker-Hood, L.K., Clougherty, J.E., Dodson, R.E., Steinbach, S., Hynes, H.P., 2004. Lung function, asthma symptoms, and quality of life for children in public housing in Boston: a case-series analysis. Environmental Health 3 (1), 13.

Mannino, D.M., Homa, D.M., Akinbami, L.J., Moorman, J.E., Gwynn, C., Redd, S.C., 2002. Surveillance for Asthma—United States, 1980–1999. In: CDC Surveillance Summaries, March 29, 2002, Mortality and Morbidity Weekly Report, no. 51, pp. 1–13.

Mannino, D.M., Homa, D.M., Pertowski, C.A., Ashizawa, A., Nixon, L.L., Johnson, C.A., Ball, L.B., Jack, E., Kang, D.S. (1998) Surveillance for asthma –United States, 1960–1995. In: cDC Surveillance Summaries, April 24, 1998, Mortality and Morbidity Weekly Report, no. 47, pp. 1–28.

Matsui, E.C., Simons, E., Rand, C., Butz, A., Buckley, T.J., Breysse, P., Eggleston, P.A., 2005. Airborne mouse allergen in the homes of inner-city children with asthma. Journal of Allergy and Clinical Immunology 115, 358–363.

Meijer, G.G., van der Heide, S., Postma, D.S., de Reus, D.M., Koeter, G.H., van Aalderen, W.M., 1995. House dust mite exposure in asthmatic and healthy children: the difference is carpeting. Pediatric Allergy and Immunology 6, 187–191.

Moorman JE, Rudd RA, Johnson CA King M, Minor P, Bailey C, Scalia, MR, Akinbami LJ, National Surveillance for Asthma—United States, 1980–2004. MMWR October 19, 2007/56(SS08); no. 1–14, pp. 18–54.

Munir, A.K., Bjorksten, B., Einarsson, R., Ekstrand-Tobin, A., Moller, C., Warner, A., Kjellman, N.I., 1995. Mite allergens in relation to home conditions and sensitization of asthmatic children from three climatic regions. Allergy 50, 55–64.

Ogg, B., Ferraro, D., Ogg, C., 2006. Cockroach Control Manual. University of Nebraska-Lincoln, Institute of Agriculture and Natural Resources, Lancaster County Cooperative Extension Office. Lincoln, NE. Available online: http://www.pested.unl.edu/pesticide/pages/index.jsp (accessed: 15 May 2007).

Perry, T.T., Wood, R.A., Matsui, E.C., Curtin-Brosnan, J., Rand, C., Eggleston, P.A., 2006. Room-specific characteristics of suburban homes as predictors of indoor allergen concentrations. Annals of Allergy, Asthma and Immunology 97 (5), 628–635.

Peters, J.L., Levy, J.I., Rogers, C.A., Burge, H.A., Spengler, J.D., 2007. Determinants of allergen concentrations in apartments of asthmatic children living in public housing. Journal of Urban Health 84, 185–197.

Phipatanakul, W., Eggleston, P.A., Wright, E.C., Wood, R.A., National Cooperative Inner-City Asthma Study, 2000. Mouse allergen. II. The relationship of mouse allergen exposure to mouse sensitization and asthma morbidity in inner-city children with asthma. Journal of Allergy and Clinical Immunology 106, 1075–1080.

Pollart, S.M., Smith, T.F., Morris, E.C., Gelber, L.E., Platts-Mills, T.A., Chapman, M.D., 1991. Environmental exposure to cockroach allergens: analysis with monoclonal antibody-based enzyme immunoassays. Journal of Allergy and Clinical Immunology 87 (2), 505–510.

Platts-Mills, T.A., Sporik, R.B., Wheatley, L.M., Haymann, P.W., 1995. Is there a dose response relationship between exposure to indoor allergens and symptoms of asthma? Journal of Allergy and Clinical Immunology 96, 435–440.

Rosenstreich, D.L., Eggleston, P., Kattan, M., Baker, D., Slavin, R.G., Gergen, P., Mitchell, H., McNiff-Mortimer, K., Lynn, H., Ownby, D., Malveaux, F., 1997. The role of cockroach allergy and exposure to cockroach allergen in causing morbidity among inner-city children with asthma. New England Journal of Medicine 336, 1356–1363.

Simons, E, Curtin-Brosnan, J, Buckley, T, Breysse, P, Eggleston, P.A., 2007. Indoor environmental differences between inner city and suburban homes of children with asthma. Journal of Urban Health 84 (4), 577–590.

Takaro, T.K., Krieger, J.W., Song, L., 2004. Effect of environmental interventions to reduce exposure to asthma triggers in homes of low-income children in

Seattle. Journal of Exposure Analysis and Environmental Epidemiology 14, S133–S143.
Turyk, M, Curtis, L, Scheff, P, Contraras, A, Coover, L, Hernandez, E, Freels, S, Persky, V., 2006. Environmental allergens and asthma morbidity in low-income children. Journal of Asthma 43 (6), 453–457.
van Strien, R.T., Driessen, M.N.B.M., Oldenweining, M., Doekes, G., Brunekreef, B., 2004. Do central vacuum cleaners produce less indoor airborne dust or airborne cat allergen, during and after vacuuming, compared with regular vacuum cleaners? Indoor Air 14 (3), 174–177.
Vojta, P.J., Friedman, W., Marker, D.A., Clickner, R., Rogers, J.W., Viet, S.M., Muilenberg, M.L., Thorne, P.S., Arbes Jr., S.J., Zeldin, D.C., 2002. First National Survey of Lead and Allergens in Housing: survey design and methods for the allergen and endotoxin components. Environmental Health Perspectives 110, 527–532.
Wickens, K., Mason, K., Fitzharris, P., Siebers, R., Hearfield, M., Cunningham, M., Crane, J., 2001. The importance of housing characteristics in determining Der p 1 levels in carpets in New Zealand homes. Clinical and Experimental Allergy 31, 827–835.