

Exposure to multiple indoor allergens in US homes and its relationship to asthma

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Background: The National Survey of Lead and Allergens in Housing was the first population-based study to measure indoor allergen levels in US homes.

Objective: We characterized the overall burden to multiple allergens and examined whether increased allergen levels were associated with occupants' asthma status.

Methods: This cross-sectional study surveyed a nationally representative sample of 831 housing units in 75 different locations throughout the United States. Information was collected by means of questionnaire and environmental assessment. Allergen concentrations in dust samples were assessed by using immunoassays. The following cutoff points were used to define increased allergen levels: 10 µg/g for Der p 1, Der f 1, and Can f 1; 8 µg/g for Fel d 1; 8 U/g for Bla g 1; 1.6 µg/g for mouse urinary protein; and 7 µg/g for *Alternaria alternata* antigens. Allergen burden was considered high when 4 or more allergens exceeded increased levels in any of the sampling locations.

Results: Exposure to multiple allergens was common in US homes. Of the surveyed homes, 51.5% had at least 6 detectable allergens and 45.8% had at least 3 allergens exceeding increased levels. Race, income, housing type, absence of children, and presence of smokers, pets, cockroaches, rodents, and mold/moisture-related problems were independent predictors of high allergen burden. Among atopic subjects, high allergen burden increased the odds of having asthma symptoms (odds ratio, 1.81; 95% CI, 1.04-3.15).

Conclusion: Increased allergen levels in the home are associated with asthma symptoms in allergic individuals. (J Allergy Clin Immunol ■■■■;■■■:■■■-■■■.)

Key words: Allergen, indoor, exposure, asthma, allergy

Asthma morbidity is a significant public health concern, not only in terms of health care costs but also in terms of lost productivity and reduced quality of life.¹ More than 30 million

Abbreviations used

MUP: Mouse urinary protein (mouse allergen)

NSLAH: National Survey of Lead and Allergens in Housing

persons in the United States have been given diagnoses of asthma, and at least two thirds of the patients with diagnosed asthma have current asthma with active symptoms.²

Indoor exposures are of great importance in relation to asthma because most persons spend a large amount of their time indoors, especially at home.³ Exposure to indoor allergens generated from animals, arthropods, rodents, and molds is considered an important risk factor for asthma.^{4,5} Although the role of indoor allergen exposure in the development of sensitization and asthma has remained a subject of controversy, there is strong evidence that indoor allergens play a key role in triggering and exacerbating asthma, particularly in sensitized individuals.⁶

In the United States numerous studies of indoor allergens have been conducted; however, many of the studies have focused on single allergens, selected populations (eg, asthmatic, allergic, and inner-city populations), or both.^{4,7} Types and levels of allergens have been found to vary substantially by socioeconomic, ethnic, and regional factors among the studied populations, which predominantly represent high-risk groups.^{8,9} Yet little information is available about how levels of common indoor allergens vary in the general US population. Although studies suggest that exposure to multiple allergens in homes is not uncommon,^{10,11} few studies have examined factors that contribute to high allergen burden across multiple allergens¹² or the role of multiple allergen exposures in relation to asthma.

To characterize and achieve better understanding of the exposure variability in homes, the National Institute of Environmental Health Sciences and the US Department of Housing and Urban Development conducted a survey that assessed levels of several indoor allergens (Bla g 1, Can f 1, Der f 1, Der p 1, Fel d 1, mouse urinary protein [MUP], and *Alternaria alternata*) and endotoxin in the US housing stock. It has been postulated that in addition to allergens, exposure to endotoxin might also influence asthma morbidity.¹³ The National Survey of Lead and Allergens in Housing (NSLAH) provides a unique opportunity to examine allergen and endotoxin exposures in relation to asthma in a nationally representative sample of the US population.¹⁴ Our previous publications have described the details of the individual exposures.^{13,15-19} In this article we estimate the burden of exposure to multiple allergens in US homes, identify independent predictors of high allergen burden, explore interrelationships between allergen and endotoxin levels, and examine the associations between

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high allergen burden and asthma-related outcomes among the study population.

METHODS

The data for this cross-sectional study were collected as part of the NSLAH, which used a complex multistage design to sample the US population of permanently occupied noninstitutional housing units that permit children. The survey was approved by the National Institute of Environmental Health Sciences Institutional Review Board in 1998. Details of the survey methodology and population characteristics have been previously published.¹⁴ Briefly, a nationally representative sample of 831 housing units inhabited by 2456 individuals within 75 different locations throughout the United States was surveyed. At each home, a residential questionnaire was administered, and environmental data were acquired through inspection and sample collection.

Environmental sampling

Single-surface dust samples were collected from a bed, a sofa, or a chair and from bedroom, living room, and kitchen floors, as previously described.¹⁴ Concentrations of the indoor allergens were measured with immunoassays. Dust mite (Der f 1 and Der p 1), dog (Can f 1), cat (Fel d 1), and cockroach (Bla g 1) allergens were measured by using mAb-based ELISAs.¹⁴ MUP and *A alternata* antigens were assayed with ELISAs by using polyclonal antibodies.^{14,18,19} The *A alternata* assay has been shown to measure overall *A alternata* exposure in environmental samples; the polyclonal antibody used is directed against a large range of *A alternata* proteins, including but not limited to known allergens.²⁰ For most samples, the lower limits of detection were as follows: 0.025 µg/g for Der p 1 and Der f 1; 0.050 µg/g for Can f 1; 0.012 µg/g for Fel d 1; 0.10 U/g for Bla g 1; 0.25 µg/g for MUP; and 0.14 µg/g for *A alternata*. Concentrations less than the lower limits of detection were considered nondetectable. Endotoxin concentrations in the samples were assessed by using the kinetic chromogenic Limulus amoebocyte lysate assay with the detection limit of 0.001 EU/mg of sieved dust.¹³ The samples that had insufficient amount of dust for the analysis were considered missing. However, allergen measurements were available from at least one room for 99% of the homes. The corresponding percentage for endotoxin was 95%.

Assessment of asthma and allergy

The interviewer-administered questionnaire obtained information on doctor-diagnosed asthma and allergies. Current symptomatic asthma among the subjects with diagnosed asthma was ascertained with a question confirming asthma symptoms in the past year. Atopic status was assessed by report of physician diagnosis of allergies. Although these self-reported health outcomes were assessed and primarily analyzed at the individual level, we also evaluated the outcomes at the household level (ie, household-level definition was based on whether anyone in the household reported the health outcome or none of the residents reported it).

Statistical analysis

All statistical analyses were conducted with SUDAAN software (version 9.1; RTI, Research Triangle Park, NC), and sample weights were applied to all estimates. Details of statistical weighting for the NSLAH have been described elsewhere.¹⁴

For the purpose of analysis, we dichotomized allergen concentrations using provisional cutoff points that have been associated with asthma morbidity and allergic sensitization.²¹⁻²⁵ Such cutoff points, however, are not as well established for *A alternata* and mouse allergen as they are for other indoor allergens. For mouse allergen, we used a threshold that has been associated with sensitization in recent publications.^{18,26} For *A alternata*, we chose a cutoff point that has been associated with increased odds of asthma symptoms in the NSLAH.²⁷ The cutoff points used in the analysis were as follows: 10 µg/g for Der p 1, Der f 1, and Can f 1; 8 µg/g for Fel d 1; 8 U/g for Bla g 1; 1.6 µg/g for MUP; and 7 µg/g for *A alternata*.

We evaluated the overall burden of exposure to multiple allergens by assessing how many allergens exceeded detection limits and allergen-specific thresholds for increased levels in each home. The allergen-specific exposure level in the home was considered increased if the allergen concentration exceeded the cutoff point in any of the sampling locations. Exposure to dust mite allergens was defined as increased if either Der f 1 or Der p 1 concentrations exceeded 10 µg/g in any of the sampling locations. Exposure to multiple allergens in the home was dichotomized to reflect high (≥4 allergens exceeding increased levels) versus low-medium levels (0-3 allergens exceeding increased levels).

To identify factors that predicted a high burden of exposure to multiple allergens, we performed logistic regression analysis. All potential sociodemographic and housing-related variables were first evaluated by using bivariate analyses. Of the evaluated variables, we selected those with *P* values of less than or equal to .25 (race, income/poverty level, census region, housing type, building year, use of air conditioning/dehumidifier, cleaning frequency, presence of children, smokers, pets, cockroaches, rodents, or mold/moisture-related problems) for inclusion in the regression analysis. In our data-driven modeling approach, we used backward elimination for model selection; starting from the full model, variables with the highest *P* value (Wald *F* test) were dropped until all remaining predictors in the model had *P* values less than or equal to .05.

For descriptive purposes, we explored exposure patterns in the allergen data. We used logistic regression analysis to determine which allergens cluster together in high levels. To evaluate associations between pairs of allergens, we calculated odds ratios (ORs) with 95% CIs for each pair using dichotomized allergen levels (increased level: yes vs no). Because exposure to endotoxin has been associated with asthma morbidity,¹³ we not only looked at interrelationships between different allergens but also at associations between allergen and endotoxin levels. To further characterize the relationship between allergen burden and endotoxin levels, we estimated mean (geometric) endotoxin concentrations for each level of allergen burden. Comparisons of the means were assessed with ANOVA using Wald *F* statistics.

We compared the allergen burden between asthmatic and nonasthmatic households by using χ^2 statistics. To examine whether high allergen burden was associated with occupants' asthma status at the individual level, we calculated ORs with 95% CIs for the asthma-related outcomes by using logistic regression. The models we present here are adjusted for age, sex, race, education, smoking, season, and endotoxin levels. Because we did not have information on personal smoking, smoking exposure was assessed at the household level (indoor smoking in the home). Although total amount of dust can influence inhaled exposure levels, we did not adjust for dust weight because the adjustment did not appreciably change the ORs (change <5%). We present separate ORs for atopic and nonatopic individuals; the observed effect was modified by atopic status. Subjects with missing data on the exposures were excluded from the analyses at the individual level, leaving 1953 (80%) of 2456 subjects for the analysis.

RESULTS

Distributions of allergen levels

Table 1 shows percentages of US households with detectable and increased levels of measured allergens. *A alternata*, cat (Fel d 1), and dog (Can f 1) allergens were the most commonly detected allergens; virtually all homes (>99%) had detectable levels in at least 1 sampling location. Detectable levels of dust mite allergens (Der f 1 and Der p 1) were found in at least 85% of the surveyed homes, and mouse (MUP) and cockroach (Bla g 1) allergens were detected in 82% and 63% of the households, respectively. Of the dust mite allergens, Der f 1 had highest levels in bedrooms; *A alternata*, cat, and dog allergens were found to be highest in living rooms; and mouse and cockroach allergen levels tended to be most increased in kitchens (Table 1). More detailed information on the distributions can be found elsewhere.¹⁵⁻¹⁹

TABLE I. Estimated distributions of detectable and increased allergen levels in US homes by sampling location*

Allergen levels	Percentage (SE) of households by sampling location					
	Bedroom bed	Bedroom floor	Kitchen floor	Living room floor	Living room upholstery	Any location
<i>A alternata</i>						
Detectable	92.9 (1.4)	99.6 (0.2)	98.1 (0.5)	98.7 (0.4)	98.6 (0.5)	99.9 (0.1)
>7 µg/g	10.4 (1.6)	30.4 (2.4)	24.0 (2.4)	38.8 (1.9)	24.6 (2.2)	56.5 (2.3)
<i>Bla g 1</i>						
Detectable	6.1 (0.8)	17.6 (1.6)	28.5 (1.9)	44.4 (2.1)	38.4 (2.0)	62.7 (1.8)
>8 U/g	0.5 (0.2)	3.2 (0.7)	9.5 (1.0)	2.7 (0.7)	1.1 (0.4)	10.2 (1.1)
<i>Can f 1</i>						
Detectable	93.8 (1.1)	95.6 (0.9)	82.6 (2.4)	94.9 (0.9)	98.0 (0.5)	99.2 (0.3)
>10 µg/g	28.9 (1.9)	30.3 (2.0)	27.2 (3.9)	34.6 (2.0)	37.7 (2.0)	42.2 (2.1)
<i>Der f 1</i>						
Detectable	82.3 (2.0)	80.7 (2.1)	42.8 (3.5)	73.5 (2.2)	78.3 (2.2)	89.5 (1.8)
>10 µg/g	17.4 (2.1)	24.2 (2.5)	1.1 (0.6)	15.6 (1.6)	15.3 (2.2)	35.5 (2.6)
<i>Der p 1</i>						
Detectable	68.7 (2.7)	70.3 (2.2)	39.0 (4.4)	63.6 (3.0)	72.1 (3.0)	85.9 (2.2)
>10 µg/g	8.4 (0.9)	11.6 (1.5)	1.0 (0.5)	8.6 (1.1)	14.6 (1.7)	22.1 (1.5)
<i>Fel d 1</i>						
Detectable	96.7 (0.6)	96.9 (0.8)	83.5 (2.0)	96.0 (0.8)	97.9 (0.5)	99.7 (0.2)
>8 µg/g	30.9 (1.9)	28.3 (1.6)	22.3 (2.2)	26.9 (1.8)	40.2 (1.8)	43.4 (1.7)
MUP						
Detectable	41.2 (2.2)	50.0 (2.1)	57.0 (2.2)	40.7 (2.5)	37.4 (2.4)	82.3 (1.6)
>1.6 µg/g	8.4 (1.2)	13.5 (1.2)	21.6 (2.1)	12.1 (1.4)	7.9 (1.2)	34.6 (2.3)

*Allergen measurements were available from at least 1 room for 99% (n = 822) of the households.

Overall burden of multiple indoor allergens

Exposure to multiple allergens in US homes was common (Fig 1). More than half of the homes (51.5%) had detectable levels of all measured allergens. At least 2 allergens were detected in every home (Fig 1, A). In less than 8% of the homes, allergen levels did not exceed any of the threshold values for increased levels. Most homes had 2 to 3 allergens at increased levels, and 18.0% (SE = 1.8) of the homes had 4 or more allergens exceeding increased levels (Fig 1, B). Table E1 in the Online Repository at www.jacionline.org shows how increased allergen levels were distributed among those who had a high burden of exposure to multiple allergens (≥ 4 allergens exceeding increased levels). As in the total study population, *A alternata* was the most common and cockroach the least common allergen to exceed increased levels.

Independent predictors of high allergen burden

We used multivariable logistic regression to identify independent predictors of high allergen burden. The following predictors remained in the final model: family race, income level, housing type, absence of children, and presence of smokers, pets, cockroaches, rodents, and mold/moisture-related problems. Table II shows estimated prevalences and ORs for the independent predictors of high allergen burden in US homes. Table E2 in the Online Repository (available at www.jacionline.org) shows allergen-specific prevalences by the predictors (bivariate analysis).

Interrelationships between endotoxin and multiple indoor allergens

We examined the association between the allergen burden and endotoxin levels by comparing the geometric mean concentration of endotoxin across the levels of allergen burden (Fig 2). Endotoxin levels increased with increasing allergen burden ($P < .01$ for trend).

Table III demonstrates interrelationships between the allergens and endotoxin in more detail. Increased levels of cat (Fel d 1), dog (Can f 1), and dust mite (Der f 1) allergens were inversely associated with increased cockroach allergen levels. Increased levels of all other allergens, except cockroach, were positively associated with increased *A alternata* levels. Although concentrations of Der f 1 and Der p 1 were interrelated, they appeared to have distinct associations with other allergens, reflecting perhaps biologic and ecologic differences between the 2 mite species. Increased cat and dog allergen levels were significantly associated with each other, and increased mouse allergen levels were most strongly associated with increased cockroach and *A alternata* levels. Of the measured allergens, increased *A alternata*, cockroach, and mouse allergen levels were also associated with increased endotoxin levels.

Asthma and exposure to multiple allergens

Of the surveyed homes, 25.0% (SE = 2.3) had at least 1 resident who had been given a diagnosis of asthma. Four or more allergens in increased levels were present in 23.4% of asthmatic homes compared with 16.2% of nonasthmatic homes ($P = .03$ for difference), indicating that homes of asthmatic subjects were more likely to have a greater number of allergens exceeding increased levels than homes in which no asthmatic individuals resided.

Among the study participants, lifetime prevalence of doctor-diagnosed asthma was 11.2%, and 6.9% of the study subjects reported active asthma symptoms in the past 12 months. The majority of the current asthmatic subjects (77%) reported doctor-diagnosed allergies. We examined whether increased burden of exposure to multiple allergens was associated with the prevalence of current symptomatic asthma. Table IV shows separate ORs for atopic and nonatopic individuals because the observed effect was modified by atopic status. After adjusting for potential confounders, high exposure burden significantly increased the odds

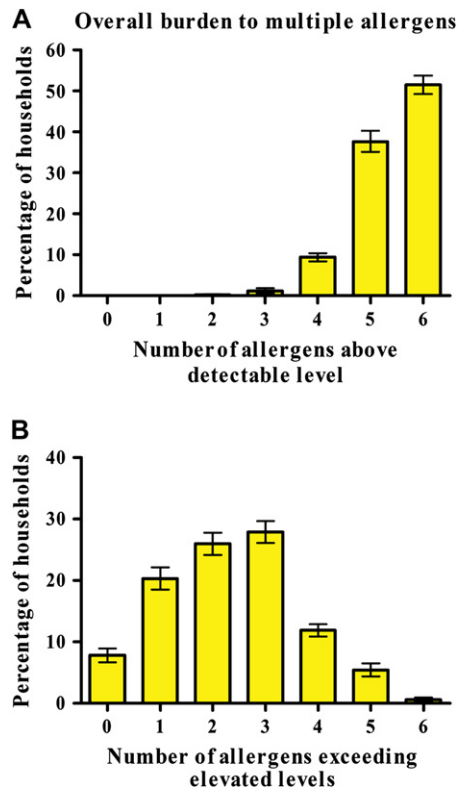


FIG 1. Overall burden of multiple allergens in US homes. The bar graph shows percentages ($\pm$ SEs) of homes with detectable (**A**) and increased (**B**) levels of allergens by numbers of allergens exceeding allergen-specific thresholds.

of having asthma symptoms in the past year (OR, 1.81; 95% CI, 1.04-3.15) among atopic individuals. This association was not seen in nonatopic individuals. Reported wheezing was not associated with high allergen burden (data not shown). The majority (69.9%) of those who reported wheezing in the past year did not report asthma symptoms. Because wheezing was not restricted to asthma, diseases other than asthma might have contributed to wheezing. Of the current asthmatic subjects, 71.2% used asthma medication. In atopic individuals, high allergen burden was associated with asthma symptoms, irrespective of medication use; among atopic subjects, the OR (unadjusted) was 1.91 (95% CI, 1.15-3.17) for asthmatic subjects who used medication and 2.04 (95% CI, 0.95-4.38) for those who did not use medication.

DISCUSSION

Exposure to multiple indoor allergens in US homes is common; more than half of the surveyed homes had detectable levels of all studied allergens (dust mite, dog, cat, cockroach, mouse, and *A alternata*), and most homes had 2 to 3 allergens at increased levels. Race, income level, housing type, absence of children, and presence of smokers, pets, cockroaches, rodents, and mold/moisture-related problems contributed independently to high allergen burden in the home. Households with asthmatic subjects were more likely to have a greater number of increased allergens than households without asthmatic subjects. Among atopic individuals, high allergen burden in the home significantly increased the odds of having asthma symptoms.

TABLE II. Estimated prevalences and ORs for the independent predictors of high allergen burden* in US homes (NSLAH, 1998-1999)

Predictor	Percentage (SE)	OR (95% CI) [†]	P value [‡]
Race			<.01
White	19.84 (2.14)	2.64 (1.50-4.63)	
Other	10.94 (1.80)	1.00	
Family income			<.01
\$0-\$19,999	22.56 (4.71)	1.84 (0.85-3.98)	
\$20,000-\$39,000	23.87 (3.46)	2.44 (1.14-5.22)	
\$40,000-\$59,000	11.53 (2.96)	0.72 (0.30-1.74)	
$\geq$ \$60,000	12.12 (2.96)	1.00	
Housing type			.04
Single-family home	19.06 (2.01)	1.94 (1.02-3.67)	
Multifamily home	11.36 (2.32)	1.00	
Child resident(s)			.01
No	19.43 (1.92)	1.65 (1.16-2.34)	
Yes	15.95 (2.36)	1.00	
Smoker(s) in the household			<.01
Yes	23.47 (2.01)	1.74 (1.19-2.53)	
No	13.23 (2.01)	1.00	
Mold/moisture problems [§]			<.01
Yes	24.21 (2.63)	2.06 (1.28-3.30)	
No	11.76 (1.80)	1.00	
Pets in the household			<.01
Yes	24.82 (2.55)	2.98 (1.67-5.31)	
No	11.31 (2.19)	1.00	
Cockroaches [§]			.05
Yes	24.12 (4.65)	1.80 (1.00-3.24)	
No	16.73 (1.84)	1.00	
Rodents [§]			.01
Yes	26.01 (4.33)	1.75 (1.15-2.66)	
No	16.55 (1.77)	1.00	

*Four or more allergens exceeding increased levels in the household. Cutoff points for increased allergen levels were as follows: 10 μ g/g for Der f 1, Der p 1, and Can f 1; 8 μ g/g for Fel d 1; 8 U/g for Bla g 1; 1.6 μ g/g for MUP; and 7 μ g/g for *A alternata*.

[†]OR adjusted for each variable in the table.

[‡]Wald F test.

[§]Assessed by observation (occupants and field team).

The NSLAH was the first study to characterize how indoor allergen exposures vary in homes throughout the United States. Of the measured allergens, *A alternata*, cat, and dog allergens were the most commonly detected, and they were also the ones that were most often found in increased levels. Individual allergen levels were strongly associated with regional, ethnic, and socioeconomic factors, but each allergen appeared to have a distinct set of predictors.¹⁵⁻¹⁹ Consistent with previous studies,^{9,28,29} allergen levels in homes varied by location in the home.

Beyond individual allergen exposures, it is important to characterize which factors contribute to total allergen burden in homes. The NSLAH data suggested that one of the strongest predictors of high allergen burden was race; burden of exposure was significantly higher among white than nonwhite residents. White households were more likely to have increased levels of *A alternata*, cat, dog, and dust mite (Der f 1) allergens than nonwhite households, whereas the presence of cockroach and mouse allergens in increased levels was significantly more prevalent in nonwhite households.

Family income influenced allergen burden significantly; households with lower income (<\$40,000) were more likely to have high allergen burden than households with higher income levels

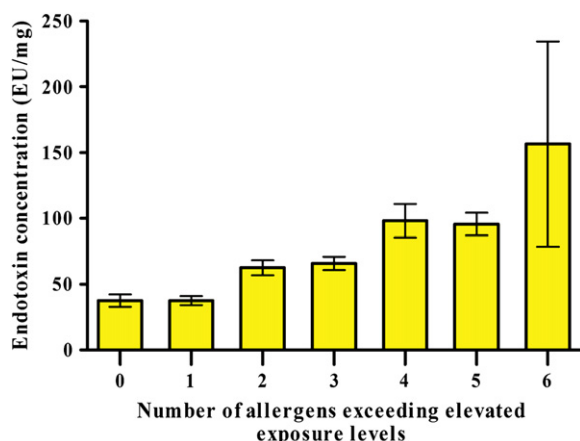


FIG 2. Relationship between allergen burden and endotoxin levels. The bar graph displays the geometric mean concentration of endotoxin (the mean of all sampling location concentrations) across the levels of allergen burden ($\pm$ geometric standard error).

(23.3% vs 11.9%, $P < .01$ for the difference). The prevalence of increased levels of cockroach, mouse, and dust mite (Der p 1) allergens was significantly higher in homes with lower income. Although increased cat and dog allergen levels were strongly associated with higher income levels, the majority of the homes with high allergen burden and lower income (<\$40,000) had increased cat and dog allergen levels (73.0% and 74.5%, respectively). Living in a single-family home was a strong predictor of high allergen burden. Except for cockroach and mouse allergens, increased allergen levels were more prevalent in single-family homes than in multifamily homes; differences were statistically significant for *A alternata*, dog, and dust mite (Der p 1) allergens. Consistent with published literature, the presence of increased cockroach allergen was significantly higher in multifamily homes.^{10,30} Previous studies suggest that allergen levels are not only associated with socioeconomic factors and ethnicity but are also influenced by environmental factors that tend to differ between housing types (eg, temperature and humidity levels and differences in the likelihood of having pets).^{9,10,30}

Smoking is typically associated with socioeconomic factors,³¹ but the presence of smokers remained an independent predictor of high allergen burden in our multiple regression models. In particular, increased levels of cockroach and dog allergen were more frequently detected in homes of smokers than in homes of non-smokers. Interestingly, homes with children were less likely to have high allergen burden. It is possible that cleaning frequency is higher in homes in which children reside. Indeed, the presence of smokers and less frequent cleaning have been found to contribute increased dust weight levels in homes.³²

As expected, the presence of pets, cockroaches, and rodents in the home predicted high allergen burden. The presence of pets was the strongest predictor of allergen burden; pets in the home, particularly cats and dogs, increased the odds of having high allergen burden by 3-fold. Other recent studies have also shown that signs of roach and rodent activities in the home tend to predict increased levels of cockroach and mouse allergens.^{33,34} The reported presence of roaches and rodents contributed significantly to increased cockroach and mouse allergen levels, whereas the presence of household pests tended to be inversely associated with increased levels of cat, dog, and dust mite (Der f 1) allergens,

which is consistent with previous findings.^{9,10} Mold- and moisture-related problems were not only associated with increased fungal (*A alternata*) levels but also with increased levels of several other allergens, including dust mite (Der p 1), cockroach, cat, and mouse allergens, in agreement with published work.³⁵

Although regional factors can influence allergen-specific levels significantly,⁸ census region and level of urbanization (metropolitan statistical area) did not remain significant predictors of high allergen burden in US homes. The relative importance of different allergens can vary regionally. For example, *A alternata*, cat, and dust mite levels differed significantly by census region, and concentrations of *A alternata* and cockroach allergen were strongly associated with the level of urbanization.^{15-17,19} Nevertheless, geographic and climatic factors seemed to play a less significant role in overall exposure burden. Racial and socioeconomic factors are strongly associated with the exposure burden and types of allergens that are present in increased levels. However, high exposure burden to multiple allergens is not limited to populations that have been found to be at disproportionately high risk for adverse asthma outcomes (eg, children in inner-city neighborhoods of low socioeconomic status and high minority representation).³⁶

Our analyses showed that allergens tend to cluster together in high levels. We found the strongest positive associations between the following allergens: mouse and cockroach, *A alternata* and dust mite (Der p 1), *A alternata* and mouse, and cat and dog. On the contrary, increased concentrations of cockroach allergen were inversely associated with increased levels of cat, dog, and dust mite (Der f 1) allergens. It is likely that both sociodemographic and environmental factors contribute to the observed patterns.

We found that endotoxin levels increased with increasing allergen burden. Our results suggest that residents who have high exposure burden to allergens are also apt to be exposed to increased levels of endotoxin in their home environment. Increased endotoxin levels were particularly associated with increased *A alternata*, cockroach, and mouse allergen levels. Thorne et al¹³ have previously shown that household endotoxin exposure is associated with asthma-related outcomes in this population.

Many studies have shown that exposure to allergens contributes to exacerbation of allergic asthma and persistence of symptoms.^{4,6,37} Our results reinforce the important role of indoor allergen exposures in asthma exacerbations. Among atopic individuals, high allergen burden in the home was significantly associated with current asthma. Atopy per se, however, was not associated with high allergen burden. We did not have detailed information on subjects' asthma severity, but high allergen burden was associated with asthma symptoms among atopic subjects, irrespective of medication use. Although allergen exposure and sensitization have been predominantly linked to asthma morbidity among children, it has been shown that this relationship also persists in older populations.^{38,39} We did not find strong evidence that the observed effect differed significantly by age, although the point estimate was higher among children than adults (data not shown). The association between asthma symptoms and high burden of allergens remained consistent after adjusting for potential confounders, including exposure to endotoxin.

Temporal relationships can be difficult to determine in cross-sectional studies. To reduce bias caused by temporal changes over time, we focused primarily on asthma symptoms in the past year. We were not able to ascertain allergen-specific sensitization among the participants but assessed atopy based on self-reported

TABLE III. ORs (95% CIs) for bivariate associations between increased levels of allergens and endotoxin*†

	<i>A alternata</i>	Bla g 1	Can f 1	Der f 1	Der p 1	Fel d 1	MUP	Endotoxin
	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)
<i>A alternata</i>	NA	1.40 (0.78-2.51)	1.63 (1.07-2.50)	1.79 (1.17-2.72)	2.87 (1.72-4.79)	1.79 (1.25-2.56)	2.54 (1.57-4.10)	2.21 (1.56-3.14)
Bla g 1		NA	0.56 (0.32-0.97)	0.47 (0.27-0.83)	1.73 (1.03-2.91)	0.42 (0.25-0.71)	3.00 (1.85-4.87)	2.44 (1.49-3.98)
Can f 1			NA	0.75 (0.56-1.01)	1.26 (0.85-1.87)	2.01 (1.39-2.90)	0.95 (0.70-1.27)	1.24 (0.80-1.91)
Der f 1				NA	1.81 (1.18-2.77)	0.93 (0.71-1.21)	0.99 (0.65-1.52)	1.00 (0.79-1.27)
Der p 1					NA	1.53 (1.10-2.13)	1.38 (0.93-2.05)	1.43 (0.88-2.33)
Fel d 1						NA	1.09 (0.75-1.57)	1.26 (0.92-1.72)
MUP							NA	1.65 (1.17-2.32)
Endotoxin								NA

NA, Not applicable.

*The unadjusted ORs are calculated by using dichotomous allergen/endotoxin levels (increased level: yes vs no). Cutoff points for increased allergen levels were as follows: 10 µg/g for Der f 1, Der p 1, and Can f 1; 8 µg/g for Fel d 1; 8 U/g for Bla g 1; 1.6 µg/g for MUP; and 7 µg/g for *A alternata*. For endotoxin, the cutoff value was 107 EU/mg (75th percentile of the average endotoxin concentration in the household).

†Statistically significant associations ($P < .05$) are shown in boldface.

TABLE IV. Current asthma in relation to high allergen burden (≥ 4 allergens exceeding increased levels in the home) stratified by atopic status

Logistic models	Current asthma, OR (95% CI)	P value for interaction
Unadjusted model		
All subjects	1.57 (0.99-2.50)	
Diagnosed allergies*		.03
No	0.65 (0.25-1.69)	
Yes	2.18 (1.28-3.69)	
Adjusted model†		
All subjects	1.39 (0.91-2.14)	
Diagnosed allergies*		.07
No	0.62 (0.24-1.60)	
Yes	1.81 (1.04-3.15)	

*Atopy assessed by reported doctor-diagnosed allergies.

†Adjusted for age, sex, race, education, smoking, season, and endotoxin levels (current asthma/no current asthma [n/N] = 165/1788).

physician-diagnosed allergies. We used the reservoir concentration as a surrogate measure of recent exposure, which might not necessarily reflect personal exposure levels. For example, activity levels of subjects, occupant density, air-exchange rates, and air movement within the indoor environment can affect individual exposure levels. Although airborne concentrations are considered more relevant measures of exposure, single-time-point air sampling for aeroallergens and endotoxin is usually a weak exposure measure because of large within-subject variance caused by temporal, spatial, and activity-related effects. In general, using allergen concentrations in dust as a proxy of exposure is an accepted and widely used method to assess indoor allergen exposures, particularly in large-scale epidemiologic studies. To characterize the exposures in detail, we assessed exposure levels across multiple sampling locations. Although we were not able to assess seasonal variability in allergen levels in individual homes, sampling in the survey was conducted throughout the summer, fall, and winter months in each geographic region to capture seasonal variation in the data. We acknowledge that the literature-derived cutoff points used to assess the allergen burden are somewhat arbitrary and need to be interpreted with caution. The thresholds can be influenced by host factors and are not well established for all allergens. For example, clinically relevant exposure levels for *A alternata* remain unknown because

immunoassays to assess fungal exposures (antigens and allergens) have not yet attained the same reliability as similar assays for other allergens. The possibility of fungal cross-reactivity cannot be excluded in the current study, but exposure to *A alternata* was estimated with the best available assay that minimizes cross-reactivity between genera.²⁰ Despite the limitations, this study provides valuable information about allergen burden and variability across the US housing stock.

One of the greatest strengths of this study is that the weighted characteristics of the survey sample, including distributions of housing characteristics and socioeconomic and demographic factors, were very similar to characteristics obtained from other national surveys.¹⁴ Moreover, the prevalence of asthma in this population was comparable with other national prevalence estimates.^{2,40}

This study demonstrated that exposure to multiple indoor allergens in US homes is common. Residential allergen burden and the variability of allergens that are present in increased levels were strongly affected by sociodemographic factors and the presence of apparent sources of allergens in the home. Allergen burden was also strongly associated with endotoxin levels in the home. Current asthma was positively associated with high allergen burden among atopic individuals, suggesting that atopic asthmatic subjects might achieve better asthma control by reducing allergen burden at home. Our results highlight the importance of exposure reduction as a fundamental part of asthma management.

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Clinical implications: In allergic asthma, indoor allergen exposures play an important role in asthma exacerbations.

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TABLE E1. Prevalences of increased allergen levels in homes with high exposure burden to multiple allergens*

Allergen exceeding high levels	Percentage (SE)
<i>A alternata</i>	95.0 (1.6)
Bla g 1	24.7 (4.0)
Can f 1	76.2 (4.7)
Der f 1	57.5 (5.3)
Der p 1	48.0 (5.0)
Der f 1 or Der p 1	86.6 (2.7)
Fel d 1	77.9 (4.2)
MUP	76.4 (3.8)

*Four or more allergens exceeding increased levels in the household. Cutoff points for high allergen levels were as follows: 10 $\mu\text{g/g}$ for Der f 1, Der p 1, and Can f 1; 8 $\mu\text{g/g}$ for Fel d 1; 8 U/g for Bla g 1; 1.6 $\mu\text{g/g}$ for MUP; and 7 $\mu\text{g/g}$ for *A alternata*.

TABLE E2. Increased allergen levels in US homes: Allergen-specific prevalences by predictors of high allergen burden*

Predictor variable	Percentage (SE) of households with high allergen levels							
	<i>A alternata</i>	Bla g 1	Can f 1	Der f or Der p	Der f 1	Der p 1	Fel d 1	MUP
Race								
White	60.15 (2.48)†	7.15 (1.21)†	47.78 (2.24)†	49.14 (2.33)†	37.73 (2.92)†	22.80 (1.69)	47.98 (1.86)†	31.19 (2.58)†
Other	42.27 (3.16)	22.29 (3.05)	20.28 (3.91)	39.98 (3.72)	26.53 (3.62)	19.55 (2.05)	25.53 (3.38)	47.90 (3.08)
Income								
\$0-\$19,999	60.08 (3.77)	21.49 (2.80)†	29.91 (4.20)†	51.27 (3.95)	36.57 (4.33)	27.94 (3.26)†	35.96 (4.02)	44.24 (4.33)†
\$20,000-\$39,999	58.48 (3.41)	13.82 (2.04)	37.86 (3.29)	52.75 (3.64)	36.34 (5.21)	27.08 (3.22)	42.94 (4.51)	39.37 (3.59)
\$40,000-\$59,999	54.93 (5.12)	1.55 (0.56)	53.14 (5.88)	42.05 (5.38)	30.77 (5.36)	20.20 (3.14)	47.81 (4.36)	26.76 (4.79)
≥\$60,000+	51.23 (4.73)	2.51 (1.06)	46.54 (3.96)	42.48 (4.52)	35.29 (4.12)	14.52 (2.86)	47.61 (4.09)	26.73 (3.51)
Housing type								
Single-family home	60.01 (2.37)†	8.54 (1.12)†	45.51 (2.24)†	48.94 (2.24)†	36.49 (2.75)	23.21 (1.57)†	44.41 (1.89)	34.27 (2.45)
Multifamily home	34.00 (5.50)	21.01 (4.26)	21.07 (4.25)	36.74 (4.88)	28.86 (4.75)	15.35 (3.84)	37.03 (6.55)	36.70 (5.06)
Child resident(s)								
No	58.62 (2.69)	9.46 (1.48)	41.93 (3.13)	51.41 (2.61)†	40.56 (3.35)†	22.75 (1.73)	42.89 (2.24)	34.68 (2.89)
Yes	52.81 (2.93)	11.54 (1.59)	42.43 (2.61)	40.83 (3.07)	27.37 (3.15)	21.35 (2.24)	44.28 (2.60)	34.76 (3.03)
Smoker(s) in the home								
No	53.39 (3.33)	7.07 (1.13)†	37.97 (2.71)†	47.54 (2.74)	38.09 (2.91)†	20.96 (2.20)	42.63 (2.46)	30.97 (2.53)
Yes	59.96 (3.37)	14.21 (2.03)	47.87 (3.29)	46.34 (3.08)	31.50 (3.21)	23.02 (2.59)	43.94 (2.93)	38.76 (3.81)
Mold/moisture problems‡								
No	48.37 (3.13)†	7.05 (1.37)†	44.58 (2.63)	43.01 (3.18)	34.58 (2.94)	17.93 (2.67)†	37.98 (2.42)†	29.95 (3.13)†
Yes	64.52 (3.04)	13.38 (1.67)	39.81 (2.66)	51.50 (2.92)	36.31 (3.47)	26.30 (2.04)	48.77 (2.98)	39.19 (3.35)
Pets								
No	53.06 (3.10)	12.15 (1.54)	16.17 (2.14)†	48.70 (3.27)	38.98 (3.69)	21.31 (2.21)	24.50 (2.00)†	37.57 (2.48)
Yes	60.09 (3.26)	8.25 (1.47)	68.60 (2.47)	45.65 (2.52)	31.59 (2.74)	23.20 (2.12)	62.15 (2.99)	32.09 (3.07)
Cockroaches‡								
No	54.85 (2.73)	4.12 (0.85)†	44.23 (2.51)†	48.39 (2.69)	38.40 (3.00)†	20.49 (1.74)†	45.02 (1.86)†	30.91 (2.32)†
Yes	64.25 (3.88)	38.99 (5.08)	32.52 (3.89)	42.03 (3.96)	21.60 (3.88)	29.88 (3.84)	35.82 (3.92)	52.02 (5.12)
Rodents‡								
No	54.19 (2.50)†	8.64 (1.11)†	43.71 (2.52)†	47.20 (2.56)	36.91 (2.71)†	21.03 (1.84)	42.67 (1.72)	30.26 (2.67)†
Yes	68.98 (4.97)	18.93 (3.48)	33.83 (3.85)	47.69 (4.17)	27.51 (3.77)	28.18 (4.60)	47.41 (4.46)	58.18 (4.83)

*Four or more allergens exceeding increased levels in the household. Cutoff points for increased allergen levels were as follows: 10 µg/g for Der f 1, Der p 1, and Can f 1; 8 µg/g for Fel d 1; 8 U/g for Bla g 1; 1.6 µg/g for MUP; and 7 µg/g for *A alternata*.

†*P* < .05 for difference.

‡Assessed by observation (occupants and field team).