

Bedroom exposure to airborne allergens in the Chicago area using a patient-operated sampling device



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ABSTRACT

Background: In current practice, allergens in vacuum-collected dust are used as surrogates for inhalable allergens. We developed an air-sampling device that can be used by patients for direct measurement of airborne allergen concentrations in their own homes.

Objective: To demonstrate the use of this device to establish allergen concentration reference ranges in a target population and to evaluate associations between patient-reported information and measured allergen concentrations.

Methods: Patients from 5 allergist's practices in the Chicagoland region were provided with instructions, questionnaires, informed consent forms, and samplers to run for 5 days in their bedrooms. Samples were collected from cartridges and assayed by multiplex immunoassays for 12 common household allergens and enzyme-linked immunosorbent assay for ragweed.

Results: Unique allergen profiles were obtained for 102 patient homes. Samples with allergen concentrations above the limit of detection were as follows: total dust mite, 28%; cat, 61%; dog, 64%; mouse, 12%; rat, 0%; cockroach, 4%; *Alternaria*, 6%; *Aspergillus*, 21%; birch pollen 1%; grass, 8%; and ragweed, 5%. Of those, 75 completed questionnaires, providing meta-data for further analysis. Pet allergens correlated significantly with number of pets owned. Humidity correlated with dust mite allergens, open windows with *Alternaria* and mouse allergens, and high-efficiency particulate air filter use with reduced levels of several allergens. Many other variables showed no significant correlations.

Conclusion: The combination of ease of use, high air-sampling rate, and sensitive immunoassays permitted the measurement of airborne allergen concentrations in homes and establishment of reference ranges. Patient-reported information permitted identification of factors that could relate to allergen concentrations and suggested remedial measures.

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Introduction

Indoor allergen exposure is an important risk factor for allergic respiratory disease.¹ A recent European Academy of Allergy and Clinical Immunology position paper² states that allergen exposure assessment should ideally be based on measurement of airborne concentration because this is a truer reflection of airway exposure. Because clinically relevant thresholds have not been established for all allergens tested, in a recent comprehensive US survey, part of the

National Health and Nutrition Examination Survey (NHANES) 2005–2006 program, Salo et al³ used percentile cutoffs as a consistent analytic approach. The same group also defined morbidity threshold levels in dust for some allergens.⁴ They also state that exposure could be assessed more accurately with personal monitors. Sampling of the airborne compartment is a closer approximation to personal exposure. We have compared the performance of the Inspirotec airborne allergen sampling device with reference sampling methods, including settled dust.⁵ Settled dust collection has been the standard for many years² because air sampling methods have been technically demanding and intrusive. The Inspirotec sampler now provides an air sampling method that is unobtrusive and requires no technical skill to operate.⁶

A smaller-scale study with the Inspirotec sampler, run by patients themselves,⁶ demonstrated correlation of cat or dog presence in the

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home with the corresponding allergen in the bedroom. Bedrooms are considered an important site for allergen exposure because of the time spent in bed and the proximity of allergen reservoirs.³ The work that will be described here was with a larger number of homes than the earlier study,⁶ a broader menu of common household allergens, and evaluation of the importance of a variety of socioeconomic, demographic, and environmental factors. Furthermore, the data collected are used to establish percentile ranges³ for this population for the airborne compartment as a reference frame for evaluating exposure in individual patient homes.

Methods

Patient Selection and Sample Collection

Collaborating physicians were independent, academically affiliated general clinical allergists who treated children and adults. Patients from these practices were selected on a volunteer basis with no other selection criteria. The physicians provided patients with verbal instructions and a package that consisted of a plastic-bagged sampler, instruction sheets, Health Insurance Portability and Accountability Act of 1996 release forms, a digital temperature-humidity meter (LaCrosse Instruments, LaCrosse, WI), and a label to indicate start and stop time and date, height above floor, distance from bed, and start and stop temperature and humidity. Average conditions are reported in [eTable 1](#). There was no special control of the timing of collection of the samples. The timing was determined by time to distribute samplers to the patients and the patients' convenience. In practice, samples were collected from September 2015 through February 2016. Patients were instructed to plug in the sampler for 5 days in the bedroom. A questionnaire was provided ([eTable 2](#)) to be completed as a hard copy or an online version. The project was approved by the Quantum Review Institutional Review Board.

Patient Population Characteristics

The responses to the questionnaire that relate directly to characteristics of homes and residents are summarized in [eTable 3](#). The population was dispersed through zip codes and across medical practices. The only overlaps were where practice 2 and practice 3 had a patient each in zip code 60601 and practice 4 and practice 3 had a patient in zip code 60614. The distribution in sites in the greater Chicago area is shown in a map in [eFigure 1](#). Number of homes with pets ranged from 37 homes with neither cats nor dogs to 20 homes with both cats and dogs.

Sampling Methods

Airborne samples were calculated as the amount of air based on run times and flow rates. Capture efficiency of the Inspirotec sampler has been measured with established methods^{7,8} using a model system of fluorescent latex microparticles and a reference filter of 0.45-mm polycarbonate by Alburtylab Inc (Drexel, Missouri). Efficiency was 23%. Stainless steel electrode strips were released from the cartridges and transferred to 15-mL centrifuge tubes. One milliliter of 1 × phosphate-buffered saline, with 0.02% Tween 20, was added to the tubes and vortexed intermittently for 10 minutes. Samples were removed from tubes and centrifuged at 15,000g for 30 minutes. The supernatants were removed and subject to immunoassays for the specified allergens.

Assay Methods

Samples were assayed for 12 common household allergens with kits (MARIA, Indoor Biotechnologies, Charlottesville, Virginia) composed of 3 dust mite antigens (Der p 1, Der f 1, mite group 2), cat (Fel d 1), dog (Can f 1), mouse (Mus m 1), rat (Rat n 1), cockroach (Bla g 2), molds (Alt a 1, Asp f 1), and pollens (Bet v 1, Phl p 5) and by enzyme-linked

immunosorbent assay (ELISA) for ragweed (Am b 1, Indoor Biotechnologies). The allergen samples were analyzed with the Bioplex 200 (Bio-Rad Laboratories, Hercules, California) at the University of Illinois, Chicago, Flow Cytometry Facility. ELISA plates were analyzed with a Biotek Synergy HTX plate reader kindly made available by Shahila Mehboob Christie of Novalex Therapeutics (Chicago, Illinois). Analytical lower limits of detection (LLODs) for the assays were determined according to the package inserts. Concentrations in the air were calculated as the amount of air based on concentrations determined for original extracts, sampler flow rates, and flow times. Field LLODs were calculated from analytical LLODs, mean flow rate, and mean time.

Statistical Analysis

Statistical analysis was performed with JMP Pro 13.0.0 statistical software (SAS Institute Inc, Cary, North Carolina). For the purpose of the analysis, values below the LLOD were assigned a value of LLOD/2. For statistical purposes, where indicated, total mite is defined as the sum of the values for Der p 1, Der f 1, and mite group 2. Log₁₀ transformation of allergen concentrations in the air were used for all statistical analyses to prevent bias from a few samples with high values. $P < .05$ was considered to be statistically significant.

Results

Allergen Profiles

The results of all the allergen assays are shown in [Table 1](#). The data are sorted by physician practice and date on which the sampling was started. For some samples, the device had been run, but the label data were incomplete (no date given in [Table 1](#)). We assumed for those samples that the run had been for exactly 5 days in the calculation of the amount of air. Each home had a unique profile. As found in the work of Salo et al,³ for dust samples, we found that most homes are positive for at least one allergen and many have multiple allergens in the airborne samples. Most homes have at least some cat allergen and some dog allergen ([Fig 1A](#)). A measure of allergen burden is the number of different allergens that are significantly above the LLOD.³ The results of such an analysis shown in [Figure 1B](#) approximate to a Poisson distribution with mode of 30% of the population having 2 allergens above the LLOD.

By inspection of [Table 1](#), it is apparent that dust mite allergens were found more frequently in homes of practice 2 than in the others. This finding is verified by a *t* test pairwise comparison analysis. A statistically significant difference was found for total dust mite allergen between practice 2 and practice 4 ($P = .045$). Similarly, Mus m 1 was found more frequently in practice 5. Pairwise comparison between practice 5 and practice 2 was significant by *t* test for Mus m 1 ($P = .01$). Samples in practice 5 differ from others in that they were mostly from a lower income area in Indiana ([eFig 1](#)). Others were not significantly different or there were too few positive samples to allow for any conclusion.

No statistically significant correlation was found between patient-reported allergies and symptoms with concentration of any one allergen (data not shown). This finding could be accounted for by the subjective nature of the reported symptoms and the fact that this was a patient population receiving medical care.

Pet Allergens

Patients reported on the number of pets and efforts taken to reduce exposure to pet allergens. [Figure 2](#) shows the association between the number of pets owned and pet allergens in the air in bedrooms. There was a significant correlation between number of cats or dogs owned and the corresponding airborne allergen ([Fig 2B](#)

Table 1
Allergen Profiles in Homes^a

Physician practice	Patient No.	Date started	Allergen concentration, pg/m ³												Amb a 1, IU/10 ⁶ L
			Der p 1	Der f 1	MG-2	Fel d 1	Can f 1	Mus m 1	Rat n 1	Bla g 2	Alt a 1	Bet v 1	Asp f 1	Phl p 5	
2	152	9/24/2015					17.35^b								ND
2	108	9/30/2015	<i>0.11^c</i>		0.32^b	<i>0.04^c</i>	<i>0.09^c</i>								
2	94	10/2/2015				36.7^b								<i>0.6^d</i>	
2	95	10/2/2015		<i>0.21^d</i>	<i>0.13^e</i>	44.12^b	<i>0.16^c</i>				<i>0.02^c</i>			<i>0.64^d</i>	
2	154	10/4/2015				<i>1.71^e</i>	49.17						<i>0.16^c</i>	<i>0.54^c</i>	ND
2	96	10/5/2015				8.31^b	<i>0.17^c</i>								
2	97	10/5/2015		<i>0.35^d</i>		28.39^b									
2	102	10/6/2015		1.36^b			<i>3.49^e</i>						8.93^b		<i>0.0018^c</i>
2	100	10/7/2015	<i>0.2^e</i>	1.87^b	0.6	<i>0.2^d</i>	36.32^b				0.11^b			2.21^b	
2	101	10/7/2015					<i>0.39^d</i>				<i>0.05^d</i>		7.4^b	0.75^b	
2	104	10/11/2015													
2	103	10/16/2015				<i>0.19^d</i>	<i>0.11^c</i>								
-2	41	10/20/2015		0.86^b	0.47^b		<i>0.12^c</i>								
2	33	10/21/2015					<i>0.12^c</i>								
2	106	10/21/2015			<i>0.13^e</i>	18.39^b	<i>4.09^e</i>								ND
2	35	10/23/2015	<i>0.18^d</i>												
2	38	10/26/2015													
2	105	10/26/2015			<i>0.02^c</i>										
2	36	10/27/2015		<i>0.34^d</i>		<i>1.27^e</i>	<i>0.33^d</i>								
2	43	10/29/2015		<i>0.28^d</i>	<i>0.06^d</i>	<i>0.16^d</i>	<i>7.27^e</i>								
2	34	11/5/2015													
2	39	11/5/2015				<i>0.13^d</i>	<i>0.18^c</i>								
2	40	11/13/2015		<i>0.18^d</i>	<i>0.03^c</i>	<i>0.1^c</i>	<i>0.11^c</i>								
2	138	2/10/2016													ND
2	139	2/11/2016													ND
2	107				<i>0.11^d</i>	28.16^b	<i>0.2^c</i>								
2	155					<i>0.07^c</i>	<i>2^e</i>								ND
2	156					16.12^b	<i>6.08^e</i>			<i>0.22^c</i>			<i>0.18^d</i>		ND
4	183	9/23/2015			<i>0.17^e</i>		<i>0.27^d</i>						5.53^b		
4	160	9/24/2015				<i>0.24^d</i>	<i>0.38^d</i>								
4	170	9/24/2015					<i>0.17^c</i>						<i>1.51^e</i>		
4	141	9/29/2015	<i>0.09^c</i>		<i>0.04^c</i>	<i>0.55^e</i>	40.91^b			<i>0.57^d</i>			<i>0.31^d</i>		
4	143	9/29/2015											<i>0.35^e</i>		
4	165	10/4/2015				<i>0.2^d</i>							<i>0.05^c</i>		
4	144	10/6/2015				<i>0.72^e</i>									
4	140	10/16/2015													
4	147	10/22/2015				9.74^b	<i>0.11^c</i>						10.4^b		
4	149	10/22/2015		<i>0.49^e</i>	<i>0.29^e</i>	<i>0.26^e</i>		<i>0.05^e</i>							
4	179	10/22/2015					<i>4.09^e</i>								
4	146	10/24/2015			<i>0.12^e</i>	<i>0.05^c</i>									
4	177	10/26/2015													
4	176	10/27/2015					<i>0.27^d</i>								
4	182	10/27/2015				10.01^b	<i>2.85^e</i>								0.0041^b
4	180	10/31/2015				<i>0.52^e</i>	15.34^b								
4	148	11/3/2015					<i>0.08^c</i>								
4	174	11/5/2015				<i>0.4^e</i>	41.4^b								
4	175	11/12/2015				<i>0.41^e</i>	<i>0.61^d</i>								
4	172	11/13/2015						<i>0.03^d</i>						<i>0.72^c</i>	
4	151	12/9/2015				<i>0.39^e</i>									
4	142	12/19/2015				<i>0.6^c</i>									
4	137	2/3/2016					<i>0.89^e</i>								ND
5	203	9/28/2015				<i>1.16^e</i>	<i>0.08^c</i>	<i>0.01^c</i>							
5	204	10/1/2015											<i>1.12^e</i>		
5	187	10/4/2015				<i>0.18^d</i>	<i>0.52^d</i>								
5	190	10/12/2015	1.7^b			209.6^b	<i>1.37^e</i>	0.14^b		25.08^b	<i>0.06^c</i>				
5	185	10/16/2015				<i>0.1^c</i>	23.1^b								<i>0.0022^d</i>
5	194	10/16/2015				37.22	<i>0.13^c</i>	<i>0.01^c</i>					<i>0.06^c</i>		
5	199	10/16/2015				<i>0.48^e</i>	12.67^b								
5	202	10/17/2015					<i>0.16^c</i>								
5	188	10/18/2015				<i>0.11^d</i>									
5	193	10/19/2015					35.82^b			<i>1.27^e</i>			<i>0.33^e</i>		
5	195	10/19/2015				<i>0.06^c</i>	17.53^b	<i>0.01^c</i>					<i>0.31^d</i>		
5	198	10/19/2015				<i>0.16^d</i>	51.33^b								
5	196	10/20/2015				<i>0.1^c</i>	<i>6.4^e</i>	0.09^b							
5	192	10/22/2015				<i>0.05^c</i>	<i>0.14^c</i>								
5	201	10/25/2015											<i>0.11^c</i>	<i>0.66^c</i>	
5	186	10/31/2015	<i>0.13^d</i>		0.59^b	201.2^b	34.09^b						<i>0.13^c</i>		
5	189		<i>0.49^e</i>					<i>0.05^e</i>							
3	114	10/3/2015					51.8^b						<i>2.46^e</i>		<i>0.0022^d</i>
3	121	10/3/2015			<i>0.06^d</i>			<i>0.03^d</i>					<i>2.7^e</i>		
3	111	10/4/2015					<i>0.47^d</i>								
3	133	10/4/2015													

(continued)

Table 1 (Continued)

Physician practice	Patient No.	Date started	Allergen concentration, pg/m ³												
			Der p 1	Der f 1	MG-2	Fel d 1	Can f 1	Mus m 1	Rat n 1	Bla g 2	Alt a 1	Bet v 1	Asp f 1	Phl p 5	Amb a 1, IU/10 ⁶ L
3	124	10/22/2015				0.13 ^d	0.89 ^e								
3	117	10/26/2015				0.18 ^d	0.14 ^c								
3	120	10/26/2015													
3	115	10/27/2015		1.63^b	0.28 ^e	0.05 ^c	4.72 ^e								
3	119	10/27/2015													
3	116	10/28/2015													
3	126	10/30/2015				168.4^b									
3	112	11/2/2015													
3	123	11/9/2015				0.38 ^e	0.23 ^d								
3	125	11/23/2015	3.09^b	0.51 ^e	1.5^b	2.18 ^e	1.56 ^e	0.08^b							
3	129	12/9/2015				0.06 ^c	0.83 ^d								ND
3	132	12/14/2015				19.35^b									ND
3	131	12/17/2015				0.06 ^c									ND
3	127	12/23/2015				0.03 ^c	10.82 ^e								ND
3	109					0.19 ^d	39.91^b								
3	110					0.16 ^d	45.94^b								
3	122					0.04 ^c							0.24 ^d		
1	93	9/25/2015				0.22 ^d	159.7^b								ND
1	76	10/1/2015													
1	77	10/3/2015					6.07 ^e								
1	78	10/3/2015		0.39 ^d	0.04 ^c										
1	79	10/6/2015			0.08 ^d		43.88^b				0.05 ^e			0.59 ^c	
1	80	10/6/2015		0.42 ^d	0.04 ^c	4.05 ^e	0.62 ^d						0.16 ^d		
1	83	10/6/2015				8.2^b	0.44 ^d								
1	85	10/7/2015				0.06 ^c	1.23						9.98^b		
1	89	10/18/2015				69.67^b					0.04 ^d				
1	84	10/20/2015													
1	86	10/20/2015		0.16 ^d	0.08 ^d	0.21 ^d	0.54 ^d	0.03 ^d				0.54 ^c			ND
1	92	10/22/2015				0.44 ^e	2.05 ^e	0.05 ^e							
1	91	10/31/2015		0.45 ^c	0.12 ^e	0.09 ^c	0.43 ^d								ND
LLOD ^f			0.08	0.08	0.03	0.03	0.08	0.01	0.03	0.07	0.03	0.31	0.03	0.49	0.0014

Abbreviation: LLOD, lower limit of detection.

^aData are the concentrations of allergens in the air as measured per the description in the "Materials and Methods" section, except for Amb a 1 (ragweed pollen), which is expressed in IU/10⁶ L of air and was analyzed with enzyme-linked immunosorbent assay. Results are arranged in groups by physician practice and by date when sampling was started. Missing dates are from samplers where patient ran sampler but failed to complete the required data on the label. For the purposes of this calculation, it was assumed the sampler was run for exactly 5 days. Empty cells are values <LLOD. Indicated by ND where the Amb a 1 was not performed because it was out of season.

^bLLOD greater than 75, in bold.

^cLLOD less than 25, in italic.

^dLLOD greater than 25 and less than 50.

^eLLOD greater than 50 and less than 75.

^fThe actual mean LLOD for all runs.

and C). There was no significant correlation between number of dogs owned and cat allergen ($P = .63$) (Fig 2A). In contrast, a borderline significant negative correlation was between number of dogs owned and level of cat allergen ($P = .02$) (Fig 2D), despite the fact that 66% of the dog owners also owned at least one cat. Possible explanations are an unknown influence of the presence of dogs on the dispersal of cat allergen or the owners of larger numbers of dogs are less likely to also own any cats. In contrast, there was only a borderline significant effect of patient-reported efforts at dog exclusion from the bedroom on Can f 1 and an insignificant effect for cat exclusion on Fel d 1 (eTable 4). These results may be attributable to a combination of the inaccuracy of the patient-reported information or failure to keep the bedroom door closed even if the pet is excluded.

Other Variables

In addition to pet ownership, other patient-reported information included temperature, humidity, distance of sampler from bed, height above floor, and family size and income (eTables 1 and 2). The likelihood of any of these having an effect on airborne allergen distribution is small, but we wish to establish that these will not be confounding factors in our overall assessment, except when there might have been active intervention. The results of the bivariate analysis for this group are summarized in Table 2. The allergens Bla g 2, Rat n 1, Bet v 1, and Amb a 1 showed too few occurrences above the LLOD to draw

any conclusions and so are not included in the table. Of the remainder, none of these variables except relative humidity showed significant correlation. Noteworthy is the significant lack of correlation between allergens and positioning of the sampler (height from the floor and distance from the bed). Total dust mite allergens showed a significant correlation with humidity. Humidity is known to be required for the growth of dust mites. Can f 1 and Asp f 1 showed a borderline significant correlation with humidity. *Aspergillus* may be more likely to be actively growing in higher humidity.

Patient estimates of the fraction of the time windows were open may not be as precise as other patient-reported information because of its subjectivity. The results might also be influenced by the width of the window opening and the number of open windows in the room, as well as air movements arising from wind speed outside. Nevertheless, significant correlations were found. The patients provided information concerning their window opening practices during the test and their window opening practices in general. The results appeared to be more influenced by the patient's window opening practices in general vs window opening practices during the test. Significant correlation was found between an increased frequency of window opening practices in general and dust mite, cat, mouse, *Alternaria*, and grass pollen allergens. This finding might reflect the degree to which the allergens penetrate from the outside longer term.

A number of questions that the patients completed required a yes or no answer. These categorical variables were analyzed with the t

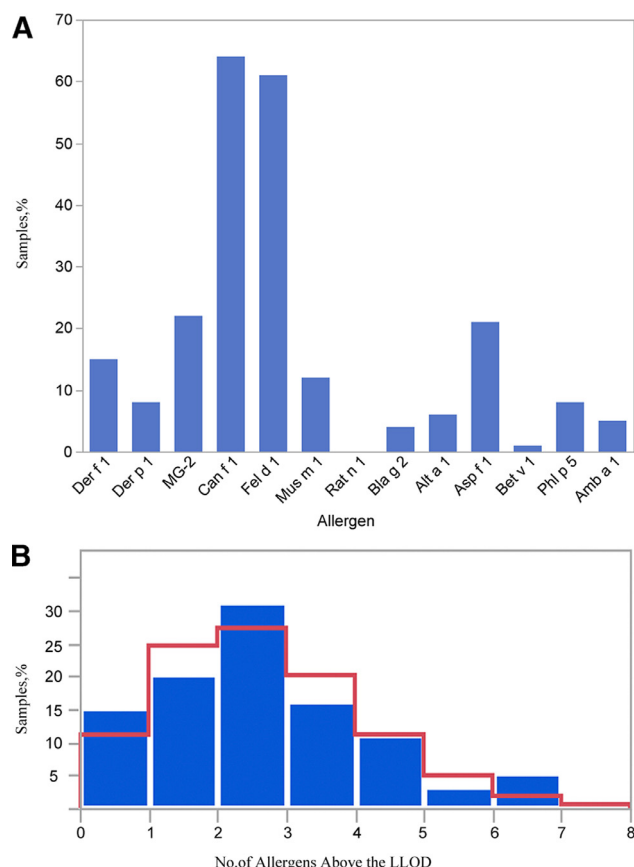


Figure 1. A, For each allergen tested, the percentage of samples having values above the lower limit of detection (LLOD) are plotted. B, A distribution plot of the percentage of samples that have the specified number of allergens above the LLOD. This is a measure of the allergen burden. Red line denotes closest-fit Poisson distribution.

test. Summary results are given in Table 3. The presence of carpets and upholstery significantly correlates with several allergens but not with total dust mite allergens. The use of dust mite covers did not significantly correlate with any airborne allergens. In addition, the use of air conditioning did not significantly correlate with any allergen concentration in the air. The use of a high-efficiency particulate air (HEPA) filter had a significant effect on all allergens except Fel d 1 and Phl p 5. The use of a fan affected total dust mite allergens and Phl p 5. The presence of trees in the neighborhood had no correlation with multiple allergens, whereas flowering plants in the neighborhood correlated with Can f 1 and Mus m 1. The reason for these last correlations is unclear. Possible explanations are higher ownership of dogs in neighborhoods where there may be flowering plants and the presence of mouse populations.

Discussion

In general, the data presented in this article indicate that the Inspirotec sampler can be run by patients in their own homes without any skilled technical support and can achieve statistically significant results. These data can then be used to augment the patient clinical picture and potentially improve patient management.

There was a significant correlation between number of pets owned and the corresponding allergen concentration averaged during 5 days in the air (Fig 2 and eTable 4). Of further interest is the fact the use of HEPA filters correlated with significant allergen reduction, although other common mitigation measures did not (Table 3). The significant lack of correlation between allergens and positioning of the sampler (height from the floor and distance from the bed) (Table 2) implies that during the 5-day period any variations that might be present because of local conditions were averaged out by general air circulation. Total dust mite allergens showed a significant correlation with humidity (Table 2), and humidity is known to be required for the growth of dust mites. Can f 1 and Asp f 1 also had a

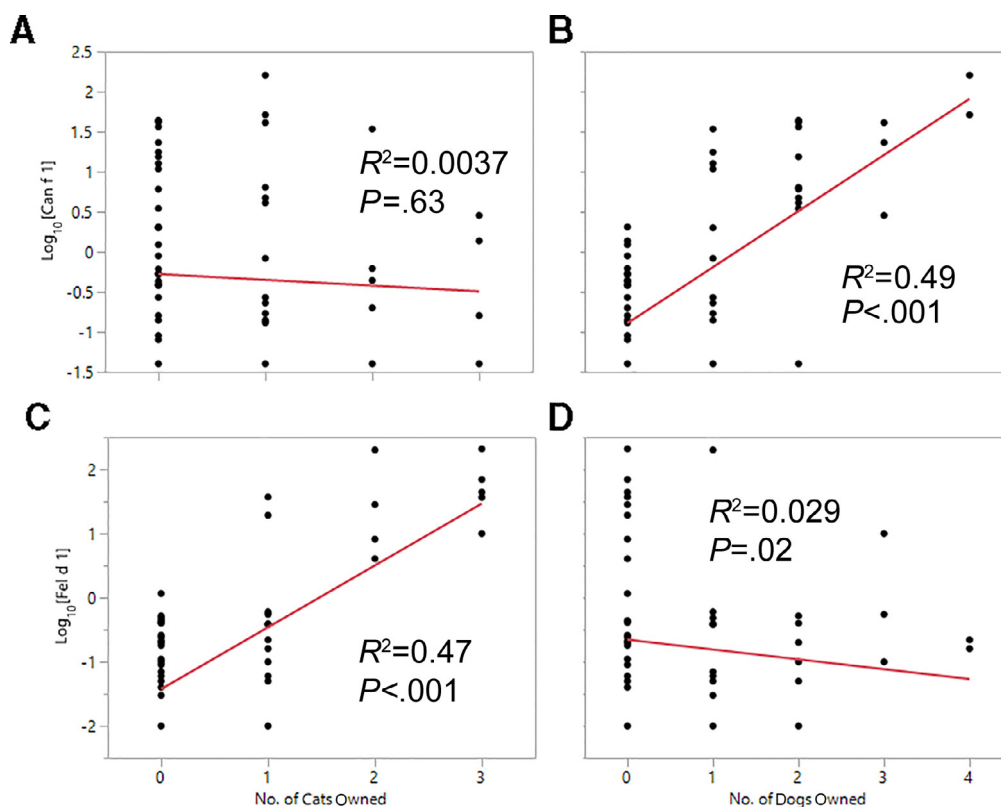


Figure 2. Bivariate analysis $\log_{10}$ of pet allergen concentration in air against the number of pets owned. A, Can f 1 and cat ownership; B, Can f 1 and dog ownership; C, Fel d 1 and cat ownership; and D, Fel d 1 and dog ownership.

Table 2

Summary of Bivariate Analysis for Allergen Levels

Variable	All mites		Fel d 1		Can f 1		Mus m 1		Alt a 1		Asp f 1		Phl p 5	
	R	P value	R	P value	R	P value	R	P value	R	P value	R	P value	R	P value
Relative humidity	0.32	.01	0.087	.47	0.26	.03	0.13	.28	0.053	.66	0.25	.03	0.16	.19
Temperature	0.04	.75	0.048	.50	0.028	.82	0.07	.56	0.019	.88	0.076	.53	0.18	.12
Distance	0.22	.13	0.065	.64	0.20	.15	0.093	.50	0.068	.62	0.17	.22	0.068	.62
Height	0.18	.12	0.038	.77	0.046	.72	0.031	.81	0.11	.41	0.036	.78	0.11	.41
Family size	0.07	.58	0.2	.13	0.057	.67	0.071	.57	0.013	.92	0.013	.92	0.057	.65
Income	0.14	.27	0	.99	0.13	.31	0.057	.67	0.013	.92	0.015	.91	0.22	.09
Open windows during test	0.13	.28	0.13	.29	0.14	.19	0.35	.004	0.37	.002	0.16	.18	0.03	.80
Open windows generally	0.34	.049	0.28	.02	0.18	.13	0.4	<.001	0.33	.007	.0093	.46	0.24	.046

NOTE. Relative humidity and temperature were from records completed by patients before and after the run, distance and height are distance from bed and height above floor, and the remainder are from a questionnaire completed by the patients (eTable 1). Pearson coefficient R and P values are from bivariate analysis (Fig 1). $P < .05$ indicates statistical significance, in bold.

borderline significant correlation with humidity. *Aspergillus* may be more likely to be actively growing in higher humidity, whereas *Alternaria* is more likely to come from the outside, and exterior humidity may vary independently of that in the house. Common human activities may cause local resuspension of particulates.^{9,10} Dust mite proof covers may affect local allergen exposure in the bed itself but not the amount that gets airborne. Furthermore, some of the questions asked can expect reasonably objective answers, whereas there may be a degree of subjectivity in the way patients report their efforts. A rigorous controlled study¹¹ found that use of mite impermeable covers indeed correlates with reduction of dust mite allergen in dust samples from beds but not from floors. Therefore, our failure to find significant correlation between airborne dust mite concentrations and patient-reported use of dust mite covers should not be taken to imply that such measures should not be undertaken. In contrast, open windows had a significant correlation with several allergens. Despite the fact that reporting of open windows may be somewhat subjective, there was nevertheless significant correlation, for example, with mouse allergen. This finding might suggest that mouse allergens may enter homes in the absence of infestation.

The data create a statistical overview, but those cases in which there was no correlation do not imply that corresponding remedial measures are fruitless. Although remedial measures may have no detectable effect on the airborne fraction of dust mite allergens in the room, it may be possible that larger allergen-bearing particles, closely associated with the bed itself, would not have been detected through air sampling efforts. However, only the inhaled smaller particles would penetrate the respiratory system deep enough to trigger asthma symptoms. The airborne fraction may affect atopic individuals through exposure outside the bed. For example, others have suggested that highest exposure to airborne dust mite allergen is not in bed¹² but in public transportation.¹³

Mouse allergen is becoming an increasingly important factor in allergen exposure in schools in low-income neighborhoods.¹⁴ The

same group observed reduction in particulate exposure when HEPA filters were used as a means of intervention¹⁵ and found a modest reduction in symptoms. This group was unable to detect a corresponding systematic change in mouse allergens. The measurements were based on settled dust samples. Another study¹⁶ found integrated pest management during 1 year failed to result in any change in mouse allergens or maximal symptoms. In contrast, we note a correlation between the use of HEPA filters in a domestic environment and lower levels of several airborne allergens, including mouse.

Although we found a high-frequency occurrence of airborne allergens in bedrooms in the Chicago area (Fig 1A), the frequencies were lower than found by Salo et al³ for dust allergens for the entire United States. In both data sets, cat and dog allergens are the most frequently found (60% in our data, >80% in their data), whereas other allergens are relatively lower frequency in ours. Differences can be accounted for by relatively higher amounts of allergens in the settled dust compared with the inhalable fraction, and our data may be skewed to a relatively wealthier subpopulation than in the national survey. Similar considerations apply to the allergen burden: Comparing our Figure 1B with the corresponding data of Salo et al³ their allergen burden has a mode of approximately 6, whereas ours has a mode of 2. This finding is consistent with the finding that dust collection detects more allergen overall than air sampling.¹⁷ Although the 2 data sets are not strictly comparable, the higher selectivity of our data will potentially help achieve a more focused approach to remedial measures.

As found in the work of Salo et al³ for dust samples, we found that most homes are positive for at least one allergen and many have multiple allergens in the airborne samples. Most homes have at least some cat allergen and some dog allergen (Fig 1A). Unlike the national population sampled by dust collection,³ no rat allergen was found in this population. In contrast, a significant number of homes were positive for airborne rat allergen with the use of the Inspirotec sampler in

Table 3Summary of t Test Results for Nonparametric Variables From the Questionnaire^a

Variable	All mites	Fel d 1	Can f 1	Mus m 1	Alt a 1	Asp f 1	Phl p 5
Carpets or rugs				+, .02	+, .02		+, .01
Upholstered furniture				-, .009		-, <.001	
Carpet, rugs, or upholstery				+, .02	+, .02		+, .01
Dust mite—proof covers							
Air conditioning							
HEPA air purifier	-, <.001		-, .002	-, .009	-, .009	-, .007	
Fan	-, .02						-, .03
Trees							
Flowering plants			+, .03	-, .03			

Abbreviation: HEPA, high-efficiency particulate air.

^aEach variable was correlated with the allergens indicated by t test 1-way analysis. Empty cells indicate insignificant correlations ($P > .05$). P values for significant correlations are given together with the sense of the association indicated by a plus or minus sign.

low-income Baltimore homes.¹⁷ In another publication on the NHANES 2005–2006 survey, Gergen et al⁴ reported on pet ownership and corresponding pet allergen exposure. These investigators define exposure by samples with values significantly above a morbidity threshold. We performed an approximate conversion of their morbidity thresholds from dust collection to equivalent airborne samples.¹⁷ The thresholds correspond approximately to the LLODs of our Can f 1 and Fel d 1 assays. For their US sample, Gergen et al⁴ reported 38% ownership of cats, 27% ownership of dogs, and 14% ownership of both. Of the population in the Chicago area described here, 87% owned cats, 89% owned dogs, and 27% owned both. The corresponding percentage of the US populations having significant exposure above the morbidity thresholds were 36% for Fel d 1, 30% for Can f 1, and 14% for both. Corresponding numbers in the Chicago population reported here (from data in Fig 1A) are 64%, 61%, and 47%. Considering the uncertainties of the conversion factors, the different geographic and economic status of the 2 populations, and the different sampling methods, the higher pet ownership in the population was nevertheless accompanied by a correspondingly higher exposure to allergens above the morbidity thresholds compared with the NHANES 2005–2006 survey.⁴ The definition of morbidity threshold defined therein corresponds approximately to low but significant levels of airborne allergen in our data.

Although part of the meta-data from the questionnaires required a subjective interpretation from patients, it was supported by some significant associations. It is current medical practice to propose exclusion of pets from the bedroom for patients with asthma. We found little or no significant correlation between reported exclusion of pets from the bedroom and airborne allergen levels in the bedroom. The strength of the airborne allergen data is attested to by the strong correlation with pet ownership and the corresponding pet allergens. The lack of correlation with the patient-reported intervention may be attributable to the unreliability of the patient-reported data, the difficulty of separating the air compartment in the bedroom from the rest of the house, or a combination of both. It is our experience that patient information on interventions may be unreliable, and the provision of objective airborne allergen data may be used to reinforce adherence.

This study provides a statistical framework as a reference point for ongoing use of the method for evaluation of home allergen profiles. In the absence of well-defined pathologic levels of airborne allergens, the data provide reference levels that can be used as a framework for patient evaluation. Previously unsuspected allergen levels may suggest remediation methods that would not otherwise have been considered, indicating that it is possible to acquire data on airborne allergens from large scale deployment that would be logistically challenging by conventional methods. We hope this study paves the way for larger-scale studies on clinical utility and possible medical cost savings of a patient-operated allergen sampling device.

Supplementary Data

Supplementary data associated with this article can be found in the online version at <https://doi.org/10.1016/j.anai.2018.05.024>.

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References

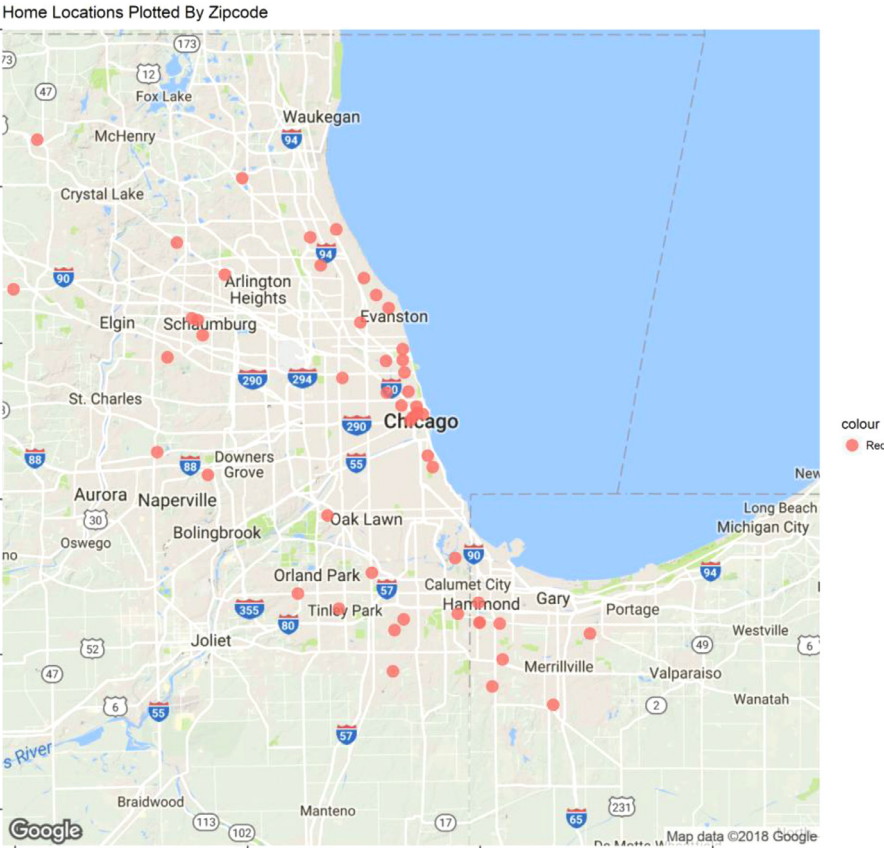
1. Custovic A. To what extent is allergen exposure a risk factor for the development of allergic disease. *Clin Exp Allergy*. 2015;45:54–62.
2. Raulf M, Buters J, Chapman M, et al. Monitoring of occupational and environmental aeroallergens: EAACI Position Paper on concerted action of the EAACI IG Occupational Allergy and Aerobiology & Air Pollution. *Allergy*. 2014;69:1280–1299.
3. Salo PM, Wilkerson J, Rose KM, et al. Bedroom allergen exposures in US households. *J Allergy Clin Immunol*. 2018;141:1870–1879. e14.
4. Gergen PJ, Mitchell HE, Calatroni A, et al. Sensitization and exposure to pets: the effect on asthma morbidity in the US population. *J Allergy Clin Immunol Pract*. 2018;6:101–107.
5. Gordon J, Reboulet R, Gandhi P, Matsui E. Validation of a novel sampling technology for airborne allergens in low-income urban homes. *Ann Allergy Asthma Immunol*. 2018;120:96–97.
6. Gordon J, Detjen P, Kelso D, Gandhi P. A new patient-operated sampling device for measurement of aeroallergens. *Ann Allergy Asthma Immunol*. 2016;116:475–476.
7. Kesavan J, Schepers D, McFarland AR. Sampling and retention efficiencies of batch-type liquid-based bioaerosol samplers. *Aerosol Sci Technol*. 2010;44:817–829.
8. Kesavan J, Bottiger JR, McFarland AR. Bioaerosol concentrator performance: comparative tests with viable and with solid and liquid nonviable particles. *J Appl Microbiol*. 2008;104:285–295.
9. Gordon J, Reboulet R, Gandhi P, Matsui H. Validation of a novel sampling technology for airborne allergens in low-income urban homes. *Ann Allergy Asthma Immunol*. 2017;120:96–97.
10. Boor BE, Spilak MP, Corsi RL, Novoselac A. Characterizing particle resuspension from mattresses: chamber study. *Indoor Air*. 2015;25:441–456.
11. Wu T, Tæbel M, Holopainen R, et al. Infant and adult inhalation exposure to resuspended biological particulate matter. *Environ Sci Technol*. 2018;52:237–247.
12. Murray CS, Foden P, Sumner H, Shepley E, Custovic A, Simpson A. Preventing severe asthma exacerbations in children. *Am J Respir Crit Care Med*. 2017;196:150–158.
13. Tovey ER, Liu-Brennan D, Garden FL, Oliver BG, Perzanowski MS, Marks GB. Time-based measurement of personal mite allergen bioaerosol exposure over 24 hour periods. *PLoS One*. 2016;11:e0153414.
14. Tovey ER, Willenborg CM, Crisafulli DA, Rimmer J, Marks GB. Most personal exposure to house dust mite aeroallergen occurs during the day. *PLoS One*. 2013;8:e69900.
15. Sheehan WJ, Permaul P, Petty CR, et al. Association between allergen exposure in inner-city schools and asthma morbidity among students. *JAMA Pediatr*. 2017;171:31–38.
16. Jhun I, Gaffin JM, Coull BA, et al. School environmental intervention to reduce particulate pollutant exposures for children with asthma. *J Allergy Clin Immunol Pract*. 2017;5:154.
17. Matsui EC, Perzanowski M, Peng RD, et al. Effect of an integrated pest management intervention on asthma symptoms among mouse-sensitized children and adolescents with asthma: a randomized clinical trial. *JAMA*. 2017;317:1027–1036.

Supplementary Data

eTable 1
Running Environment of Samplers

Variable	Mean (SD)	Highest	Lowest
Relative humidity	51.8 (9.2)	70	19
Temperature, °C	21.6 (1.7)	27	16
Distance from bed, cm	43.6 (33.7)	417	30
Height above floor, cm	14.9 (9.8)	107	3

NOTE. Means, standard deviations and ranges of temperature, humidity and localization noted by patients before and after run. The temperature and humidity were from means of the values recorded by the patients at the beginning and end of the run.



eFigure 1. Distribution of sites within the greater Chicago area. Each zip code is represented by a flag. One home was in zip codes 46307, 46321, 46324, 46332, 46342, 60035, 60051, 60060, 60062, 60067, 60077, 60140, 60169, 60193, 60194, 60430, 60438, 60445, 60457, 60467, 60532, 60555, 60607, 60610, 60613, 60615, 60633, 60634, 60647, 60653, and 60661; 2 each in 46321, 46322, 46373, 46375, 60010, 60015, 60103, 60201, 60466, 60477, 60622, 60625, 60654, and 60660; 3 each in 60091, 60422, 60601, and 60640; and 4 each in 60093 and 60614.

eTable 2
Questionnaire

1. What is the ID number given on your box? It is written in black marker.

2. Is this for you and/or someone else? [check all that apply]

☐ You

☐ Your Spouse

☐ Your Child (s)

☐ Other (please specify) _____

3. What is this person (s) age? [list all]

4. Does this person (s) have allergies and/or asthma? [check all that apply]

☐ Seasonal Allergies

☐ Perennial Allergies (all year round)

☐ Food Allergies

☐ Intermittent Asthma (symptoms < 2 days/week and do not affect normal activity)

☐ Persistent Asthma (symptoms > 2 days a week and affect normal activity)

☐ Exercise Induced Asthma

☐ Occupational (Work Related) Asthma

☐ Nighttime Asthma

☐ I don't know

☐ No this person does not have allergies nor asthma

5. What environmental measures is the person taking today to manage allergies and asthma? [List all that apply]

6. How many pets does this person own? [please specify number]

☐ Cat

☐ Dog

☐ Other

7. If this person owns a pet, does the pet go into the room that will be tested? [check only one]

☐ Always (day and night)

☐ Often (only night – sleeps there)

☐ Sometimes

☐ Rarely

☐ Never

8. Does this person open windows in the room that will be tested? [check only one]

☐ Always

☐ Often

☐ Sometimes

☐ Rarely

☐ Never

9. Were windows opened in the room during the test?

☐ Always

☐ 10, 20, 30, 40, 50, 60, 70, 80, 90% of time? (Circle applicable).

☐ Never

10. Is the following in the room that was tested? [Check all that apply]

☐ Carpeting or rugs

☐ Upholstered furniture

☐ Dust-mite proof covers for mattress and/or pillows

☐ HEPA air purifier; Please specify name & type: _____

☐ Fan

☐ Air Conditioning

11. Does this person rent or own their home? [check only one]

☐ Rent

☐ Own

☐ I don't know

12. What is your zip code?

13. Is the neighborhood urban, suburban or rural? [check only one]

☐ Urban

☐ Suburban

☐ Rural

14. Describe the neighborhood? [Indicate yes or no]

☐ Are there trees in the neighborhood?

☐ Are there flowering plants in the neighborhood?

15. The following is a list of attributes/tasks. How satisfied were you with each?

Not Satisfied	Very Satisfied				
Instructions	1	2	3	4	5
Ease of installation	1	2	3	4	5
Noise level of product	1	2	3	4	5
Smell level of product	1	2	3	4	5
Noting required info on labels	1	2	3	4	5
Dropping off product at doctor's office	1	2	3	4	5

16. What is this person's annual household income? [check only one]

☐ Under \$25,000

☐ \$25,001 - \$49,999

☐ \$50,000 - \$74,999

☐ \$75,000 - \$99,999

☐ \$100,000 - \$149,999

☐ \$150,000 - \$199,999

☐ \$200,000 and over.

eTable 3
Characteristics of Homes and Residents

Characteristic	Finding ^a
No. of samplers run	102
No. of completed questionnaires	75
Physician practice	
1	12 (16)
2	13 (17)
3	13 (17)
4	20 (27)
5	17 (23)
Location	
Urban	25 (33)
Suburban	40 (53)
Rural	2 (3)
Home profile	
1 Adult	15 (20)
2 Adults	45 (60)
3 Adults	3 (4)
4 Adults	2 (3)
5 Adults	1 (1)
No children	43 (57)
1 Child	9 (12)
2 Children	6 (8)
3 Children	6 (8)
4 Children	1 (1)
1 Person	13 (17)
2 Persons	24 (32)
3 Persons	11 (15)
4 Persons	9 (12)
5 Persons	7 (9)
6 Persons	1 (1)
Ownership	
Rent	15 (20)
Own	53 (71)
Income	
<\$25,000	2 (3)
\$55,000-\$50,000	7 (9)
\$50,000-\$75,000	13 (17)
\$75,000-\$100,000	10 (13)
\$100,000-\$150,000	10 (13)
\$150,000-\$200,000	6 (8)
>\$200,000	11 (15)
No response	8 (11)
Trees in neighborhood	
Yes	62 (83)
No	5 (7)
Flowering plants in neighborhood	
Yes	55 (73)
No	12 (16)
Age, y (%)	
Mean	42 (56)
Median	38 (51)
Lowest	5 (7)
Highest	79 (105)
Pets owned	
No cat	37 (49)
1 Cat	20 (27)
2 Cats	5 (7)
3 Cats	5 (7)
No dogs	36 (48)
1 Dog	15 (20)
2 Dogs	11 (15)
3 Dogs	2 (3)
4 Dogs	1 (1)
No pets	26 (35)
1 Pet	6 (8)
2 Pets	20 (27)
3 Pets	11 (15)
4 Pets	1 (1)
5 Pets	2 (3)
6 Pets	1 (1)
At least 1 cat and 1 dog	20 (27)

^aData are presented as number (percentage) unless otherwise indicated.

eTable 4
Correlations Between Pet Ownership and Pet Access to the Bedroom With Allergen Concentrations in the Air^a

Variable	Can f 1		Fel d 1	
	R ²	P value	R ²	P value
Dogs owned	0.47	<.001	0.016	.29
Cats owned	0.0037	.63	0.49	<.001
Dog in room	0.24	.02	0.00032	.98
Cat in room	0.023	.51	0.13	.10

^aCorrelations between number of pets owned and percentage of time pet is allowed in bedroom from questionnaire (eTable 1) with measured pet allergen concentration in air. *P* < .05 was considered to be statistically significant.