

REVIEW

Indoor allergens in settled school dust: a review of findings and significant factors

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Summary

The school environment can be an important site of exposure to cat, dog, dust mite, and cockroach allergens, which have been detected in the settled dust of many schools. The sizable body of research that has been published in recent years warrants careful examination. This review article informs clinicians, researchers, and other parties about the potential for exposure in the school environment, factors that affect allergen concentrations, and areas of future research. While average concentrations in schools were usually under risk levels for symptoms or sensitization, many studies reported at least one location where the concentrations exceeded these levels. Maintenance, mechanical, and administrative factors were related to allergen levels in schools. From a clinical perspective, the school environment in industrialized nations has a lower potential for exposure than the home environment, but schools are significant for allergic individuals whose home environment has been addressed to the extent feasible. From a public health perspective, the school environment should be considered as a target for primary and secondary prevention. It can be more practical and amenable to intervene on a single school than the hundreds of homes in a community. Future research should continue to evaluate which interventions are most practical and result in the greatest measurable improvements. In addition, research should further examine the relationship between allergen exposure in schools and health effects, in order to develop an accurate exposure assessment model and risk levels that are specific to the school environment.

Introduction

Eight indoor agents are 'causally related' or 'associated' with asthma exacerbation in school-aged children, according to the US Institute of Medicine [1]. These agents are cat, cockroach, dust mite, dog, fungi, rhinovirus, environmental tobacco smoke, and nitrogen oxides. In addition, exposure to dust mites is causally related to the development of asthma. Cat, dog, dust mite, and cockroach allergens are frequently measured in settled dust reservoirs as a surrogate for airborne exposure [2–4]. The measured concentrations can be compared with 'risk levels', which are approximate indicator levels based on concentrations in homes that consistently correlated with asthma exacerbation or sensitization [1, 4–7] (see Table 1).

This article reviews the studies that measured cat, dog, dust mite, and cockroach allergens in settled school dust. Reported concentrations and critical factors that account for their variability are described and discussed. Such a narrowly focused article is warranted because of the large body of research that has been published in recent years. The findings can help clinicians advise patients about the relative importance of the school environment, and can assist researchers with future exposure assessment and reduction studies.

Moreover, the conclusions can guide governmental agencies that have begun to target the school indoor environment for exposure reduction (especially in the United States) [8–10].

Studies for this article were selected by searching the Medline database, selecting articles from bibliographies, and searching the *Indoor Air* conference proceedings. Only articles that measured allergen levels in settled dust from schools (not day-care centres or universities) were reviewed. Forty-one papers were found that fit the selection criteria, 11 from conference proceedings and 30 from journals.

Reported concentrations

Thirty-six papers reported absolute concentrations of cat, dog, dust mites, and/or cockroach allergens in settled school dust. These are shown in Table 2a–d. Studies usually reported a single average value (geometric or arithmetic mean, median) for a type or combination of surfaces, in units of nanograms (ng), micrograms (μg), or activity units (U) of antigen per gram settled dust (e.g. ng/g) or per metre square of surface area sampled (e.g. ng/m²). Almost all the studies provided some description of variability, which was used to determine the number of studies reporting at least one value over specific thresholds. Eight papers [11–18] seemed to provide the same data (regarding authors, schools, and reported results) as other papers and were deemed part of another study. These data are not included in Table 2a–d.

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Cat allergen (Fel d 1) average values range from 30 ng/g from combined surfaces in Chinese schools [19] to 11 300 ng/g in chairs and desks from Virginia (USA) schools [20] (see Table

2a). While most average values were under 1000 ng/g, 10 studies reported at least one sample over this concentration and three studies reported at least one sample exceeding 8000 ng/g.

Table 1. Risk levels for asthma were developed from home studies and have been applied to school research

Allergen	Risk levels [1, 4, 6, 22]	Alternatives levels of interest cited
Dust mite (Der p 1, Der f 1)	Sensitization (for atopic) > 2000 ng/g Symptoms > 10 000 ng/g	'Increased level' > 25 ng/m ² [69]
Cat (Fel d 1)	Sensitization > 8000 ng/g	'Moderate level': 1000–8000 ng/g [20, 49]; > 8000 ng/m ² [27]
Dog (Can f 1)	Sensitization > 10 000 ng/g	'Moderate level': 1000–10 000 ng/g [20, 49]
Cockroach (Bla g 1 or 2)	Sensitization > 2 U/g	'Symptom threshold' > 2, > 8 U/g [1] 'Sensitization threshold' > 1, > 5, > 10 U/g [1] 'Level of concern' > 1 U/g [22, 23] 'Low threshold' > 5000 ng/g [4]

The risk levels are widely accepted as a crude reference point for significant exposure risk to atopic or sensitized individuals in the home environment. They are also referred to as 'exposure risks', 'levels of concern', 'provisional standards' and 'symptom/sensitization levels'. However, they are not directly applicable to the school environment and should be seen as an approximate benchmark for discussing possible population risk. There are other alternative levels of interest cited and defined in the asthma and school literature, shown in the second column. See text for details.

Table 2a. Cat allergen (Fel d 1) concentrations in settled school dust (18 studies)[†]

Country; cat ownership	Study	School concentration (ng/g settled dust, unless noted)
New Zealand; 55% own [‡] [27]	a[27]	C: 2210 (1280–3840) H: 330 (100–1140) C: 3620 (1730–7530) ng/m ² H: 15 (2–90) ng/m ²
United States; 34% households	g[21]	C: 6000 H: 4800 C: 5500 ng/m ² H: 180 ng/m ²
	m[22]	C: 90.8 (8–1440) H: 31 (4.8–280)
	a[34]	F: 1660 (20–12 200)
	g[20]	Co: 2500 (< 400–185 000)
		Home No cat → 0.6x [68] Co: (0–57 200) r[51] Co: (< DL–4490)
Norway; 21% own [‡] [69], 31.7% households [§]	[69]	F: (< 12–24) ng/m ²
		Home No cat → lower Yes cat → higher
	a[33]	C: 262, 486 H: 107, 109
		Home No cat → No significant difference
	a[18]	C: 3275 (~ 200–16 840) ng/m ² H: 283 (4 ~ 1000) ng/m ²
		Home No cat → C: 336 ng/m ² H: 64 ng/m ²
Sweden; 19%, 34% own [*] , 18% own [‡] , 16/100 people [§]	g[36]	F: 134 (< 16–567) Fu: 953 (632–1626), 525 (29–1579)
	m[43]	F: 334, 245
	m[3]	F ~ 100
	g[20]	Co: 760 (< 100–13 000)

Table 2a. (Contd.)

Country; cat ownership	Study	School concentration (ng/g settled dust, unless noted)
		Home No cat → Co: 420 Yes cat → Co: 3300
	g[39]	Co: 240 (50–4450)
	a[66]	Co: 131 (< 16–391)
	g[67]	Co: 120 (< 20–390)
	m[42]	Co: 158
	m[52]	Co: 1200 (290–4700)
	m[48]	Co: 972
	a[70]	Co: 110
England; 12.5/100 people [§]	g[40]	C: 620
		Home No cat → C: 270
China; 3.8/100 people [§]	[52]	Co: (< 240–440)
Singapore; 3% households [‡] [19]	g[19]	Co: 30 (? – 1800)
		Home Yes+No cat → Co: 100

Data are organized by approximate descending pet ownership rates. The home comparison group is classified as homes with 'no' pets, homes with pets ('yes'), and homes that include pets and no pets ('yes+no').

[†]Average concentrations using the ELISA method are shown in bold. The min–max range of results is shown in parentheses, when provided. Where these statistics are not provided, the number or percent of samples exceeding a threshold are shown. In studies where home levels were measured, findings are shown ('x' signifies the ratio of home to school level). Data from different studies are not directly comparable because sampling methods and analysis varied. The symbols are defined as follows. *Ratio of pet owners*: *, referenced in the study; [‡], measured in the study; [§], a national statistic from the American Pet Products Manufacturers Association Inc. (<http://www.appma.org>), Euro-monitor International (<http://www.euromonitor.com>), or the Pet Food Manufacturers' Association (<http://www.pfma.com>). *Type of surface sampled*: C, carpet; H, hard floor; F, floor (type unspecified); Fu, furniture; Co, combination of surfaces. *Type of summary statistic*: g, geometric mean; a, arithmetic mean; m, median. *Specific notes on references are as follows*: [33], old vacuum, new vacuum; [36], chair, table; [37], 'Fu' means are for table, chair; [38], value is a personal correspondence; [41], before cleaning, after cleaning; [43], rooms cleaned with micro-fibre, conventional cotton mops; [71], 0.8 mites/m² reported (1 mite ~ 20 ng). DL, detection limit.

Table 2b. Dog allergen (Can f 1) concentrations in settled school dust (12 studies)†

Country; Dog ownership	Study	School concentration (ng/g settled dust, unless noted)
USA; 39% households, 21/100 people	a[34] g[20] [68]	F: 1440 (100–9600) Co: 1550 (<500–37 000) Co: (0.5–57 500)
Sweden; 9% own ‡ [39], 25% own * [52]; 10/100 people§	g[36] m[43] g[20]	F: 200 (56–506) Fu: 5300 (1700–28 200) F: 1328, 1527 Co: 3300 (<500–176 000) Home No dog → Co: 2000 Yes dog → Co: 79 000
	g[39] a[66] g[67] m[52] m[48] a[70]	Co: 1092 (300–1980) Co: 921 (<60–3990) Co: 450 (<60–3990) Co: 1525 (<200–3650) Co: 3940 Co: 468
England; 10/100 people§	g[24]	C ~ 1000 ng/m ² Home No dog → C: 900 ng/m ² Co: 100 (? – 200) Home Yes+no dog → Co: 1100
Singapore; 6% households ‡ [19]	g[19]	Co: (<200 –750)
China; 1.6/100 people§	[52]	

Data are organized by approximate descending pet ownership rates. Using the RAST inhibition method, school dust samples had 1/4 and 1/3 the levels of home with and without dogs, respectively [69], and 1–2–1.3-fold the levels of homes without dogs [18]. The home comparison group is classified as homes with 'no' pet, homes with pets ('yes'), and homes that include pets and no pets ('yes+no').

†See Table 2a for explanation.

Dog allergen (Can f 1) average concentrations range from 100 ng/g in combined surfaces in Chinese schools [19] to 15 000 ng/g in chairs and desks in Swedish schools [20]. Most average concentrations were between 1000–10 000 ng/g (see Table 2b). Nine studies reported at least one sample over 1000 ng/g, and three studies reported at least one sample over 10 000 ng/g.

Dust mite allergens (Der p 1 and/or Der f 1) average concentrations were typically low, but two studies reported averages over 2000 ng/g (from carpets and desk/chairs) (see Table 2c) [20, 21]. Nine studies reported at least one sample over 2000 ng/g, and five studies reported at least one sample over 10 000 ng/g.

Cockroach allergens (Bla g 1 or 2) were the least frequently measured allergen. Interestingly, five studies reported Bla g 1 or 2 average concentrations over 2 U/g [19, 22–24] (see Table 2d). Seven studies reported at least one sample over 2 U/g or 5000 ng/g, and three studies reported at least one sample over 10 U/g.

Factors associated with concentration differences

Many studies identified factors and outcomes that correlated with allergen concentrations in settled school dust. Table 3

Table 2c. Dust mite (Der p 1 and/or Der f 1) in settled school dust (17 studies)†

Location; time of year	Study	School concentration (ng/g settled dust, unless noted)
Shanghai, China; November–December	[52]	Co: <200
Singapore; every 3 months	g[19]; p1, f1	Co: 100 (? – 3700), 200 (? – 3300) Home Co: 400, 900 C: 7204, 3457 (42–14 646) C: 575 (42–50 900), 57 (10–4020) H: 93 (7–18 300), 34.5 (7–132)
Florida, USA; May–June	a[41]; p1+f1	C: 16 ng/m ²
Texas, USA April–May	m[22]; p1, f1	C: 7000 H: 110 C: 5900 ng/m ² H: 110 ng/m ²
California, USA; late spring	a[71]	Co: 1120 (<0.2–18 000)
North Carolina, USA; fall–spring	g[21]	F: 380 (0–11 9000)
Virginia, USA; n/a	g[20]; p1+f1	Co: (<DL –120)
Baltimore, USA; December–February	a[34]	Co: 36% > 2000
Minneapolis, USA fall–spring	[51]; f1+p1	C: 44.2 (5–18,662)
Germany; n/a	[38]	H: 22.5 (<5–193)
The Netherlands; September	g[26]; p1	C: 21 (<1–5794) ng/m ² H: 6.4 (<1–113) ng/m ² Home 15–100x C: 299 Fu: (3800–9750) Home C: 2605 Fu: 7115
Manchester, England; winter–spring	g[40]; p1	Co: (<60 –120), (<60 –70) F: 41 (16–87) Fu: 258 (16–790), 44 (16–358)
Linköping, Sweden; January	[39]; p1, f1	Co: <DL
Linköping, Sweden; fall	g[37]; p1+f1	Co: 2.3 Co: <200
Uppsala, Sweden; spring	[66]; p1+f1	
Uppsala, Sweden; March–May	a[70]; f1	
Uppsala, Sweden; November–December	[52]	
Norway; winter	[33]; p1, f1	Co: (<1 –38), (<3) Co: (<1 –104) ng/m ² , (<1 –<38) ng/m ² C: <3 , (<1 –<5) C: ? , <10 ng/m ² Home C: <48 , (<1 –19) C: 2.1x H: 4.4x
Norway; February	[18]; p1, f1	Co: <400 Home Co: <400
Northern Sweden; n/a	g[20]; p1+f1	Co: (<25) ng/m ²
Northern Norway; January–March	[69]	

Data are organized by ascending approximate geographic latitude. Where available, the results are distinguished, with 'p1' signifying Der p 1 and 'f1', signifying Der f 1. n/a, not available.

†See Table 2a for explanation.

Table 2d. Cockroach (Bla G 1 or 2) in settled school dust (10 studies)†

Location	Study	School concentration (units per gram dust, unless noted)
North Carolina, USA	g[21]	C: 4600 ng/g H: 1600 ng/g C: 5400 ng/m ² H: 50 ng/m ²
Texas, USA	m[22]	C: 5.7 (1.6–15.4) H: 5.2 (1.5–140)
Northern Sweden	g[20]	Co: 200 (<200–560) Home Co < 200 ng/g
Virginia, USA	g[20]	Co < 200 ng/g
Baltimore, USA	m[23]	F: 2.6 (0–591)
Baltimore, USA	a[34]	F: 1.49 (0–8)
Uppsala, Sweden	[52]	Co: (<200) ng/g
Shanghai, China	[52]	Co: (<200) ng/g
Minneapolis, USA	[51]	Co: (<DL–83 000) ng/g
Manchester, England	g[24]	C: 2.4 (0.8–4.4) Home C < 0.8
Singapore	g[19]	Co: 5.9 (?–26.3) Home Co: 2.5
Indiana, USA	[68]	Co: (<0.9)

†See Table 2a for explanation.

shows the 26 studies that analysed factors using a statistical model. This section describes these measured factors, as well as other possible unmeasured underlying causes that may explain the variability between and within studies.

Sample collection and analytic methods

Sample collection methods used in the studies varied. A variety of sampling equipments were used that had differing vacuum flow rate, vacuum power, and collection devices (e.g. filter bags, cassettes, etc.) (see Table 4). The type of equipment used may affect the accuracy of the results. In a laboratory comparison with known uniform carpet concentrations of cat and dust mite allergens, different sampling devices yielded ng/g results that differed from the true concentration, with one device yielding twice the concentration [4].

The number of samples collected and the size and locations of the areas sampled can influence findings because levels vary considerably within a room [3, 25–28]. For example, classroom entrances had a mean 690 ng/g compared with the 4220 ng/g in the centre [20]. A fivefold variance was found in opposite sides of rooms in homes [25].

Most studies used the ELISA method to quantify allergen concentrations. Methodological differences, such as extraction temperature, replicate precision, linearity of the reference curve, and the reference standards' true concentration can contribute to the variability of the results [4, 5, 29]. Some studies used the RAST inhibition [30, 31] or histamine response [32, 33] methods to compare allergenic activity in collected dust.

With the ELISA method, data are expressed in units of weight of allergen (e.g., ng) per gram dust collected (i.e., ng/g)

or per square metre area sampled (i.e., ng/m²). The metric used can affect whether factors significantly correlate with settled dust concentrations. For example, the total mass of settled dust collected from carpeting usually exceeds hard floors, by factors of 1.5–4 [26, 31, 32], 70 [33], and even 2300 [26]. As a result, analysis using the ng/m² (but not the ng/g metric) can produce statistically significant differences [18].

Building factors

Room use is an important determinant of cockroach concentrations. Higher cockroach allergen concentrations were found in food-related areas (kitchens, cafeteria, teachers lounges) compared with classrooms. The difference was marginal (1.9–2.2 vs. 1.8–1.9 U/g) in one study [34] and statistically significant (median 5.8 vs. 2.1 U/g, respectively) in another [23]. Yet areas not explicitly considered food-related also had elevated concentrations. A Singapore study reported a geometric mean concentration of 5.9 U/g for combined samples from classrooms, offices, and libraries (cupboards and store rooms were excluded from the sample) [19]. In contrast to studies of homes, the presence of sinks was not found to be a risk factor for elevated classroom cockroach concentrations [23]. This may have to do with the presence of more food debris around sinks in homes.

Inadequate ventilation is the most frequently reported factor associated with major indoor air quality problems [35], but few studies measured its relevance to settled school dust allergens. Higher air exchange rates were weakly associated with lower cat allergens ($r = -0.316$) [36], while continuous operation of ventilation was associated with lower dog allergens but not cat allergens [36]. A centralized heating, ventilation and air-conditioning system was associated with significantly higher cat and dust mite concentrations than other types of ventilation systems [34].

Authors frequently attribute statistically significant concentration differences between buildings to an unmeasured underlying cause. Dust mite and cockroach concentration differences between buildings within a study were attributed to infestation and humidity [21, 23, 37]. Lower cockroach concentrations found in a Baltimore school with higher socioeconomic status (median 0.8 vs. 2.6 U/g for other schools) were attributed to the observation that the school was 'better kept' (i.e. cleaning differences) [23]. Likewise, dust mite concentrations in small schools (<8 classrooms) were half the level of larger schools, which was attributed to cleaning differences [26]. Finally, dust mite concentration differences between ground and upper floors were attributed to dampness in the ground floors [36, 37].

Type of surface

Flooring is frequently analysed for allergen concentration differences. School carpeting was consistently found to have higher concentrations of cat, dog, and dust mite allergens than smooth floors (see Tables 3 and 5). But cockroach allergens were higher in carpeting in only one study [21], while no such difference was found in other studies [22, 23, 34]. This is likely because food-related areas, where cockroaches are more likely to be found, typically have smooth floors.

Table 3. Statistically significant associations between measured factors and elevated allergen concentrations in settled school dust

Association with factors	Allergen levels in settled school dust (ng/g or ng/m ²)			
	Cat	Dog	Dust mites	Cockroach
<i>Building factors</i>				
School vs. all homes	(-)[19, 69]	(-)[19, 69]	(-)[18, 19, 26, 40, 69]	(+)[19]
School vs. homes w/o pet	(+)[18, 20, 40, 69] Ø[27]	Ø[20] (+)[18]		
Type of ventilation system	Ø[36] (+)[34]		(+)[34]	
Ventilation quantity	(-)[11, 36] Ø[72]	Ø[72]		
Ground floor vs. upper floors	(-)[36] ¹		(+)[37]	Ø[23]
Variation between schools			(+ -)[37] ²	(+ -)[21, 23]
Big school vs. small school	Ø[34]	Ø[34]	(+)[26] ³ Ø[34]	Ø[23, 34]
Rural vs. urban school	Ø[20]	Ø[20]	Ø[20] (+)[26] ⁴	Ø[20]
Geographically separate schools	(+ -)[20]	(+ -)[20]	(+ -)[26, 31]	
Food-related area vs. classrooms				(+)[23]
Presence of sink				Ø[23]
<i>Surface factors</i>				
Carpet vs. smooth floor	(+)[18, 21, 22, 27, 31–34] Ø[30]	(+)[18, 30–32, 34]	(+) [18, 21, 22, 31–34] Ø[30]	(+)[21] Ø[23]
Central floor vs. entrance/border floor	(+)[27] ⁵			
Curtains vs. other surfaces	(+)[39]	(+)[39]		
Tables vs. chair			(+)[37]	
Tables vs. floor	(+)[36]			
Chairs vs. floor	(+)[36]	(+)[36]	Ø[37]	
Old (> 10 years) vs. new floor (< 10 years)			(+)[26]	
Amount open shelves	(+)[13]	(+)[13]		
<i>Cleaning factors</i>				
Wet cleaning vs. dry cleaning of carpet			(+)[26]	
Wet vs. dry cleaning of smooth floor	(-)[11, 36]	Ø[36] (-) [13]		
Wet+dry vs. wet only Cleaning	(-)[36]			
Wet vs. dry cleaning chairs	(+)[36]		(+)[37]	
Cleaning vs. no cleaning of chairs/desks	(+)[13]	(+)[13, 36] ⁶		
Washing curtains	(-)[11]	(-)[11]		
Micro-fibres vs. cotton mop	Ø[43]	Ø[43]		
Rape seed oil vs. regular wet mop	(+)[43]	Ø[43]		
More frequent floor cleaning	(-)[43] Ø[3]	(-)[43]		
<i>Asthma outcomes</i>				
Current asthma among students	(+)[66] Ø[68]	Ø[66, 68]		Ø[68] (+)[34]
Asthma incidence	(+)[67]			
<i>Ambient factors</i>				
Seasonal variation			Ø[19]	
<i>Occupant factors</i>				
Pet ownership to classroom levels (r ²)	(+)[13, 27, 36] Ø[3]	Ø[36]		

Statistically significant ($P < 0.05$) positive associations between a factor (or the first parameter in the comparison) and an elevated concentration is represented by (+). A negative association is represented by (-). Statistical tests that showed no significant associations are represented by Ø. Superscripts indicate authors' attributions as the likely explanation: (1) more pet ownership in upper floors; (2) dampness problems and number of floors; (3) better cleaning in smaller schools; (4) rural schools have higher ambient humidity; (5) children sitting on floor; (6) greater pet ownership in rooms cleaned. Some of the other speculative observations and attributions are discussed in the text.

The age of flooring can also impact allergen concentrations. Smooth and carpeted floors <10 years old had 2/3 the dust mite ng/m² levels compared with older floors [26]. Even carpeting as new as over 2 years old was attributed to the higher levels of dog and cat allergen compared with smooth floors [31].

Furnishings are an important reservoir of allergens. Classrooms with more fleecy materials and open shelves had greater cat and dog allergen concentrations [13]. Samples collected from mattresses, upholstered furniture, and carpeting in German kindergarten classrooms found 36% of samples exceeded 2000 ng/g dust mite (personal correspondence reported in [38]; not statistically analysed). Significantly

higher levels of cat, dog [36, 39], and dust mite allergens [37] were reported in furniture (curtain, chairs, tables) than in floors (see Table 2a–c). Moreover, upholstered furniture had about 10-fold higher dust mite concentration than carpets (3800–9075 vs. 299 ng/g), with the upper end of the measurement range similar to levels found in home upholstered furniture (not statistically analysed) [40].

Cleaning

The allergen removal efficiency of any cleaning method is critical to maintaining low allergen levels. The unsieved dust collected with a new vacuum cleaner had higher carpet

concentrations of cat allergen compared with the school's regular vacuum (3275 vs. 518 ng/m², 489 vs. 262 ng/g; not statistically analysed) [33]. The concentrations collected from smooth floors did not differ with vacuum cleaner. Moreover, the absence of an exhaust filter can allow allergens to return to the settled dust in classrooms. About 100 ng of cat allergen was measured in the main filter of a vacuum used to collect samples in schools, which falls in the range (3–265 ng) that has caused bronchial provocation in patients [18]. Finally, deep cleaning by a dry extraction method reduced dust mites (ng/g) by half [41].

Wet cleaning (i.e. mopping) of smooth surfaces was usually superior to dry cleaning (i.e. sweeping). Wet cleaning methods

were associated with significantly lower cat allergen concentrations on floors and other surfaces [36, 42]. On the other hand, lower concentrations of cat allergen were found on chairs cleaned by dry cleaning [36], and wet mopping may be associated with other indoor contaminants such as volatile organic compounds and bacteria [13]. Using both methods to clean seems best – this was associated with lower concentrations than each method alone [36].

The importance of cleaning frequency has been shown in a number of Scandinavian studies. Significantly lower dust mite levels were found in a school that dry swept chairs once a week, wet swept tables once a week, and dry swept floors three times a week (compared with schools which only wet swept these surfaces or did not sweep chairs) [37]. The frequency of floor and desk wet mopping and curtain washing has correlated with lower cat and dog allergen concentrations [13]. Cleaning frequency may be more important than the use of a specialized cleanser [43]. Rooms cleaned four times a day compared with rooms cleaned once a day had a 60–70% reduction for 5/6 particulate measures (including cat and dog allergens). The use of rape seed oil impregnated mops only reduced one parameter (ng/g cat allergen) compared with regular mops.

Chairs, shelves, and other surfaces are often neglected in the cleaning routine. Chairs (cleaned only once a year) were found to have 25-fold dust mite concentration as floors (cleaned several times a week) [16]. Moreover, chairs that were never cleaned had higher levels of dog allergen than chairs cleaned [36]. Likewise, curtain washing was associated with lower cat and dog allergens [42].

Occupant factors

Occupants in the classroom play an important role in the transfer of dog and cat allergens from homes to schools. The number of pet owners correlated strongly ($r^2 = 0.93$ [27]) and marginally ($r = 0.4$ [36]; $P = 0.052$ [3]) with classroom cat allergen concentrations. Concentrations in classrooms with many cat owners (>20%) were 5-fold higher than classrooms with few cat owners (<10%) [2]. The transfer mechanism is primarily clothing – children with a dog or cat at home have higher pet allergen concentrations on their clothes [27, 39]. Classrooms that banned pet ownership or instituted school-only clothes had 4–6-fold lower classroom cat allergen levels [44]. One would expect schools that had pets present would have higher concentrations than schools without pets, but one study found the highest levels were not in the two schools that had a cat present once a week [27].

Table 4. Equipment used in school studies to collect dust from surfaces

Equipment used in studies (pump, power, flow rate, collector/filter)
Volta Lite vacuum cleaner (The Electrolux Group, Volta, Sweden), 1000 W, ALK dust collector (Allergologisk Laboratorier A/S, Horsholm, Denmark) 6 µm pore size filter or dustscreen with 15 µm nylon mesh sleeve [3]
Medivac vacuum cleaner (Miele, Inc., Princeton, NJ, USA), 45 L/s [24, 40]
Eureka vacuum cleaner with detachable hose (model 3621) (Electrolux Home Care Products North America, Bloomington, IL, USA), cotton bag [22]
Schools' old and new vacuum [33]
Nilfisk GS 90 vacuum cleaner (Nilfisk – Advance Group, Broendby, Denmark), double disposable filter bag, main filter, microfilter [18]
Kirby Classic III (The Scott Fetzer Company, Cleveland, OH, USA), chamber, filter paper [19]
Hitachi 2500 1000 W vacuum cleaner (Hitachi, Ltd., Tokyo, Japan), 25 µm mesh nylon bag [27]
Nilfisk GM 90 vacuum cleaner, ALK nozzle and Whatman filter paper (Whatman, plc., Maidstone, UK) grade [69]
High-volume Small Surface Sampler, 1 hp, nozzle and cyclone trap [21]
Philips Topomatic T-518 vacuum (Koninklijke Philips Electronics N.V., Amsterdam, the Netherlands), 900 W, ALK dust collecting device, paper filters [26]
Vacuum cleaner, filter bag [23]
Residential canister-type vacuum, Dupont Hysurf filter bag (Du Pont de Nemours and Company, Wilmington, DE, USA) attached to hose end [34]
Volta Lite vacuum cleaner, 1100 kW, ALK collector, 6 µm Millipore filter (Millipore Corporation, Billerica, MA, USA) [36, 39]
Vacuum cleaner, 2.2 hp, dust trap in hose, 200-mesh filter [41]
Standardized vacuum cleaner, ALK dust collector with filter [42]
25 L/min, 37 mm cassette with 0.8 µm MCE filter [51]
Vacuum cleaner, 400 W, ALK dust collector, Millipore 6 µm filter [13, 14, 52, 70]

Studies provided limited information in the methods sections. Most used conventional vacuum cleaners, with a collector device (e.g. 'ALK', Allergologisk Laboratorier) containing a filter attached to the hose.

Table 5. Ratio of allergen concentration in carpet to smooth floor

Sample analysis	Carpet to smooth floor ratio			
	Cat	Dog	Dust mite	Cockroach
Allergen activity	1.7 [18], 1.1 [31]	1.6 [18], 1.2 [31], 1.6 [30], 1.6 [32]	6.8 [18], 3.4 [32]	
Allergen per gram floor dust	2.9 [22], 6.7 [27], 1.7 [32]		6.2 [22]	2.9 [21]
Allergen per unit floor area	241 [27], 11 [33], 31 [21]		54 [21]	108 [21]

In studies providing a quantity for each surface, the ratio was determined by dividing carpet level with smooth floor level. 'Allergen activity' refers to studies that compared samples using the RAST inhibition or histamine response method. See Table 3 for which ratios are statistically significant and for additional studies that did not report concentrations.

Cat allergens are transferred from schools to pet-free homes. Pet-free homes of students from classrooms with many cat owners had about 4-fold higher concentration than homes of students from few cat owner classrooms [2]. Likewise, mattresses had significantly higher allergen concentrations in cat-free homes of students attending classrooms with >25% cat ownership, compared with those attending classrooms with <10% cat ownership [45]. Transfer of allergens can undermine efforts to reduce levels in pet-free homes [46].

The quantity transferred to schools varies depending on the allergen. One study found a 6-fold higher dog concentration compared with cat in clothing and classroom surfaces, even though more cats were owned by students [39]. Another study reported 30% of samples exceeded 10 µg/g for dog allergen while 7% exceeded 8 µg/g for cat allergen [20]. The higher dog allergen concentrations may be due to more frequent contact, their larger size, and/or greater allergen shedding.

It is unclear whether significant amounts of dust mite allergens are transferred to schools by occupants. It has been suggested that dust mites can be transferred, for example in hair, explaining higher levels on tabletops compared with chairs and floors [37]. Moreover, schoolchildren's clothes contain dust mite allergen. One extraction method yielded an average of 15900 ng/g [47]. But much less was found using a vacuum to collect particles (median <100 ng/g), and cat and dog levels were significantly higher (median = 444 and 2676 ng/g, respectively) [39]. Higher dust mite levels in older flooring were attributed to allergen loading [26], but there may have been a population in the flooring.

The primary source for cockroach allergens appears to be current infestation, not transfer by occupants. A negative association has been observed between home and school concentrations. In an area where 1/3 of homes exceeded 1000 ng/g, no samples from the local school exceeded this threshold [20]. Inversely, another study reported all home samples were under 0.8 U/g, while 2/3 of school samples exceeded this concentration (not statistically analysed) [24]. Higher concentration in schools (geometric mean = 5.9 U/g) than homes (geometric mean = 2.5 U/g) was attributed to eating and other food-related activities in the classroom [19].

Humidity, season, geography

The relationship between indoor allergens and humidity, season, and climate has been reviewed before [1, 48]. Humidity levels in the ambient and indoor micro-environment play an important role in the levels of dust mites [49]. Dust mites require indoor absolute humidity levels above 7 g/kg, which corresponds to >45% relative humidity at room temperature [18]. In one study, 5/7 classrooms with relative humidity between 69% and 80% had dust mite concentrations over 1000 ng/g [41]. Classrooms with relative humidity between 51% and 64% had concentrations around 100 ng/g in 6/7 rooms (no statistical analysis). Dampness of school building materials is another correlate of dust mite concentrations. Flooring with visual signs of dampness had 25% higher Der p 1 ng/m² levels [26]. Ground floors can have higher dust mite levels compared with upper floors, which was attributed to moisture intrusion [37, 48].

Season and climate contribute to the variability in dust mite concentrations found in schools, primarily because of their relation to humidity (see Table 2c). In temperate climates, dust mite levels can fluctuate in homes by an order of magnitude with levels peaking in summer and gradually declining until spring [50]. But humidity is not the only underlying factor in seasonal differences – in tropical schools, dust mite concentrations fluctuated by 90% with season, independent of ambient humidity [19]. School studies performed in cold climates or seasons (northern Scandinavia [20, 38, 39], Minnesota [51]) typically found low levels of dust mites (typically well below 100 ng/g). In more humid climates (Virginia [20], North Carolina [21], UK [40], Germany [38]), school concentrations ranged from hundreds to thousands of ng/g. A study that compared schools in Sweden with Virginia, USA found low dust mite concentrations in Sweden (all below the 400 ng/g limit of detection) and moderate-to-high concentrations in the two Virginia schools (2000 and 2400 ng/g for desks and chairs and 550 and 840 ng/g for floors) [20]. Moreover, schools from different regions in the same country had a 2.5-fold difference in dust mite concentrations in the Netherlands [26] and Norway [31], which was attributed to geographic variability in ambient humidity.

The type of dominant dust mite and cockroach species can vary with geography. In tropical regions, the storage mite *Blomia tropicalis* can be detected in schools, and the cockroach *Periplaneta americana* (although not measured in the studies reviewed) may also be important [19]. In Swedish homes, different allergens (Der p 1, Der f 1, or Der m 1) dominate samples depending on the region [37, 39]. Of those school studies that reported Der p 1 and Der f 1 separately, two found Der p 1 concentrations were higher than Der f 1 (by a factor of 3–10, depending on the surface) [22, 37]. A Singapore study found the Der f 1 concentration was twice the Der p 1 concentration [19]. The differences in species dominance may be related to humidity preferences.

Pet allergen concentrations also vary with geography, which appears to be primarily influenced by regional differences in pet ownership (see Table 2a and 2b). In one study, cat allergen concentrations were higher in Virginia while the dog allergen concentrations were higher in Sweden [20]. Another study found higher cat allergen (median = 1200 ng/g vs. range <200–440 ng/g) and dog allergen (median = 1525 vs. range <200–750 ng/g) concentrations in Sweden compared with China [52]. Although not statistically analysed, the differences were attributed to domestic pet ownership, fleecy materials, and fixtures in classrooms, and the use of uniforms in the Chinese schools. In addition, the type of clothing worn, which varies with season and geography, may impact pet allergen levels in school. Wool and polyester clothes had higher concentrations than cotton clothes [27]. This was attributed to more frequent washing and less electrostatic charge of cotton clothing.

Discussion

Factors affecting allergen concentrations

It is noteworthy that few studies examined the effect of ventilation on settled dust allergen concentrations, even

though ventilation is arguably the most significant factor for indoor air quality. This may be because the importance of ventilation has been identified for 'problem' schools while the studies reviewed here are typically 'non-problem' buildings [35]. In addition, certain allergens that settle quickly (i.e., dust mite and cockroach) are not likely to be affected as much by ventilation as other indoor contaminants. Finally, studies that examine ventilation typically measure airborne levels of allergens. Nevertheless, school ventilation was a factor in settled allergen concentrations [11, 34, 36] and reported asthma symptoms [53]. A significant amount of cat and dog allergens is associated with smaller particles ($<5\mu\text{m}$) that stay airborne for many hours, allowing for removal by ventilation. Moreover, ventilation can affect humidity, and thereby impact dust mite growth. Studies in homes have found higher levels of settled cat and dust mite concentrations in autumn and winter during the heating season when outdoor air exchange is lower [48].

Higher concentrations of cat, dog, and dust mite allergens have consistently been found in carpeting compared with smooth floors. Cleaning frequency, efficiency, and thoroughness seem to be a primary cause of this difference. As significantly higher levels have been found in carpets using the ng/g metric, total dust loading alone does not explain the difference. Carpet vacuuming seems to remove larger particles while leaving behind the allergen-associated smaller particles. In comparison, smooth floor cleaning appears more efficient at capturing these smaller allergen-associated particles. The cleaning inefficiency of carpets is due to the mechanical entanglement and electrostatic sorption of particles to fibres and fibre surfaces [54]. Therefore, age, wear, type of fibre, loop density, pile height, and backing permeability will affect the amount of allergen-associated particles that collect and remain on carpets after cleaning. In addition, carpeting may have a higher capacity for moisture retention, which increases numbers of dust mites and mould.

Children from schools with carpeting were found to have an increased severity of asthma compared with children from schools with no carpeting [55]. Coupled with findings from other indoor environments, it is now common for physicians and environmental scientists to recommend the replacement of carpeting with smooth flooring. However, the Carpet and Rug Institute, a carpet industry trade group, has argued that carpets hold allergens out of the breathing zone even with activity on the carpet [56]. Carpets are desired for their comfort, aesthetic, acoustic, and fall injury prevention qualities. A rigorous comparative risk assessment should be carried out that compares the injury risks associated with falls on smooth floors to the allergic health risks associated with carpeting, to better inform decision makers about flooring choices for schools.

The practical implications of some of the findings warrant further research. Furniture can provide the conditions conducive to dust mite growth (warmth, nutrients, moisture) and retain allergens. Research should explore the types of surface materials used in school furniture that are associated with elevated allergens. Furthermore, the optimal cleaning frequencies and methods for specific surfaces in classrooms should be further explored. Such studies could help school staff develop superior furniture purchasing guidelines and cleaning routines.

Assessing risk using settled dust concentrations

Allergy researchers have developed an 'exposure assessment model' for asthma outcomes associated with cat, dog, dust mite, and cockroach allergens in homes (reviewed in [1, 5–7, 57, 58]). Part of this model is based on epidemiological studies that measured settled dust concentrations. Studies have found surprisingly consistent and strong correlations between dust mite, cockroach, and cat allergen concentrations in settled dust and asthma and allergy outcomes (e.g., IgE sensitization, respiratory function, medication use, self-reported symptoms). There are limited data for dog allergen, and conclusions are often drawn by comparison with cat allergen. It is plausible to infer that house dust concentrations do relate to inhalation dose and have some predictive value for asthma outcomes. This has been shown for cat allergen by modelling the concentration to dose [59]. Homes without cats had settled dust concentrations (range = 39–3750 ng/g; median = 258 ng/g) that weakly correlated with air concentrations (range = 2.8–88.5 ng/m³, median = 17 ng/m³). These settled dust levels were deemed clinically relevant because exposing sensitized individuals in cat rooms to $<100\text{ ng/m}^3$ caused a 15% change in forced expiratory volume.

While sampling settled dust has become an accepted index of exposure, it is an indirect assessment of presumed exposure. Air sampling would seem the only proper method to assess exposure. But air sampling is expensive, impractical, more susceptible to temporal and spatial variations, insensitive to low concentrations, and inaccurate for the measurement of transiently elevated allergens (e.g., cockroach and dust mite) [3, 24, 40, 60]. It also ignores exposure by direct contact of the nose and mouth to hands and items (e.g., pillows, clothing, etc.), which carry allergen-associated particles. Measuring personal exposure using nasal traps is hypothetically the best method, but it is cumbersome [61].

Most home studies found a narrow range of concentrations above which health outcomes were significantly associated. These concentrations have become broadly accepted as 'risk levels' and are used by researchers to approximate the potential clinical significance of their findings (see Table 1). Yet, concentrations under the risk levels should not be dismissed because they may pose a risk to a small but significant number of people. In addition to the indirect nature of the exposure measure, this is because reactivity to the same allergens can vary by 10–100-fold [1] and as much as a millionfold [57] between people sensitized to the same allergen. Thus, the risk levels are best suited to serve as indicators or benchmarks for use in population-based home-exposure research rather than as thresholds to predict an individual's health risk in any environment.

Cat, dog, dust mite, and cockroach allergen hazards have been identified repeatedly in schools of industrialized nations, and researchers have assumed that the risk levels can be used to evaluate the significance of their findings. However, the risk levels are of questionable use for the school environment as the circumstances of exposure differ. Floor levels in schools that are similar to homes do not mean comparable risk, because homes have the additional very significant exposure from bedding and upholstered furniture. For dust mites, one review article calculated that the mean of means in home studies was 297 mites per gram dust for beds and beddings, compared with

118 mites per gram dust for carpets [25]. The long periods spent in close proximity to bedding and upholstered furniture likely results in transient exposures to very high levels of allergens. This may hold true even for cockroach allergens, as cockroach allergen in bedrooms correlated with asthma severity [62]. In addition, most schools in the United States have mechanical ventilation systems, unlike many older homes that do not have mechanical outdoor air exchange. This means when settled allergens on small particles (e.g. pet) become airborne, they may be removed from indoor air more quickly in schools than in homes. In sum, school occupants are likely to be exposed to less varying and lower inhalation doses of allergens. More accurate school risk levels could be modelled by dividing the home risk levels with the fraction of exposure in homes from flooring and hard surfaces only.

There is one notable exception where the school environment is quite similar to the home environment. In the lowest grade levels (e.g. kindergarten) in the United States there are far more fleecy materials than higher grades. Children often have naptime and story time, during which they may be exposed to allergens on bedding, area rugs, and cushions. In these classrooms, comparing findings with home risk levels would be more appropriate, and bedding and other fleecy materials should be sampled to characterize risk.

There is currently some limited direct and indirect exposure assessment data for schools. For example, elevated allergen and chemical concentrations in school air [11, 15, 63–65] and allergens in settled dust [34, 66, 67] have been associated with asthma symptoms and sensitization. One study found a 1.8 odds ratio for current asthma for every 100 ng/g cat allergen [66]. In a follow-up study, the amount of cat allergen per school sample but not per gram dust was associated with asthma incidence [67]. The prevalence of students with asthma has been associated with elevated cockroach allergen concentrations, but differences in the home environment were not considered [34]. Another study did not find an association between acute asthma attacks tracked by nurses and classrooms with elevated allergen levels in settled dust [68].

To develop a good school risk assessment model, greater consistency is needed regarding expressing results and sampling methods. The ng/m^2 is preferable to ng/g as the metric for school exposure assessment and intervention research. It is better suited for environments with relatively few three-dimensional porous surfaces, represents total allergen load of a room [57], and has correlated with asthma incidence associated with the school environment [67]. A promising method that reflects airborne levels is Petri dish sampling, which measures deposition of airborne allergens in ng/m^2 [2, 3]. For each sampling method, greater standardization is needed regarding the sampling pump, air flow rate, collection device, filter type, sampling duration, sampling time of day, surface area size, number/types of surfaces sampled, controlling for the effect of cleaning, and other considerations. These parameters are especially important for developing ng/m^2 as the standard metric.

Conclusions

Generally, homes present a greater allergen exposure risk than schools, and should naturally be the focus of attention for

physicians and parents. However, when pets are removed from the home, cockroaches are eradicated, and dust mite exposures are controlled, the school environment usually becomes the primary source of exposure. Schools have concentrations of pet allergens that fall between homes with and homes without pets. Cockroach allergens have been frequently found at elevated levels in schools. While dust mite allergens are higher in homes, school studies found high humidity and cleaning deficiencies can contribute to elevated levels in some fleecy materials. Several studies reported allergens levels in schools that exceed risk levels. When exposed to these levels in homes, individuals have had a greater risk of allergic symptoms and sensitization. Parents and physicians can work with school staff to reduce exposures, primarily by controlling humidity, improving cleaning, and removing fleecy materials.

From a public health perspective, it is reasonable to focus on the school environment from the outset. Schools are public buildings that are expected to meet high standards of environmental quality. Levels of allergens in school settled dust are significantly influenced by factors that can be controlled by school staff who are accountable to the government and community. Homes, on the other hand, are largely outside the public sphere of control. Trying to impact hundreds of homes through a public health education campaign is challenging. It is more practical to intervene on one indoor environment (i.e. the school) where large numbers of atopic and allergic individuals spend significant amounts of time. This is especially relevant to reducing the risk of allergic sensitization (i.e. primary prevention). Few parents will make the impractical or costly preventive changes in their homes that would significantly reduce the risk of sensitization. As levels high enough to contribute to allergic sensitization may be found in some schools, reducing levels in schools may reduce the population risk of sensitization.

These conclusions fundamentally assume that the use of home risk levels is appropriate for the school environment, even though exposures differ in these environments. A better understanding of exposure and dose–response is needed to determine what levels in school settled dust present a significant airborne exposure risk. Based on this research, risk levels could be established for the school environment. In the meantime, the risk assessment model developed for homes should be applied to the school environment with qualified caution – the risk levels should be described as approximate and conservative indicators rather than predictors of individual risks.

Based on the consistent and sizable body of research, it is reasonable to conclude that some number of occupants will have allergic responses associated with the schools of industrialized nations, but the frequency and severity of outcomes cannot be predicted from current data. The current body of research should serve as a useful ‘hazard identification’ foundation for future research. The findings summarized in this article should help clinicians, researchers, school officials, environmental consultants, and governmental officials make decisions regarding priorities and interventions.

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