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Resuspension of house dust and allergens during walking and vacuum cleaning

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ABSTRACT

Conventional wisdom has been that hard, resilient surfaces resuspend fewer particles than carpeted surfaces, however, exceptions to this have been demonstrated and uncertainty remains about the factors that lead to this resuspension, notably, the effect of vacuum cleaning on either increasing or reducing resuspension from flooring. The purpose of this study was to determine how resuspension of house dust by aerodynamic size or particle type, including cat allergen and bacterial endotoxin, is affected by flooring, dust loading, embedding dust, and walking/cleaning activities. House dust was blown in and allowed to settle in a walk-in chamber after overnight deposition followed by walking or a vacuum cleaning procedure. Using an aerosol particle sizer and large-volume air samplers at different heights in the chamber, concentrations of airborne particles, resuspension rates, and fractions were computed for four types of flooring conditions during six walking activities. Carpeting resulted in significantly more airborne cat allergen and airborne endotoxin than a laminate floor. Height does have an effect on measured allergen over carpet and this is apparent with concentrations at the infant and adult air samplers. Walking on laminate flooring resuspends less house dust than walking on an equally dusty carpeted floor, where dust is entirely on the surface of the carpet. However, vacuum cleaning a laminate floor resuspended more dust than vacuum cleaning carpets, at large particle sizes of 5 μm and 10 μm . Activities following a deep cleaning of hard resilient or a carpeted surface is likely to leave no differences in resuspended particles between them.

KEYWORDS

Allergen; carpet; dust; endotoxin; resuspension; vacuuming

Introduction

Extrinsic-allergic asthma can be triggered by a variety of indoor substances, most notably from dust mite, cockroach, and mammalian allergens. Asthma can also be triggered by bacterial endotoxins, which trigger an allergic type reaction through a different immunological pathway than IgE mediated allergens.^[1] Reduction of allergen sources may require strict attention to building materials and furnishings in the home along with moisture reduction and frequency of cleaning. One of the materials that are thought to be responsible for serving as either a source or sink for allergen exposure indoors is carpet.

To understand how different floor coverings can affect allergen exposure to children and adults, studies need to be performed that closely simulate the conditions in the home that might affect resuspension. Once these resuspension characteristics are known they could be valuable in selecting building materials for new homes or for refurbishing old homes for the consumer who is sensitive to indoor allergens.

Swanson provided a one-compartment model, well known to the clinical community, that relates a steady state concentration of allergen to a combined indoor source substance-generation and resuspension rate, which assumes that flooring or other surfaces can both serve as sources as well as sinks for allergen.^[2] Thatcher and Layton described a mathematical relationship between the airborne concentration of fine particles in homes and the process of resuspension.^[3] This one-compartment model treats the floor as an independent source of particles activated by resuspension.

Qian et al. followed this work with experiments that considered a two-compartment model—one compartment for airborne pollutant transit, as described previously, and one compartment for resuspending particles entering the air from surfaces and redepositing back to the surface.^[4] Since some of these early modeling and measurement studies in homes or controlled chambers were conducted, many additional studies have been conducted on resuspension of particles indoors.^[5]

The resuspension rate of particles from flooring depends on particle size, type of flooring, activity pattern, intensity of the occupants, relative humidity, cleaning or vacuuming procedures, and distribution of particles in a carpeted surface.^[3,4,6–14] Utilizing both “real” carpets in schools and artificially embedded carpets and hard surfaces in chambers, Shaughnessy found that duration of activity in addition to flooring condition and surface loading affected resuspension rates.^[15]

Research on adhesion and resuspension at the particle-surface-air boundary has been described by several investigators.^[16–19] Additional investigators have determined the importance of air velocity and turbulence without regard to surface type for suspending indoor particles.^[20]

Zhang determined that shallower shoe grooves, high carpet or particle roughness, larger shoes, and higher stepping velocity increase particle resuspension from indoor surfaces, which generally agrees with principles of adhesion and resuspension of particles.^[21] Perhaps one of the most underestimated factors on resuspension rate depends on surface loading of pollutants and distribution or depth of particles in surfaces.^[10] Sehmel suggests that only resuspendable particles should be included in estimates of surface loading.^[10,22] In fact, small, aerodynamic-diameter (AED) particles, such as that of PM 2.5 are not as easily detached based on theory and while vacuuming, as opposed to the much larger AED, PM 10.^[12,17]

Causer et al. examined several tufted, wool constructions of new carpet that were placed in seven New Zealand homes and then later cross-sectioned for dust mite allergen (Der P 1).^[23] Causer et al. concluded that construction was not a significant factor in the vertical distribution of allergen in carpeting but they did find that dust mite allergen concentration was exponentially greater at the bottom of the pile than at the surface.^[23] Although much is still not known about the migration of particles or its vertical distribution in carpet, researchers have used artificial methods to embed dust and dust containing particles using a locked steel roller following an ASTM method (F608-89).^[5,24]

Few studies have examined how resuspended particles are distributed at various heights in a room, which could then be used for risk assessment of children versus adults. Also, few studies have examined how the adhesive effects of biological particles influence resuspension from carpet.^[5] Buttner found no difference among bacterial spore resuspension at the floor, 1 m and 1.5 m high.^[6]

Several studies have examined the effects of flooring and dust loading on resuspension.^[5] Few studies have examined adhesion or resuspension of biological particles to carpets.^[5] A lesser number of studies examined whether vacuum cleaning increased or decreased

resuspension of particles. Qian appeared to have an inefficient vacuum cleaner that enhanced rather than decreased 2.5 μm particles.^[4] Vacuuming can also be a source of resuspended 10 μm particles and may be vacuum-type sensitive. Good vacuum cleaners should reduce 2.5 and 10 μm particles.^[12] Vacuum cleaner technology, with the advent of onboard high efficient particle filters and cyclonic collection devices, could theoretically clean a residential floor and reduce the source of airborne particles, especially particles in the range of 2.5–10 μm .

Although previous studies have demonstrated how carpet can be more difficult to clean than a hard surface floor and can retain more dust than a hard floor, there is insufficient evidence to demonstrate how carpets are significantly different than hard floors at various heights in a home where airborne allergen exposures, especially to children, can occur. Although some studies have indicated that house dust contains a range of particle sizes that may be respirable for years after resuspension, vacuum cleaners built in later years may be useful for not only removing the source of dust in flooring but also cleaning the air as well.^[4]

Purpose

The purpose of this study was to determine how resuspension of house dust by aerodynamic size or particle type (allergen and endotoxin) is affected by various flooring, dust loading, embedding of dust, and walking/cleaning activities over a 9-hr interval. Cat allergens and endotoxin are thought to be good representatives for asthma triggers in house dust because of their range in aerodynamic diameter and frequency of occurrence in house dust. Cat allergens (and canine allergens) are carried on relatively small aerodynamic diameter dust, 1–10 μm , (Luczynska et al. found 10–60% cat allergen on particles <2.5 μm); endotoxin can be found in both inhalable and respirable fractions of air.^[25–29] Concentrations of airborne particles and resuspension rates were computed for flooring conditions that may expose children and adults to biological dusts or dusts quantified by aerodynamic diameter. This study examined disturbance activities on bulk house dust across a range of aerodynamic size while also examining release of cat allergen and bacterial endotoxin at heights that simulate exposure to toddlers, infants, and adults. It also evaluated how resuspension varies by number of walkers and how this resuspension changes after repeated walking followed by vacuuming and then walking once more.

Methods

Two walk-in chambers, each with a volume of approximately 72.5 m^3 (Figure 1), made from wood supports and

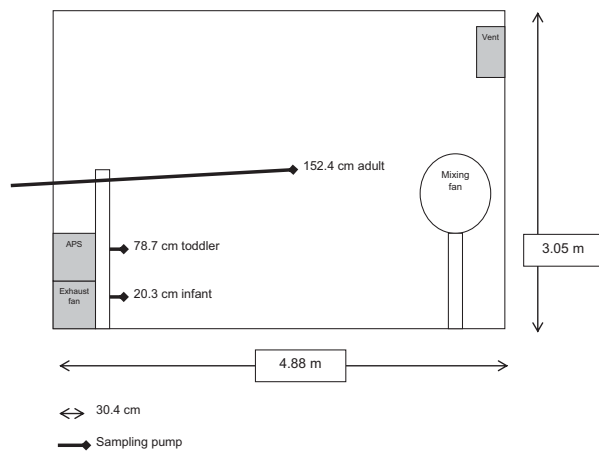


Figure 1. Chamber configuration (side view).

joists, with floor and ceiling drywall, washable latex paint and washable latex painted concrete floor, and operated at the U.S. Army's Aerosol Laboratories in Aberdeen, Maryland, were used for all the controlled studies. Each chamber was sealed to the surrounding laboratory and air was recirculated within the chamber at 0.5 air exchanges/hr or 21 ft³/min (CFM). This was determined to be comparable to American Society of Heating and Refrigerating Engineers, (ASHRAE 62–2001) = 0.35 air exchanges/hr.^[30]

Four flooring conditions—carpet or laminate surface, dust loading, and dust embedding—were employed in each chamber. Flooring was installed according to manufacturer's instructions and secured by an adhesive backing. The laminate and carpet made up an area of 3.65 × 3.65 m². A synthetic pad was installed beneath the carpet. The floor was painted concrete. These flooring conditions were as follows: (1) LLNE, hard wood laminate (Mannington) flooring, loaded with a low amount of dust (1 g/m²); (2) CLNE, Carpet (28 oz., nylon cut pile)^[31] loaded with a low amount of dust and not embedded (1 g/m²); (3) CLE, carpet loaded with a low amount of dust (1 g/m²) and embedded with four passes of a 28-lb locked steel rolling pin; and (4) CHE, carpet loaded with a larger amount of dust (3 g/m²) and embedded with the steel roller with four passes.^[32] The loading amounts were consistent with those found in a range of homes in the U.S.^[3,33] The assigned four-flooring conditions were performed in the chambers using random assignment.

Sieved house dust was (<300 µm) blown into each chamber using compressed air with an ultrasonic nozzle (70 psi) toward the center of the ceiling. This dust was allowed to settle overnight prior to each day's activities in the chamber (details of this process and the quality control measures used can be found in the supplemental materials).

Six everyday activities were simulated in the chamber in the following specific order: one person walking,

conducted twice (I, II); two people walking, conducted twice (I, II); vacuum cleaning with a HEPA-filtered upright vacuum cleaner (Bissell Powerforce Upright Vacuum 35221/35223); and one person walking (III). The activity cycle was conducted over a 9-hr period and was repeated five times per test case. An activity cycle was 90 min long. Each activity lasted 10 min, and dust was allowed to settle in the room for up to 80 min before commencing the next activity.

During each 9-hr cycle, airborne particles were measured by two types of sampling devices: (1) aerodynamic particle sizer (TSI[®] Aerosol particle sizer, APS, models 3321, 3320), 20.3 cm above floor, which measured particle concentration and particle size in real time; and (2) large-air volume area samplers with filters operated at about 80 L/min and positioned at 20.3, 78.7, and 152.4 cm off the floor to represent the heights of infants, toddlers, and adults, respectively. These large volume air sampling pumps (BGI) were turned on when each activity commenced and turned off 20 min later. The three BGI pumps, sampling at three heights with five replicates, for four separate flooring conditions, totaled 60 large volume samples. However, on one occasion, a sampling line leading to one of the APS devices malfunctioned, requiring an additional sample run, so a total of 63 large volume air samples were analyzed. Sample analysis was for gravimetric dust, endotoxin (Endotoxin units, 9 EU = 1 ng), and cat allergen (Fel D 1). Fel D 1 was analyzed by ELISA and bacterial endotoxin was analyzed by kinetic chromatography (Aerotech P and K, Philadelphia, PA).^[34,35]

The APS collected aerosol data every 30s during any given 90-min activity cycle. To smooth the excessive fluctuation in measurements from the APS, the 30-s interval measurements were averaged over 2.5 min. This reduced the amount of measurements from 16,758+3,353 inclusive of all aerodynamic cut points. To eliminate problems with non-detectable measurements in the statistical analysis, the APS data was evaluated at $t = 10$ min and $t = 70$ min during each 90-min activity. Means and standard deviations were computed for the six activities, and five replicates per activity for $n = 30$ composite measurements (C_{in} , from Equations (1) and (2); see Supplemental file). A total of $n = 90$ measurements per treatment (three cut sizes, 2.5, 5, and 10 µm × 30) and four flooring conditions (LLNE, CLNE, CLE, and CHE) = 360 composite measurements.

The size range of the APS was 0.5–20 µm with 52 size bins. The bins that were used to represent the 2.5, 5, and 10 µm were, respectively, 2.458 ± 0.177 , 5.048 ± 0.363 , and 10.37 ± 0.75 µm.

Data from the large volume area samplers were evaluated for dust mass (g), cat allergen concentration (µg/g), and endotoxin (EU/g) using descriptive statistics. Means,

standard deviations, and 95% confidence intervals were computed for each test condition. Volumetric concentrations of cat allergen ($\mu\text{g}/\text{m}^3$) and endotoxin (ng/m^3) were also calculated.

Levene's test for homogeneity of variance was evaluated prior to each ANOVA computation. One-way ANOVAs were computed to determine differences among the four flooring conditions and the height of the samplers for both resuspended cat allergen and endotoxin. An ANOVA was run on mass concentration data derived from the APS to identify main and interaction effects. Means, standard deviations, and upper and lower 95% confidence limits were calculated for each independent variable post ANOVA. The mean and standard deviation of aerosolized mass concentration was calculated from the APS data by treatment, activity, and particle size.

Resuspension rate (1/hr) was calculated for the same sets of parameters. Resuspension rates were calculated using the APS mass concentration data based on Thatcher's one-compartment model, which was described earlier in Equation (1). The supplemental file describes the final calculation for the resuspension rate that we used based on the conditions in the chamber. Resuspension fractions were developed following Karlsson et al. and later Tian et al.^[14,36] A post-hoc conversion of our calculated resuspension rates was made assuming a size 10 shoe and a step rate of 75 steps/min.^[14,36] The SPSS software was used in all computations.

Results

The airborne concentrations for cat allergens and bacterial endotoxin, respectively, representing the four conditions, had a grand mean and standard deviation ($n = 63$), $0.31 \mu\text{g}/\text{m}^3 \pm 0.34 \mu\text{g}/\text{m}^3$ and $36.21 \pm 26.05 \text{ ng}/\text{m}^3$. The data were evaluated by cat allergen and bacterial endotoxin for each of the four treatment scenarios. Levene's statistic for homogeneity of variance indicated unequal variance for both the cat allergen and endotoxin for the four flooring conditions ($p < 0.001$ and 0.026 , respectively) but the large sample size and nearly equal cell number, for each independent variable, gave us confidence that the ANOVA could be interpreted conservatively without use of a nonparametric test.^[37] A one-way ANOVA was conducted to compare the effect of flooring condition on resuspended cat allergen or endotoxin concentration. There was a significant effect of flooring condition on resuspension of cat allergen [$F(3, 59) = 10.42, p < 0.001$]. An examination of Figure 2a indicates that this difference is due to the effect of the LLNE. There was also a significant effect of flooring condition on resuspension of endotoxin [$F(3, 59) = 10, 17.25, p < 0.001$]. By examination

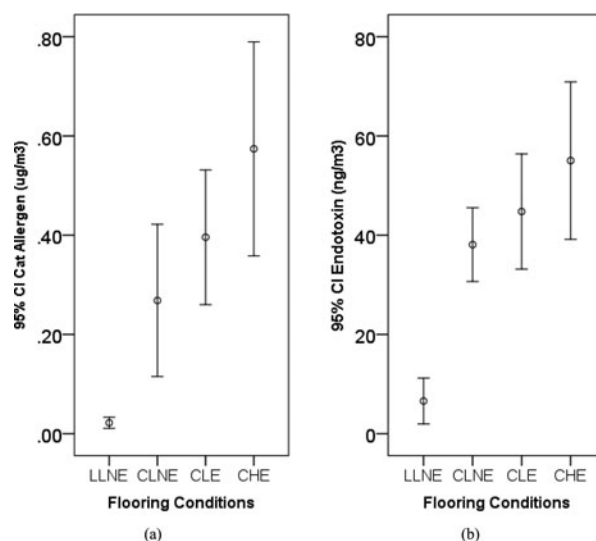


Figure 2. Cat allergen (a) and endotoxin air concentration (b) by flooring conditions.

of Figure 2b; this difference can also be attributed to the LLNE.

Although the mean cat allergen and endotoxin for the carpet embedded scenarios, CLE and CHE, were greater than the non-embedded scenarios, LLNE and CLNE, these were not significant. This can be observed by examining the 95% confidence intervals in Figure 2 that overlap.

To evaluate the effect of carpeted flooring only on allergen and endotoxin concentrations the LLNE was removed from the data set. Levene's statistic indicated homogeneity of variance (cat allergen $p = 0.291$, endotoxin, $p = 0.410$) prior to running the one-way ANOVA. The cat allergen

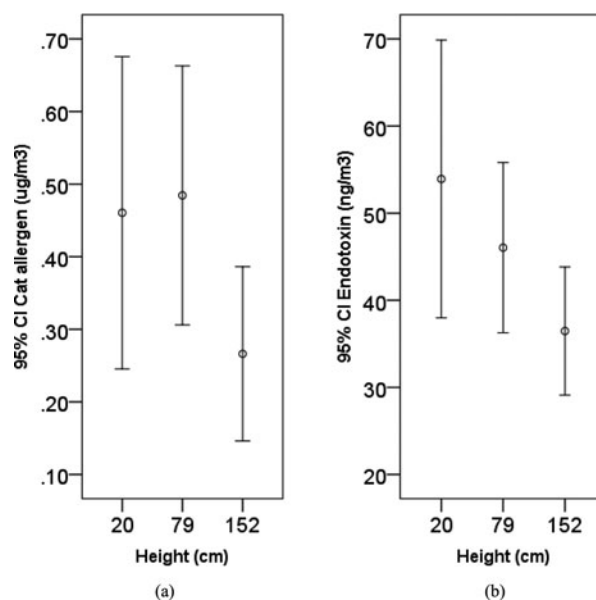


Figure 3. Height of sampler vs. cat allergen concentration (a) and endotoxin (b), LLNE, removed.

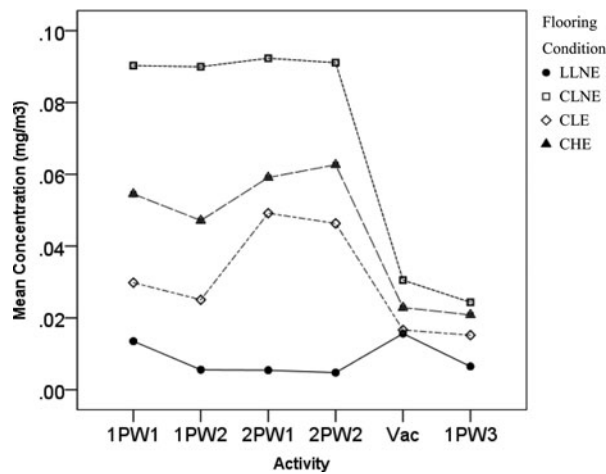


Figure 4. Concentrations of 2.5 µm dust during resuspension activities.

ANOVA without LLNE was not significant, [$F(2,47) = 2.11$, $p = 0.133$]; the endotoxin ANOVA was also not significant, [$F(2,47) = 2.57$, $p = 0.087$]. Post hoc differences (Tukey's LSD, $\alpha = 0.05$), however, were found for cat allergen and endotoxin between the carpet-high loading embedded (CHE) and the carpet-low loading not embedded (CLNE), mean and standard error: cat allergen, $0.305 \pm 0.111 \mu\text{g}/\text{m}^3$, $p = 0.009$; endotoxin, $16.93 \pm 7.62 \mu\text{g}/\text{m}^3$, $p = 0.031$.

Levene's statistic did not support the hypothesis of unequal variance for cat allergen and endotoxin measured, without the LLNE, at the three height locations ($p = 0.085$ and 0.055 , respectively). The Welch and Forsyth test for robustness of means (Table 1) were evaluated and there were differences among the means but not at $P < 0.05$. This was particularly the case with endotoxin.

Figure 3 illustrates the differences in means although overlapping confidence intervals exist. Mean differences of cat allergen or endotoxin concentration at the three heights were evaluated after the LLNE was removed from the data. There was one significant difference (Tukey's LSD, $\alpha = 0.05$), endotoxin, ($P = 0.027$) between mean concentrations at 152 and 20 cm; mean difference = $-17.45 \mu\text{g}/\text{m}^3$ and standard error = $7.57 \mu\text{g}/\text{m}^3$. The endotoxin data had a linear downward trend by height: [$F(1,45) = 5.15$, $p = 0.028$].

The APS mass concentration data ranged from 8.6 ± 1.2 (LLNE, 2.5 µm) to 148.2 ± 114 (CHE, 10 µm) mg/m^3

Table 1. Robust Tests of Equality of Means.

		Statistic ^a	df1	df2	Sig.
Cat allergen ($\mu\text{g}/\text{m}^3$)	Welch	2.914	2	28.204	.071
	Brown-Forsythe	2.110	2	38.194	.135
Endotoxin (ng/m^3)	Welch	2.861	2	27.942	.074
	Brown-Forsythe	2.576	2	31.918	.092

^aAsymptotically F distributed.

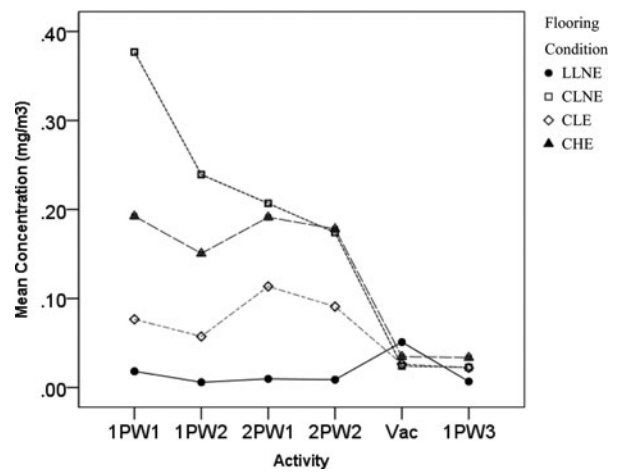


Figure 5. Concentrations of 5.0 µm dust during resuspension activities.

and the grand mean and sd. for these 360 composite measurements was $74.6 \pm 90.8 \text{ mg}/\text{m}^3$. The flooring treatment with the lowest mass concentration was LLNE at $12.6 \pm 32.6 \text{ mg}/\text{m}^3$ and the highest was CLNE at $127.5 \pm 118.1 \text{ mg}/\text{m}^3$. The activity with the lowest mass concentration was one-person walking III (after vacuuming step) at $17.5 \pm 16.4 \text{ mg}/\text{m}^3$ and the highest was one-person walking I at $127 \pm 131.7 \text{ mg}/\text{m}^3$. At aerodynamic cut-points, 2.5 and 5 µm, the highest mass concentrations were a result of two-person walking I, respectively, 51.5 ± 39.3 , $130.3 \pm 97.6 \text{ mg}/\text{m}^3$, however, the highest mass concentration at 10 µm resulted from one-person walking I, $168 \pm 143.5 \text{ mg}/\text{m}^3$. An ANOVA was conducted to evaluate the effects of flooring, particle size, activity, and interactions of these factors, assuming unequal variance in factor levels (since cell sizes were equal and samples numbers large), on mean mass concentration.^[37] The following effects were found to be significant on the mass concentration: flooring-condition, [$F(3, 288) = 145$, $p < 0.001$]; particle size, [$F(2, 288) = 69$, $p < 0.001$]; activity, [$F(5, 288)$, $p < 0.001$]; interaction of flooring-condition and particle size, [$F(6, 288) = , p < 0.001$]; interaction of flooring-condition and activity, [$F(15, 288) = p < 0.001$]; interaction of particle size and activity, [$F(10, 288) = p < 0.001$]; and interaction of flooring-condition, particle size, and activity [$F(30, 288) = p < 0.001$]. The model demonstrated an adjusted r-square of 0.79.

Several interactions occurred within all three particle cut points. The most pronounced interactions were at cut sizes 5 and 10 µm (Figure 5 and 6, respectively) during and after the vacuuming activity. At these particle cut points, the LLNE (which had a much lower mass mean concentration than the other flooring conditions), exceeded mass concentrations of the other three conditions during the vacuum activity, and then declined during the sixth and final activity, one-person walking III.

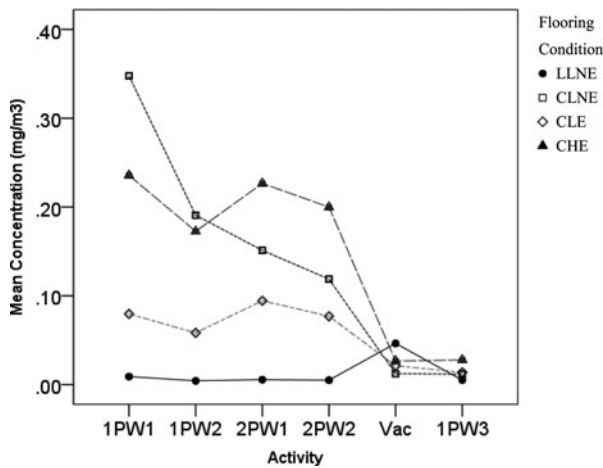


Figure 6. Concentrations of 10 µm dust during resuspension activities.

However, this same trend was not demonstrated with particles 2.5 µm (Figure 4). At this particle cut point, the mean mass concentration for LLNE remained below other flooring conditions throughout all activities, with the exception of the vacuuming activity. An additional interaction occurred with 10 µm particles. CHE was lower than CLNE during the first two activities, one-person walking I, II, then exceeded CLNE during two-person walking I, II. At 5 µm, CHE crossed with CLNE at one point, during the two-person walking II.

The resuspension rate data ranged from 1.2×10^{-5} to $7.3 \times 10^{-3} \text{ hr}^{-1}$ and the grand mean and sd. for these 72 composite measurements was $6.0 \times 10^{-4} \pm 1.1 \times 10^{-3} \text{ hr}^{-1}$. The flooring condition with the lowest resuspension rate was LLNE at $9.2 \times 10^{-5} \pm 1.4 \times 10^{-4} \text{ hr}^{-1}$ and the highest was CLNE at $1.4 \times 10^{-3} \pm 1.9 \times 10^{-3} \text{ hr}^{-1}$. The activity with the lowest resuspension rate was one-person walking III (after vacuuming step) at $6.9 \times 10^{-5} \pm 4.8 \times 10^{-5} \text{ hr}^{-1}$ and the highest was one-person walking I at $1.3 \times 10^{-3} \pm 2.1 \times 10^{-3} \text{ hr}^{-1}$.

The greatest variation in resuspension rate (Table 2) was with the CLNE condition and it was 13x the standard deviation of the LLNE. The means and standard deviation of resuspension rates for the CLE and CHE were practically equivalent.

Table 2. Resuspension mean and standard deviation rates (R)* by flooring condition.

R (mean), hr^{-1}	R (SD), hr^{-1}	Flooring condition
9.18E-05	1.46E-04	LLNE
1.44E-03	1.88E-03	CLNE
4.79E-04	4.36E-04	CLE
4.28E-04	4.93E-04	CHE

N = 72

* = (R represents particles 2.5, 5, and 10 µm for each flooring condition)

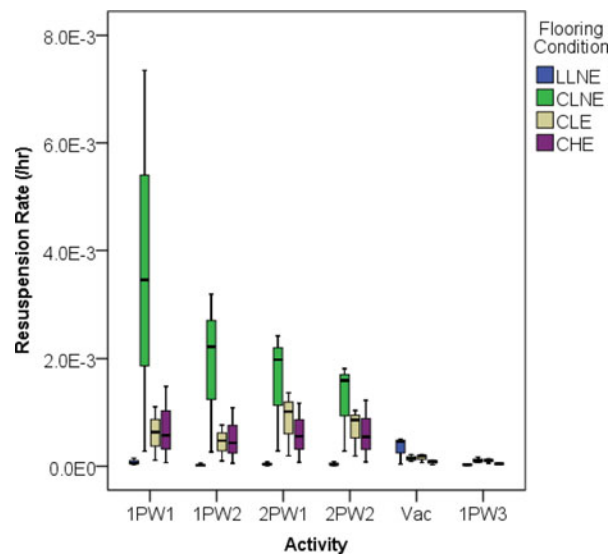


Figure 7. Resuspension rate boxplots of activity and flooring condition.

Figure 7 illustrates the small variation in resuspension rates across all activities, with the exception of the carpet, low loading, not embedded. Resuspension rates were highly correlated to resuspension fraction, Pearson correlation, $r^2 = 0.971$, $p = 0.01$. Resuspension fractions were an order of magnitude smaller for 2.5 µm ($n = 24$, $1.72 \times 10^{-5} \pm 1.58 \times 10^{-6}$) then for 5 µm ($1.17 \times 10^{-4} \pm 1.72 \times 10^{-4}$) and 10 µm ($1.92 \times 10^{-4} \pm 3.43 \times 10^{-4}$) particles. This follows both theory and empirical studies that predict larger particles within this range will more easily detach and resuspend.^[17] An examination of resuspension fractions, (Figure 8) across all particle sizes and

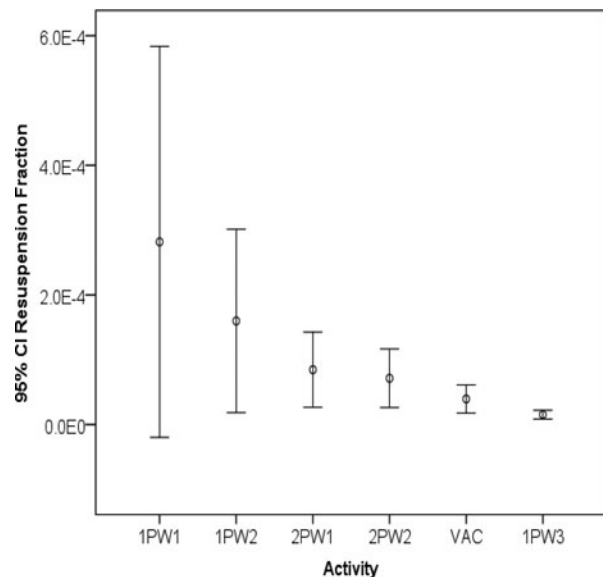


Figure 8. Resuspension fractions by activities, mean, and 95% confidence intervals. ** = Resuspension fractions are not negative numbers but development of a 95% confidence interval for 1PW1 yields this result in the statistical model.

Table 3. Resuspension fraction mean and standard deviation rates (R)* by flooring condition.

R (mean), hr ⁻¹	R (SD), hr ⁻¹	Flooring Condition
1.88E-05	3.27E-05	LLNE
2.67E-04	4.12E-04	CLNE
7.73E-05	6.73E-05	CLE
7.23E-05	9.12E-05	CHE

N = 72

* = (R represents particles 2.5, 5, and 10 μm for each flooring condition)

floor/loading conditions (Table 3) indicate that the medians of one person and two persons walking are nearly the same, the exception being the one-person walking III, which is much lower than all the previous activities; one-person I, one-person II, two-person I, and two-person II.

Discussion

One of the primary purposes of this study was to determine the effects of surface conditions on resuspension of allergens and fine particles. The intent of this work was also to examine whether resuspended allergens would be found in different quantities at heights suggestive of infants, toddlers, and adults. Our results indicated that the surface conditions were a significant factor in resuspension of dust, cat allergen, and endotoxin. We found that this was significant for LLNE but not for the other conditions. The highest mean value concentrations for both cat allergen and endotoxin was the CHE. Although this was not significantly greater than the other two carpet conditions it suggests that the higher loading could release more allergens than lower loading carpet conditions. Embedding can affect allergen concentration in carpets but unless the embedding provides a bias toward the bottom of the carpet, much of this allergen can be available for resuspension.^[10,11]

The variance in the results, observed in the overlapping confidence limits among conditions and heights, suggests that our methods were not sensitive enough to find differences where some may have existed, using a gravimetric approach and using house dust containing cat allergen and endotoxin. The variance of the cat allergen and endotoxin in the bulk dust was probably responsible for the large error bars observed in the results. Although there was significant correlation between our dust, cat allergen, and endotoxin measurements, it was likely not a sufficient correlation and inherent variation in the allergen content of the bulk house dust made finding significant results a challenge.

To reduce some of the “noise” in the cat allergen and endotoxin data, the LLNE condition was removed from

the data set. After the LLNE was removed, there were significant differences between the CHE and CLNE for both mean cat allergen ($p = 0.009$) and endotoxin concentrations ($p = 0.031$), respectively. However, there was no significant difference between the carpet embedded at low (CLE) or high loading (CHE) for either cat allergen or endotoxin. This may suggest that this experiment was sensitive to resuspension with different loading conditions but the embedding did not have a significant effect. Height does have an effect on measured cat allergen and endotoxin over carpet but not a significant one ($p = 0.071$ and 0.074 , respectively) and this is apparent with the height at the infant and adult samplers (20 and 152 cm). Buttner found a non-significant trend ($p = 0.076$) for height when measuring *P. Chrysogenum* resuspended over carpet.^[6] The results from our cat allergen data mirror their results where the middle height, between the floor and an adult height, had the highest concentration. However, the results from our endotoxin measurements suggest concentration is inversely related to ceiling height. Other investigators found relatively uniform vertical distribution of particles or allergens under similar conditions as ours while investigating resuspension.^[6] Rosati found no gradient in sampling resuspended particles indoors when a ceiling fan pulling air upward was operating but when not operating found a gradient inversely related to ceiling height and corresponding to particle diameter.^[11] Clearly, the data from the endotoxin (without LLNE) demonstrates a linear trend from lowest to highest height. This linear trend is likely due to the particle aerodynamic diameter and other settling properties of particles containing the endotoxin. Our results, however, need to be understood as representative of a relatively still room. The particle concentration indoors, as determined at a specific height, after detachment from the floor surface, will also be influenced by the presence of walkers’ thermal plumes and the additive effect of the walkers’ air wake on the concentration gradient.^[5] The averaging time of the large volume sampler will also have an effect on the particle concentration reported since a large averaging time would tend to smooth the variation in the results and steer the data toward no gradient effect.

Data from the APS resulted in three-way interactions at all three particle cut sizes. At 2.5 μm , particle mass for the LLNE interacts during vacuuming with the other low-loading condition CLNE, suggesting that vacuum cleaning a moderately dusty laminate floor will result in the same resuspension as vacuum cleaning a moderately dusty carpet. There is additional evidence for this when examining the same interaction of laminate flooring and vacuuming at larger particle sizes, except, at larger particle

sizes (5, 10 μm) vacuum cleaning a laminate floor results in *slightly* more resuspended dust mass than that of any carpet condition studied. At 5 μm , during the second two-person walking activity, carpet that is highly soiled (high loading) but embedded yields the same resuspended mass as a carpet with moderate soiling (low loading) that is not embedded. This may indicate that after successive walking over time, resuspended particles from carpets that have been moderately trafficked with heavy soiling may not differ from newer carpets, with less soiling. At 10 μm , this same pattern is repeated but the similarity emerges at the first person, walking II, with an increase over the less soiled, non-embedded carpet until the vacuuming cleaning activity is reached. The easily resuspended 10 μm particle, reaches its zenith during the two-person walking activities, and as expected exceeds the 2.5 and 5 μm particle resuspended mass when there are sufficient steps taken within the confines of a highly soiled and trafficked carpet.

Resuspension rates (1/hr) were calculated across floor/loading conditions and activities. Although the mean resuspension rates were highest among the carpet with low loading, not-embedded, there were no significant differences among flooring, even when the LLNE is considered. Like Qian's results for particles in the size range 2.0–10 μm , the resuspension rate for the hard surfaces in our study were much less than that of equally loaded carpeted surfaces. Our CLE condition is similar to Qian's new carpet-seeded condition, since both methods embedded dust using a similar method.^[10] Qian's studies resulted, however, in a much higher resuspension rate for similar carpet conditions, seeded new carpet: with resuspension rates (hr^{-1}) ranging from (2.0–5.0 μm) $1.0 \pm 1.0 \times 10^{-2}$ to $4.0 \pm 3.8 \times 10^{-3} \text{ hr}^{-1}$.^[10]

The differences in resuspension rates for similar carpet conditions could be due to a number of factors, including our use of sieved house dust, <300 μm , in our experiments and Qian's use of A1 ultrafine test dust (ATD).^[10] Additional reasons for these differences could be a much higher loading level of dust in carpet than ours (our use of 3 g/m^2 to Qian's 9.8 g/m^2 for 2.0–5.0 μm). Qian also used air exchange in their study, likely decreasing resuspended concentrations of dust compared to our work that recirculate but did not exchange air.^[10]

The resuspension rate for our CLE treatment is in range with resuspension rates of Shaughnessy's study of real carpeting in schools at three different loading rates, many times greater than the loading rate we used $2.76 \pm 0.69 \times 10^{-3}$ to $7.25 \pm 1.98 \times 10^{-3} \text{ hr}^{-1}$.^[15] As pointed out earlier, this may imply that what is available at the surface of the carpet is more important to resuspension and therefore provide more risk to occupants than what is much deeper in the carpet.

Most of the variation in resuspension rates across floor/loading conditions is small, with the exception of the CLNE (carpet, low loading, not embedded treatment). The larger variation in resuspension rates in this floor/loading condition is likely due to the surface borne dust that is resting on top of carpet and is more available for resuspension than the more trafficked, or embedded carpets. Moreover, as some investigators have pointed out, the "spring action" of the carpet in this situation is likely to exceed resuspension rates than other surfaces, particularly that of the laminate surface with the same loading.^[6,11]

The rates for the final walking activity have essentially equivalent resuspension rates, across all surface types, after the vacuum cleaning step. This suggests that cleaning can equally mitigate resuspension across several flooring conditions. The mean and UCLs (upper confidence limits) of the resuspension rates gradually decline prior to the dramatic decline during the vacuuming activity. This decline was observed in another study and is likely due to a decrease in number of particles available as the particles become embedded through a number of adhesion forces or a harvesting effect of the carpet.^[4] Shaughnessy et al. demonstrated that new carpet in chamber studies did not show a decreasing trend over time, however, they did demonstrate that old carpet in schools shows a decreasing amount of resuspension over time, consistent with our findings.^[15]

The agreement between resuspension among one-person and two-person activities agrees with Karlsson's model and observations about normalizing resuspension by step rate.^[36] The resuspension rate and fraction for one-person walking III, is likely driven by the removal of source and ambient dust during the vacuuming cleaning activity. The vacuum cleaning step results in a resuspension fraction, among all particle sizes and flooring conditions, of 3.9×10^{-5} . The vacuum cleaning condition in our study, unlike other studies, reduces rather than increases resuspension.^[6,8] This may be due to the different nature of vacuum cleaning devices used in these studies. The cleaner used in our study was apparently not only cleaning the surface but likely cleaning the air as well while it was used. Buttner et al., in a study of fungal spore dispersal from three types of flooring materials (vinyl, cut pile, and loop carpet), determined that vacuum cleaning did not have any greater release of spores in the air than after simple walking.^[6]

The greatest mean and standard variation for resuspension fraction were the carpet-low loaded, not embedded condition (CLNE, one-person I, $8.12 \times 10^{-4} \pm 7.83 \times 10^{-4}$). However, this value diminishes by about 50% from one-person walking I to one-person walking II, suggesting that carpet that is minimally trafficked (embedded)

may serve to make the dust less available for resuspension than new carpets that have not been trafficked.

Tian et al.'s work demonstrated a slight decrease in resuspension fraction with increased loading while our study resulted in essentially an equivalent result, CLE, $7.73 \pm 6.73 \times 10^{-5}$ and CHE, $7.23 \pm 9.12 \times 10^{-5}$.^[14] The difference between our results and that of Tian et al. may be due to the embedding process of the sample dust, where we dragged a weight across a carpet 4x and Tian et al.'s approach was to drag the weight 30x; thus they may have had slightly more particles at lower strata in a carpet than our method.^[14] Causer et al. found no significant difference in allergen distribution in a carpet when the roller was dragged 4x rather than 30x. However, the 30x approach did have a greater bias toward the bottom of the carpet.^[32,38]

The results of our studies are clearly affected by flooring conditions but we used only one type of carpet in this study. The surface dynamics of carpet and other flooring are complex and will influence particle resuspension. Lewis and Chen, Qian et al., Tian et al., and others have reviewed the work that has been done to study the effects of different carpeting structures on retention, release, and resuspension of particles.^[5,14,39] Comparing retention results across studies require care due to a multiplicity of carpet specifications that are used in these studies. We chose to use one type of carpet in this study in order to reduce the number of variables tested and to increase the power to find statistical differences if they existed. The LEED standards for green buildings, to our knowledge, do not address selection of flooring based on resuspension of particles indoors. Our study combined with many others cited here appear to be sufficient for warranting new standards and policies for use of selection of flooring and cleaning.^[5] This may affect both the comfort and health of occupants from resuspended allergens and other harmful particles on/in flooring.

Conclusions

Allergen and endotoxin concentrations may be dependent on dust loading and height over carpet

A floor treatment, such as a laminate surface, undergoes significantly less resuspension of cat allergens and endotoxin than equally loaded carpeted surfaces. Carpets with lower dust loading resuspend significantly less cat allergen and endotoxin than higher dust loadings.

Resuspended endotoxin concentration is inversely related to height over a carpet. Although this same relationship is not as straightforward for cat allergen, where a middle height (79 cm) has greater resuspension than

that of the lower height (20 cm), there still is a gradient between the lowest and highest height.

Vacuum cleaning may dramatically reduce small and large particles

Vacuum cleaning in our studies has a significant effect on reducing resuspension of small and larger particles, 2.5–10 µm particles.^[3,8]

Laminates may not always be superior to carpets

Vacuum cleaning a moderately dusty floor may result in the same resuspension as vacuum cleaning a moderately dusty carpet. At larger particle sizes (5, 10 µm), the LLNE (lamine-flooring condition) resuspends slightly more dust while vacuuming than any carpet-loading condition tested.

Carpets over time may have less available dust after foot traffic

Successive walking over time, on carpets that have been moderately trafficked with heavy soiling, may pose no differences in resuspension than newer carpets, with less soiling. This decline was observed in another study and is likely due to a decrease in number of particles available as the particles become embedded through a number of adhesion forces or a harvesting effect of the carpet.^[10]

Recommendations

We recommend that consensus organizations in indoor health and buildings develop policies governing the selection of flooring and cleaning based on the collective literature of resuspended particles.

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SUPPLEMENTAL MATERIALS

Resuspension of house dust and allergens during walking and vacuum cleaning

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Contents:

- Calculation for resuspension rate
- Dust deposition studies in the chambers
- Carpet selected for study
- Supplemental section references

Calculation for resuspension rate

Resuspension (based on Thatcher and Layton, main text, reference 2)

Equation 1

$$R = \frac{C_{in}(A_d v_d + \lambda_v V) - C_o \lambda_v V}{L_{fl} A_{fl}}$$

Where:

- R = Resuspension rate (h^{-1})
- C_{in} = Particle concentration indoors (mg m^{-3})
- A_d = Interior total deposition surface area (m^2)
- v_d = Deposition velocity (m h^{-1});
- λ_v = Air exchange rate (h^{-1})
- V = Volume (m^3)
- C_o = Particle concentration outdoors (mg m^{-3})
- L_{fl} = Mass loading of particulate on floor (mg m^{-2})
- A_{fl} = floor surface area (m^2)

The outdoor particle penetration expression in the numerator of Equation 1, $C_o \lambda_v V$, was assumed to be zero since no outdoor air was let into the chamber and similarly, the volumetric dilution expression from equation 1 in the numerator, $\lambda_v V$, was also assumed to be 0, since all the air was recirculated in each of two chambers. There was no deposition materials outside of the floor that was assumed to be acting on

resuspension, and the term Ad , from equation 1, was cancelled out from the expression in the numerator with the same term in the denominator from deposition velocity, vd . The mean and standard deviation for each resuspension activity, at each particle-cutpoint, Cin , was previously described. Deposition velocity, vd , was based on the slope of the decay curve between the concentration at 10 minutes (C_1) and that at 70 minutes (C_2). The area of the floor carpeting or laminate (Afl) and the mass loading of the floor ($Lf1$) were previously described. After term cancellations, the final calculation that was used to calculate resuspension rate is found in Equation 2.

Final simplified formula used for resuspension rate

Equation 2

$$R = \frac{Cin(vd)}{Lf1(Af1)}$$

- R = Resuspension rate (h^{-1})
- Ad = Interior total deposition surface area, (m^2)
- V = Volume of chamber, (m^3)
- vd = Deposition velocity, ($m \cdot h^{-1}$)
- $vd = \lambda_d V / Ad$
- λ_d = Deposition loss rate, (h^{-1})
- $\lambda_d = (1/t) \ln (C_1)/(C_2)$
- C_1 = concentration of suspended particles at 10 minutes (mg/m³)
- C_2 = concentration of suspended particles at 70 minutes (mg/m³)
- t = time between C_1 and C_2 , (h)
- $Lf1$ = mass loading of particulate on floor, (mg.m²)
- Afl = floor surface area, (m^2)
- Cin = Mean concentration indoors during resuspension activity

Methods, Results, Discussion, and Tables on Dust Deposition Studies in the Chambers

An ante-chamber was used to minimize the mixing with outside air when technicians entered and left the chamber between activities. The conditions in the chambers were kept at $23 \pm 0.9^{\circ}\text{C}$ and 48 ± 5 RH. ~~Sieved-H~~house dust (~~< 300 μm~~), was collected from various home cleaning companies in St. Louis, sieved at < 300 μm , then treated with 1% Cab-O-Sil[®] fumed silica and desiccated until used. The dust was ~~were~~ blown into each chamber using compressed air with an ultrasonic nozzle (70 psi) toward the center of the ceiling. After dust was introduced, the compressor was shut off and a propeller fan was turned on in the chamber to mix the dust for 1 minute. The dust was then allowed to settle overnight prior to activities produced to resuspend dust in the chambers.

To determine the dust loading and the distribution of dust in the chamber prior to each day's tasks, four petri dishes containing 47 mm (diameter) Whatman filters were distributed along the center of each side of the chamber, where the heaviest amount of dust was expected to settle. These filters were preweighed and postweighed each morning after overnight settling of particulate. The filters were then eluted for cat allergen or endotoxin by the laboratory together to obtain composite sample measures (Table 1). ~~Pearson and Kendall's Tau-B correlations were established between airborne dust mass and cat allergen and endotoxin to determine if the allergen and endotoxin resuspend similarly to bulk house dust.~~

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Table 1. Concentrations of allergen in settled dust (* composite samples of 4 filters each)

	<u>Cat allergen (low load)</u>	<u>Cat allergen (high load)</u>	<u>Endotoxin</u>	<u>Endotoxin</u>
	<u>ng/g</u>	<u>ng/g</u>	<u>(low load)</u>	<u>(high load)</u>
			<u>µg/g</u>	<u>µg/g</u>
<u>N *</u>	<u>16</u>	<u>4</u>	<u>16</u>	<u>4</u>
<u>Mean</u>	<u>69</u>	<u>80</u>	<u>1.5 x 10⁻⁵</u>	<u>2.1 x 10⁻⁵</u>
<u>SD</u>	<u>42</u>	<u>13</u>	<u>5.3 x 10⁻⁶</u>	<u>4.2 x 10⁻⁶</u>
<u>CV</u>	<u>61%</u>	<u>16%</u>	<u>35%</u>	<u>20%</u>

Tabella formattata

Results from settling plates that were distributed in the chamber for the purpose of determining dust loading and distribution of dust on the floor found, low loading (n = 20) and high loading (n = 60) respectively, had a mean, standard deviation, and upper and low confidence limits of 0.765 ± 0.275 , 95%CI [0.696, 0.834] and 3.21 ± 1.62 , 95% CI [2.49,3.92] g/m². Dust mass (g) found on the large volume sampler-filters were compared to concentrations of cat (ng/g) and endotoxin on these same filters (EU/g, 1 ng = 9 EU). Correlations were obtained using parametric (Pearsons, Table 2) and non-parametric tests (Kendall's Tau, Table 3) and were significant at $p < 0.01$ for both tests. This suggested that the sieved bulk dust was resuspended similarly to cat allergen and endotoxin.

It was necessary to provide reproducible levels of dust loading in the chambers for all resuspension activities and the results confirmed our predetermined targets for low loading, ~ 1 g/m², and high loading, ~ 3 g/m², conditions. Also significant correlations were found between airborne mass concentrations of the endotoxin and cat allergen with the sieved house dust, suggesting that uniform and reproducible dust deposition provided a proportional measure of cat allergen and endotoxin in the chambers.

Correlations between dust and resuspended cat allergen and endotoxin

Table 21. Pearson Correlations between airborne dust mass and cat allergen and endotoxin
(n= 63)

	Cat allergen (ng/g)	Endotoxin (EU/g)	Dust mass (g)
Cat allergen (ng/g) correlation	1	0.714**	0.415**
Sig.(2-tailed)		<0.001	0.001
Endotoxin (EU/g) correlation	0.714**	1	0.395**
Sig.(2-tailed)	<0.001		0.001
Dust mass correlation	0.415**	0.395**	1
Sig.(2-tailed)	0.001	0.001	

** = Correlation is significant at the (0.01) level (2 tailed).

Table 32. Kendall's Tau B (Non-Parametric) Correlations between airborne dust mass and cat allergen and endotoxin (n= 63)

	Cat allergen (ng/g)	Endotoxin (EU/g)	Dust mass (g)
Cat allergen (ng/g) correlation	1	0.463**	0.261**
Sig.(2-tailed)		<0.001	0.003
Endotoxin (EU/g) correlation	0.463**	1	0.253**
Sig.(2-tailed)	<0.001		0.004
Dust mass correlation	0.261**	0.253**	1
Sig.(2-tailed)	0.003	0.004	

** = Correlation is significant at the (0.01) level (2 tailed).

Carpets selected for study

———— A rigorous description of how carpet properties affect retention and release of cat allergen indoors has been described. ⁽¹⁾ The face weight of a carpet in residential carpet is one of several characteristic's that impact retention and release of dust and allergens in homes. The face weight is considered in a formula for pile density which is key for selection of carpeting. ⁽²⁾ The face weight that was chosen in this study was selected in part to be in a moderate to heavily trafficked area such as a bedroom or living area in public housing. The range of face weights for this kind of application in HUD housing is 20 – 30 ounces/yd². We used a carpet that had a face weight of 28 ounces/yd².

Formattato: Tipo di carattere:
Grassetto

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