

Effect of Floorcovering Construction on Content and Vertical Distribution of House Dust Mite Allergen, Der p I

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Domestic floorcoverings often contain appreciable quantities of particulate pollutants, such as house dust mite allergen, Der p I. Exposure to Der p I is a risk factor for the development of mite sensitization and asthma. We investigated whether carpet construction was related to the Der p I content in normal use, and its vertical distribution. We hoped to inform development of methods to remove such material. Along with one hard flooring surface, a range of carpets with differing pile conformations (loop vs. cut), pile heights, yarn twists, and pile densities were placed in houses for 13 months. The carpets were later sectioned to allow profiling of Der p I throughout the pile strata using monoclonal antibody, enzyme-linked immunosorbent assay. Not surprisingly, significantly lower amounts of Der p I were found on hard flooring than any of the carpets, which all contained similar amounts of mite allergen. For all carpets, the Der p I concentration per unit area was found to be inversely related to the distance from the carpet backing. We conclude that carpet construction is not a good predictor of Der p I content in the home. We also suggest that, as carpet construction likely influences ease of disturbance of material within the pile, methods to remove or denature particulate pollutants such as Der p I will be most effective if they are able to target the bulk of allergenic material, found toward the base of the pile.

Keywords allergens, aeroallergens, carpets, Der p I, ELISA, house dust mites

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House dust mites are recognized as the major source of allergenic material to which individuals are exposed in the home,^(1,2) exposure being a risk factor for mite sensitization and asthma.^(2–4) Thus, minimization of reservoir allergen levels has become a cornerstone of many asthma avoidance regimes. Many studies have reported higher concentrations of house dust mite allergen, Der p I, in carpets than on hard flooring.^(5–12) However, to be inhaled and provoke an allergic response, mite allergen must first be disturbed from any floorcovering, the propensity for which will be dependent on a variety of factors. These

include the type of disturbance, environmental conditions, the level of contamination, and the nature of the floorcovering and where the allergen resides within it—the interplay among all of which is poorly understood. The same factors are also likely to influence the ease of cleaning of such materials. To better understand the influence of floorcovering construction on allergen accumulation and retention, we compared the Der p I content (after placement in the same domestic environment) of wool carpets differing in pile conformation, pile height, yarn twist, and pile density. We also examined where allergen lodged in the same carpets, so as to allow the targeting of such material during removal processes.

MATERIALS AND METHODS

Floorcoverings

Tufted carpet is usually produced by threading a pile yarn through a woven fabric (the primary backing) and locking it in place with the application of a styrene butadiene filled-latex to the back of the carpet. Invariably, a layer of woven fabric (the secondary backing) made of synthetic fibers or jute is bonded under this to improve dimensional stability. All carpets in this study were constructed in such a manner, on an 1/8th gauge tufter, with specifications chosen to represent both “typical” constructions and those with extremes of pile height and density. The 2-ply yarns used were 100% wool and all had a linear density of 600 g/1000 m. Six carpets were made with yarn of “medium” twist, having 150 turns per meter (TPM) singles twist and 130 TPM folding twist, whereas one other carpet was made with a “high twist” yarn of 180 TPM singles twist and 300 TPM of folding twist. Folding (or plying) is the process by which two singles yarns are twisted around each other to form a twist-balanced 2-ply structure. A hard flooring surface, linoleum, was also included in the study for a total of eight floorcoverings investigated (Table I).

Whereas synthetic carpets predominate in many parts of the world, wool and wool-blend carpets are the most common construction found in Australia and New Zealand, so it was these we concentrated on.

TABLE I. Floorcoverings Tested

Sample	Pile Conformation	Nominal Pile Height (mm)	Yarn Twist	Stitch Density (stitches/m)
1	Loop	6.5	Medium	350
2	Cut	6.5	Medium	350
3	Loop	9	Medium	350
4	Cut	9	Medium	350
5 ^A	Cut	6.5	Medium	250
6 ^A	Cut	9	Medium	450
7	Cut	9	High	350
8	Linoleum (vinyl)	n/a	n/a	n/a

^ADenotes carpet construction that might be considered atypical.

Field Study and Der p I Measurement

The pile height of each carpet was measured (10 replicates each) using a pile height gauge (WRONZ Developments Ltd., Christchurch, New Zealand) that exerted a foot pressure of 20 g/cm². Four squares (250 mm × 250 mm) of each carpet were latexed to the same piece of jute secondary backing (that also incorporated cutouts for the linoleum samples) in a grouped random plot design (Figure 1). Six houses in Christchurch, New Zealand, were then selected from a pool of those known to contain appreciable populations of the European house dust mite, *Dermatophagoides pteronyssinus*. In one bedroom of each house, a section of carpet adjacent to the bed was cut out and replaced with the composite test sample. In all cases the existing underlay was left in place, except under the linoleum samples where it was replaced with a section of 7 mm thick particleboard to bring the surface up to approximately the same level as the carpet pile. Each participant in the trial was instructed to apply their usual dry vacuuming regime to the house (including the test site) over the following 13 months, after which time the samples were removed by first separating them using a scalpel, then carefully lifting each one and remeasuring the pile height.

After lifting, one replicate of each carpet type was randomly selected from each site (i.e., to give six replicates per carpet, each from a different house) and a set of electric animal grooming clippers (Oster 1506-01E, Oster Professional Products, McMinnville, Tenn.) used to trim consecutive planar sections of pile (2 mm thick) from a random subsample of each (150 mm × 50 mm). Because the carpet backing was of a known thickness (approximately 2.7 mm), the secondary backing was used as a datum point, and intervals for sectioning (0–3, 3–5, 5–7, 7–9 and >9 mm above the lowest point of the secondary backing) selected so that any excess composed only a small portion of the total pile. To perform the sectioning operation, each subsample was held at a 45° angle, pile side down, in a jig that ensured minimal disturbance or contamination of layers closer to the backing.

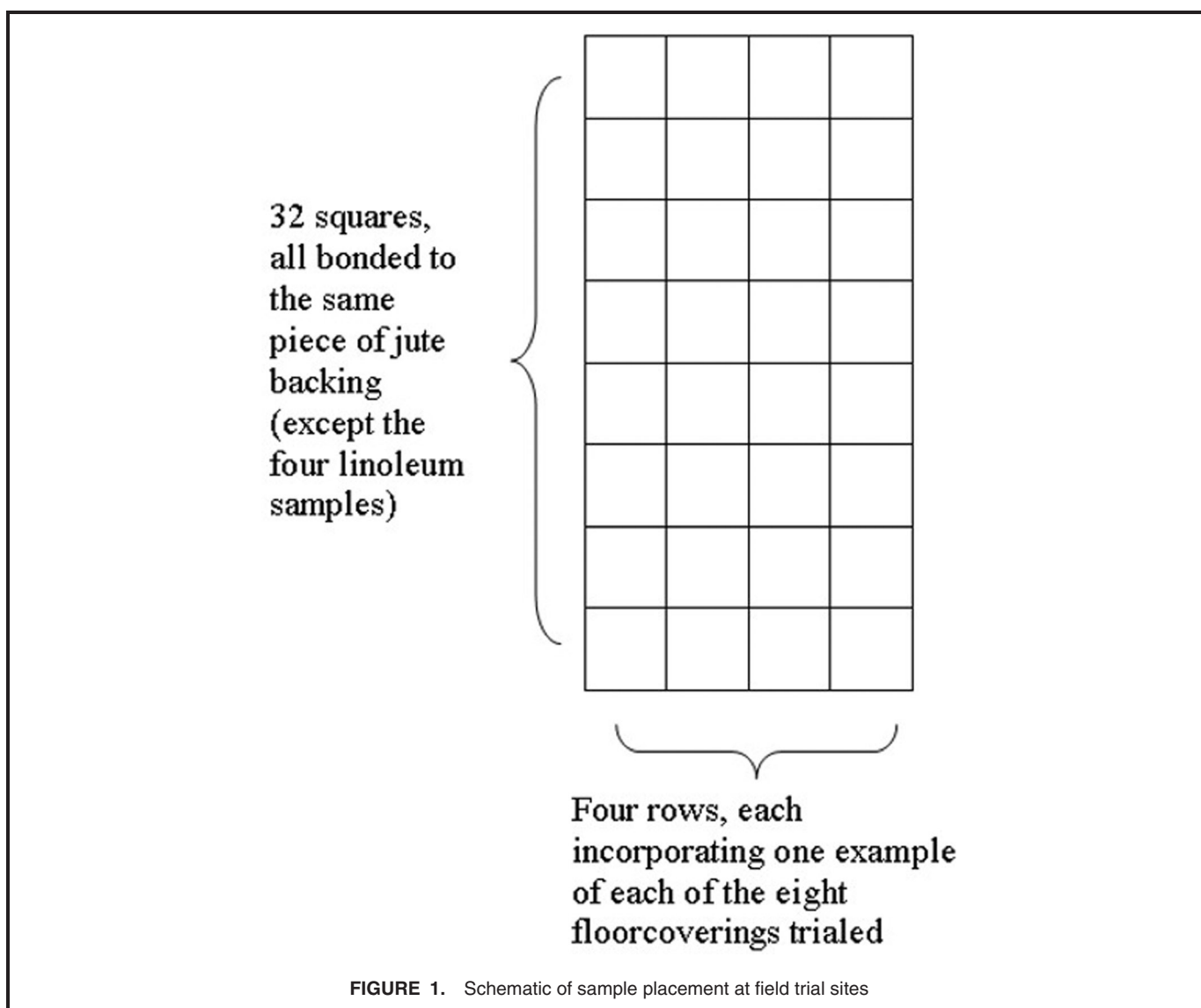
This technique was a modification of that described previously,⁽¹³⁾ with the fiber and dust obtained from two passes

of the clippers over the pile being collected and extracted in a known volume of phosphate buffered saline (between 1 and 15 mL, depending on the mass of sample to be extracted). The Der p I content of the resultant solution was then determined by double monoclonal antibody, enzyme-linked immunosorbent assay (ELISA)⁽¹⁴⁾ (ELISA kit; Indoor Biotechnologies Ltd., Cardiff, Wales). For extraction of dust samples, between batch coefficients of variation of the order of 10–20% are typical using this technique.^(15–17) To facilitate easier extraction, the 0–3 mm layer sample, which was composed of mainly latex and backing, was cut into smaller pieces (5 mm × 5 mm) using a razor blade. Two 1134 mm² cores (38 mm diameter disks) were then taken from each of the remaining replicates of carpet or linoleum and extracted in phosphate buffered saline (15 mL each), the extracts pooled, and the Der p I concentration per unit area determined.

Probability plots were used to confirm all data were normally distributed, after which they were analyzed using a Student's t test or, for Der p I distribution data, by multiple analyses of variance (ANOVAs) (i.e., a series of ANOVAs examining differences between levels within the same carpet construction, followed by a second series examining differences between carpets for a given level within the pile). Bonferroni's correction⁽¹⁸⁾ was applied in each case, and the least significant difference (LSD) also calculated. Statistical significance was set at the 0.05 level.

RESULTS

The seven carpet constructions started the trial with a nominal pile height of either 6.5 mm or 9 mm (range = 6.27–7.12 mm and 8.48–9.20 mm, respectively), but all experienced a significant ($p \leq 0.05$) reduction in pile height during 13 months of domestic use (Table II). At the end of this period, no significant difference ($p > 0.05$) was found between carpet types for the total Der p I content determined by extraction of cores (Table II). However, some differences were suggested if the values obtained by summation of the Der p I concentration (per area) of the individual layers are compared. In some cases,



the two methods of determining the total Der p I content showed good agreement; however, the overall correlation was poor ($r^2 = 0.13$). For all carpets, the allergen content was inversely related to the distance from the primary backing (Table III, Figure 2), and it was found that a regression of the form $y = 1/e^x$ resulted in a range of r^2 values from 0.86 to 0.98.

The Der p I content of the linoleum (mean = $15.1 \mu\text{g}/\text{m}^2$; range = $0\text{--}47.2 \mu\text{g}/\text{m}^2$) was found to be significantly lower ($p \leq 0.05$) than that in virtually all of the carpets (mean = $341.5 \mu\text{g}/\text{m}^2$; range = $33.5\text{--}1567.7 \mu\text{g}/\text{m}^2$). For the carpets, considerable variation existed in the Der p I concentration per unit area found at any given layer (within replicates of the same carpet), with the 95% confidence interval exceeding 50% of the mean in some cases (Figure 2). However, irrespective of carpet construction, significant differences ($p \leq 0.05$) were found between the Der p I concentration per unit area at the base of the carpet pile (highest amount) and that in all other layers (lower amounts) (Table III). No significant difference in the Der p I concentration per unit area was noted between carpets

for the 0–3 mm layer ($p > 0.05$), except for the 9-mm cut-pile carpet and the low pile density carpet, which were significantly higher ($p \leq 0.05$) (Table III). Similar variations existed within the 3–5 mm layer but were not consistent with those observed in the 0–3 mm layer. Though we recorded values (Table III), a statistical analysis was not performed for layers above 5 mm because the reduction in pile height that occurred after wear meant that the 5–7 mm, 7–9 mm, and >9 mm intervals did not always compose a full fiber sample (i.e., the pile height did not exceed the top of the interval).

When determining the allergen concentration per unit mass (as opposed to per unit area), the fact some samples composed an incomplete layer had an even greater impact. For example, in only two of the four worn 9-mm pile height carpets did any fiber protrude above the 9-mm level, enabling a sample to be taken and, in both cases, this constituted mainly surface fluff plus a small quantity of dust that fell out. Even though the amount involved was small, the presence of this dust resulted in the Der p I concentration per unit mass in this

TABLE II. Carpet Pile Heights and Allergen Contents

Carpet Type and Nominal Pile Height	Pile Height Before Trial (mm)		Pile Height After Trial (mm)		Pile Height Reduction (%)	Total Der p I ($\mu\text{g}/\text{m}^2$) ^A	
	Mean	SEM ^B	Mean	SEM ^B		From Core Samples	Sum of Layers
6.5 mm loop pile	6.27	0.02	4.86	0.05	22.5	237.6 ab	270.5 ab
6.5 mm cut pile	6.95	0.05	5.46	0.07	21.4	391.2 b	320.0 abc
9 mm loop pile	8.91	0.05	7.25	0.05	18.6	398.5 b	310.8 abc
9 mm cut pile	9.20	0.04	7.34	0.07	20.2	431.0 b	469.2 c
6.5 mm cut pile, low pile density	7.12	0.04	4.98	0.09	30.0	248.8 ab	425.6 bc
9 mm cut pile, high pile density	8.48	0.03	6.92	0.05	18.4	379.6 b	417.7 bc
9 mm cut pile, hard twist yarn	8.76	0.06	6.71	0.07	23.4	303.9 b	192.7 a
Linoleum	n/a	n/a	n/a	n/a	n/a	15.1 a	n/a
LSD (p ≤ 0.05) ^C	—	—	—	—	—	274.7	172.4
F ^D	—	—	—	—	—	7.6	2.4
p ^E	—	—	—	—	—	4.8 × 10 ^{−8}	0.03
df ^F	—	—	—	—	—	7, 184	6, 35

^A Comparing down a column, values followed by the same letter are not significantly different from each other ($p > 0.05$).

^B SEM = standard error of means.

^C LSD = least significant difference.

^D F = F-statistic.

^E p = probability.

^F df = degrees of freedom.

sample being significantly higher ($p \leq 0.05$) and having a greater variability (mean = 31.81, range = 7.91–67.16 ng/g) than that found at all other levels (mean = 0.72, range = 0.21–1.68 ng/g). In contrast, the Der p I concentration per unit mass

in the backing layer (0–3 mm) differed only slightly between carpets (mean = 0.41, range = 0.21–0.57 ng/g, $p = 0.04$), and no significant difference was found within any other layers of the pile (mean = 0.86, range = 0.41–1.68 ng/g, $p > 0.05$).

TABLE III. Concentration per unit Area of Der p I in Layers of Carpets of Different Construction

Carpet Type and Nominal Pile Height	Mean Der p I Content ^{A,B} ($\mu\text{g}/\text{m}^2$)					F ^C
	0–3 mm	3–5 mm	5–7 mm	7–9 mm	>9 mm	
6.5 mm loop pile	168.3 Aab	65.9 Bab	31.9 BC	4.5 C	n/a	33.8
6.5 mm cut pile	206.5 Aabc	76.0 Bab	31.5 C	6.0 C	n/a	18.5
9 mm loop pile	174.7 Aab	52.8 Ba	48.7 B	30.8 BC	3.9 C	22.0
9 mm cut pile	298.3 Ac	81.1 Bab	51.0 B	29.5 B	9.3 B	10.7
6.5 mm cut pile, low pile density	298.7 Ac	98.0 Bb	25.3 C	3.6 C	n/a	38.8
9 mm cut pile, high pile density	242.6 Aabc	98.3 Bb	62.0 B	14.8 B	n/a	10.9
9 mm cut pile, hard twist yarn	108.3 Aa	45.2 Ba	32.2 BC	6.9 C	n/a	14.5
Mean	213.9	73.9	40.4	13.7	6.6	—
LSD ($p \leq 0.05$) ^B	119.2	45.1	—	—	—	—
F ^D	2.9	1.7	—	—	—	—
p ^E	0.02	0.14	—	—	—	—

^A Values for Der p I at different levels within the same carpet (i.e., comparing values across a row) are not significantly different ($p > 0.05$) if followed by the same letter in upper case type.

^B Values for Der p I concentration at the same level but in different carpet types (i.e., comparing values down a column) are not significantly different ($p > 0.05$) if followed by the same letter in lower case type (analysis not carried out for intervals above 5 mm).

^C Between layers, all p-values ≤ 0.001 ; therefore, statistical significance of differences remains after application of Bonferroni's correction.

^D F = F-statistic.

^E Between carpets, all p-values > 0.0025 (df = 6,35); therefore, statistical significance of differences remains after application of Bonferroni's correction.

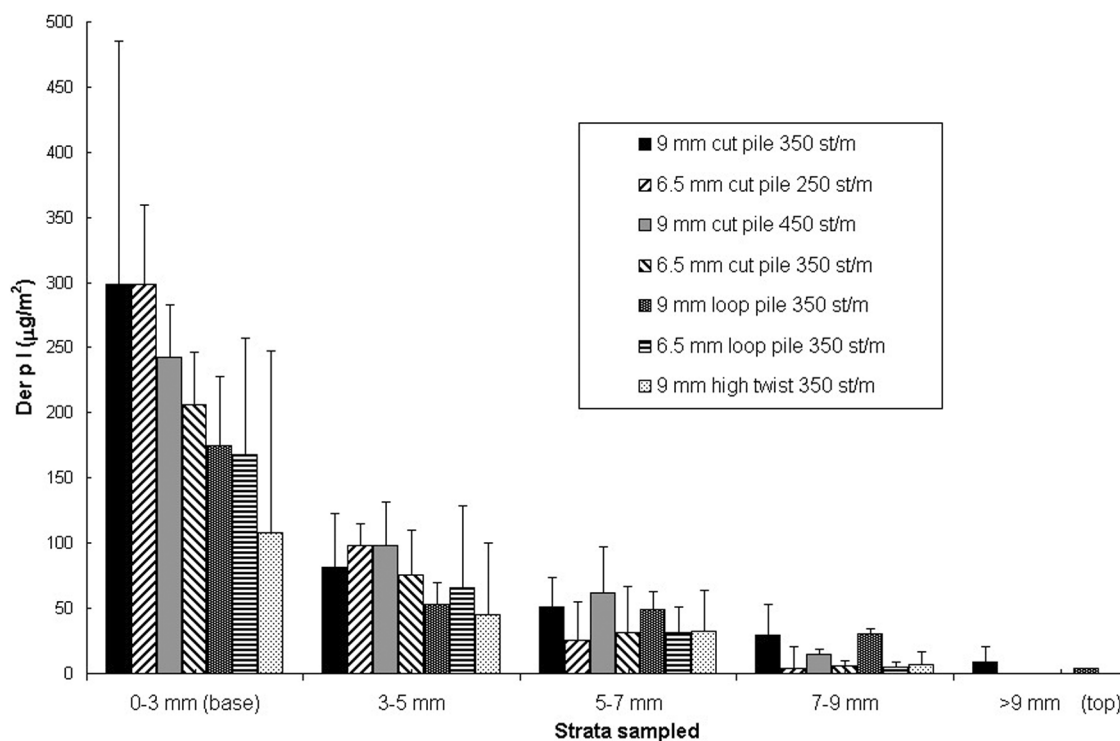


FIGURE 2. Der p I concentration in pile strata of carpets of different construction, with upper 95% confidence intervals (CIs) indicated

DISCUSSION

Whereas little is known about whether differences in allergen loading exist between carpet types, rather more study has been carried out to examine both nonallergen particulate loading and the numbers of mites present on different flooring surfaces. For example, researchers have reported differences in rates of visible soiling (for which some parallels may exist with allergen loading) between different carpet and fiber types,^(19–22) and that long pile carpets harbor significantly more mites than wood floors or those covered with tiles or short pile carpet.⁽⁷⁾ Differences in both mite and cat allergen removal rates have also been reported for carpets of different construction and degree of wear.^(23–25) Circumstantial evidence to suggest a relationship between carpet construction and allergen content exists also. For example, carpet installed in commercial premises is typically of low pile and if such constructions offer a reduced particulate-carrying capacity, this may be a contributing reason why allergen levels reported in such premises are invariably lower than those found in homes.^(26,27)

Based on a simple consideration of pile volume, one might expect that higher pile carpets would have a greater capacity to entrain particulate matter; however, this was not reflected in Der p I contents determined in the cores, which were found to be similar for all carpets. In contrast, statistically significant differences were suggested when the Der p I concentrations in individual layers were added to give a total Der p I content. Each of the two methods used to determine the total Der p I

content had its own errors associated with it, but analysis of floorcovering cores was carried out on a greater number of samples and involved less sample manipulation and so is likely to provide a better estimate of the total allergen content.

From this study it appears that the extent of the pile flattening that occurs after carpet wear differs between carpet types, but neither pile height, pile conformation, pile density, nor yarn twist greatly influence how much Der p I collects within the carpet pile. This suggests that differences in the total particulate-carrying capacity exhibited by different carpet types⁽²⁸⁾ may not reflect their propensity to entrain allergen. That Der p I levels were much higher on carpet than on the linoleum also agrees with previous studies^(5–12) and, although the result for the linoleum may have been depressed somewhat by the close proximity of the carpets (which could have served to trap allergen deposited on the surface of the linoleum, but subsequently moved around by external forces), it appears clear that the allergen retention capacity of carpet is much higher than for hard flooring. While it is also possible that different cleaning or usage patterns (within sample sites) may have confounded results, the chances of this were minimized by careful selection of the test sites themselves and by incorporating a high level of replication both between and within sites.

Assuming that retention of aeroallergens by carpet can be modeled after traditional textile soiling mechanisms (macro-occlusion, micro-occlusion, hydrophobic attraction and sorption by Coulombic forces at the fiber surface),^(23,25,29)

some of the early studies of carpet soiling are useful when considering how carpet structure might dictate the behavior of particulate pollutants such as mite allergen. Such studies typically involved the artificial soiling of carpets with dust, followed by cleaning processes and an assessment of residual contamination. For example, Benisek⁽²¹⁾ reported an increased resistance to soiling for higher pile densities that he attributed to a reduced "free volume," or particulate-carrying capacity of the carpet.

However, in another investigation of the effect of pile density on carpet soiling, McKinnon and McLaughlin⁽²²⁾ report conflicting results to those of Benisek,⁽²¹⁾ their prediction more closely mirroring our observation that higher pile height and density carpets generally contained an (albeit not statistically significantly) higher level of Der p I. There was also a suggestion the low density carpet and some of the cut pile constructions had more allergen toward the base, possibly reflecting an increased "free space" in the lower levels. The inference of these findings is that, like carpet soiling, the exact behavior involved in Der p I accumulation in soft floorcoverings is determined by a complex interaction of internal factors associated with carpet structure, coupled with external factors such as contaminant nature.

Of the external factors that promote carpet soiling, it is likely that the presence of hydrophobic substances on the fiber is the most important and may also play a role in determining where allergen lodges in the pile. The presence of such substances in carpet may be attributed to spillages, residual fiber fat, residual spinning/carding lubricants, or wicking of oils from the jute secondary backing.⁽²¹⁾ Conversely, the presence of fluorochemical stain resistant coatings on the surface of carpet fibers has been shown to promote ease of Der p I and Fel d I removal^(23,24) and may retard buildup.

The finding that Der p I concentrations increased with proximity to the carpet backing agrees with only the first of the two somewhat limited studies on this topic that have been carried out to date.^(13,30) These reported an increasing concentration of allergen with increasing depth into the pile of some carpets (but no obvious pattern in others) and, moreover, that vacuum cleaning had inconsistent effects on this allergen distribution. The implications for the removal of such material are clear. Cleaning techniques that do not penetrate to the base of the pile (e.g., bonnet buffing) are unlikely to result in significant reductions in the allergen content. Similarly, the efficacy of other common cleaning techniques, including dry- and wet-vacuum extraction, will be dependent on factors such as degree of pile agitation, airflow, and number of vacuum passes, as well as carpet construction and level of wear.⁽²⁵⁾ Previous researchers^(23,24) have suggested low pile density carpets may be easier to clean than those of higher density and/or pile height. The former might therefore be expected to contain lower levels of allergen; however, even though there was a hint of such differences in the present study, they did not approach statistical significance.

Minor differences were found between carpets for where allergen collects within the pile. While the Der p I concen-

tration per unit area appeared to increase as the base of the pile was approached, a different pattern emerged for Der p I concentration per unit mass. Even though the nature of sampling dictated that Der p I concentration had to be expressed per the combined mass of carpet fiber and dust (not in terms of mass of dust, as is more common), this was shown to be reasonably constant throughout the pile of any given carpet, with the notable exception of the uppermost layer where concentrations up to two orders of magnitude greater than the mean were occasionally observed. Two reasons are suggested for the magnitude and variability of this parameter: either high surface loadings of dust were present, or it was an artifact of the sampling method and arose because a small component of loosely bound allergen fell out of the carpet when first disturbed by the clippers, leading to an artificially high Der p I loading in the comparatively small mass of fiber sampled. That this effect was not evident when considering the allergen concentration per unit area and that there was a considerable variation in the mass of the fiber collected in the uppermost sample tend to support the latter hypothesis.

Regardless of the cause of the high, variable readings in the upper surface layer, the sampling method was consistent because Der p I was measured relative to the mass of all material (be it carpet fiber, carpet backing, or other dust) present in each layer of carpet, with the belief that this would give an indication of the "allergen risk" and the challenge to cleaning posed by each carpet. It should also be considered that, by necessity, the 0–3 mm layer was thicker than the other layers and that the substrate did not constitute fiber, rather it was latex and backing material. As such, this layer would have had a much greater mass per square meter than that of the pile and a correspondingly lower amount of free space to hold allergen. That high variances were associated with values for the Der p I content of identical carpets in different houses and in the same layer within identical carpets is also not surprising because a significant variation in allergen levels has been shown to exist both within and between houses^(31–33) and even within the same room.^(32–34) However, there is no defined dose-response or indeed "threshold" level for Der p I sensitization, so the clinical significance of such differences also remains unknown. Nonetheless, accounting for such variations in Der p I content within the same carpet was of concern to us when developing our experimental protocol, and we attempted to minimize its potential impact by selecting test sites with similar attributes, placing samples in areas where they could be expected to experience similar levels of wear across the whole site, and by incorporating a high degree of between- and within-site replication.

CONCLUSION

We conclude that, in the same environment, mite allergen levels on hard flooring surfaces will be lower than on carpet. We also conclude that considerable pile flattening occurs with wear on a new carpet, and that pile conformation (loop vs. cut), pile density, pile height, and yarn twist have

variable but generally negligible effects on the capacity of wool carpets to entrain mite allergen. Whereas pile conformation and yarn twist dictate the propensity for the pile to flatten during wear (thus reducing the voids available within the pile in which particulate matter might lodge), at the same time the difficulty of removal by cleaning processes probably increases. This effect has been reported previously for mite allergen,⁽²⁵⁾ so we speculate that some merit may exist in selecting carpets on the basis of low pile height and high resistance to wear if seeking to minimize allergen levels.

Our field trial also revealed few differences between carpets for the Der p I concentration per unit area at any given level within the pile, suggesting that (in addition to having no influence on mite allergen content) pile structure may not be particularly important in determining how far mite allergen works into wool carpet. Again, it is the amount of mite allergen located in regions of the pile where it is likely to become aerosolized during activities such as cleaning or use that is probably more important than the total content. Ultimately, most mite allergen appears to collect at the base of the pile where it is probably less readily aerosolized than if it were located farther up the pile. Whereas this might sound desirable for sensitized individuals, such material is also likely to be less easily removed by cleaning techniques that would need to target this area of the pile to have any substantial impact on reservoir allergen levels. The extent to which conventional dry vacuuming achieves this remains unknown but, at least for worn carpet structures, this appears comparatively low. In the absence of more efficient extraction processes, dry vacuuming is likely to remain most valuable where it is used as an adjunct to other allergen avoidance techniques.

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