

The vertical distribution of house dust mite allergen in carpet and the effect of dry vacuum cleaning

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Abstract

Background: Carpets are large reservoirs of the dust mite allergen Der p 1. The effect of vacuum cleaning on the distribution of Der p 1 in carpets is poorly understood.

Methods: Samples were cut from 7 used household carpets, all over 5 years of age. From each carpet, 10 samples were left untreated, 10 vacuumed with an upright vacuum cleaner, and 10 vacuumed with a canister vacuum cleaner. Each section was then cut into 3 horizontal layers: the top 2 mm, the remainder of the carpet pile, and the carpet base. The mass of Der p 1 as a proportion of carpet volume was then determined.

Results: The concentrations of Der p 1 in each depth layer varied considerably between the 7 untreated carpets. In the top layer, Der p 1 concentrations were (median; 25th–75th percentiles): 41.9; 28.3–92.6 pg/mm³. For the middle layer they were similar (38.1; 22.4–108.5 pg/mm³), and for the carpet base, higher (212.4; 98.8–456.2 pg/mm³).

In most cases, cleaning using either type of vacuum cleaner resulted in no significant reduction in allergen concentration throughout all depth layers. A subset of carpets showed an apparent increase in Der p 1 concentration in one or more layers following vacuum cleaning. In all tests Der p 1 was collected in the vacuum cleaners' filter bags.

Conclusions: The depth-distribution of Der p 1 differs widely amongst used carpets. Vacuum cleaning changes the distribution of Der p 1 within such carpets but does not necessarily result in a reduction in the overall content.

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Introduction

Indoor allergens, particularly those produced by house dust mites, are known to trigger allergic responses

including asthma (Peat et al., 1996; Platts-Mills and Carter, 1997). Reduction of mite allergen levels in the indoor environment has been attempted in many studies, utilising methods such as intensive carpet cleaning, laundering of bedding and the use of occlusive mattress covers (Htut et al., 2001; Cloosterman et al., 1999; Lau et al., 2002; Woodcock et al., 2003; van den Bemt et al., 2004). In some such studies, reductions in patients' prevalence of allergic symptoms have been

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reported (Htut et al., 2001; Cloosterman et al., 1999) while, in others, substantial reductions in exposure have not been achieved, or they have been ineffective in reducing symptoms (Lau et al., 2002; Woodcock et al., 2003; van den Bemt et al., 2004).

Household carpets are known reservoirs of large amounts of indoor allergens, including the house dust mite allergen Der p 1. The large size of carpets means that they are likely to contain a larger total amount of allergen than any other item in a home.

Interpreting the concentration of allergen in dust collected from a carpet as a proxy for concurrent allergen exposure is subject to confounding factors. One of these is that much of the dust may be located in a position where it is unlikely to be aerosolised. In a preliminary examination of the vertical distribution of house dust mite allergen within a single used carpet, we observed that the majority of allergen was found at the base of the pile (Sercombe et al., 2000), suggesting that aerosolisation of trapped allergen may require significant disturbance, and also that any carpet cleaning methods applied to the top surface of carpets would have to be capable of penetrating to this depth to be effective at removing such material.

Carpets are usually maintained by dry vacuum cleaning, which is the primary means by which Der p 1 and other allergens in carpets are removed. However, both the distribution of Der p 1 within household carpets and the effect of vacuum cleaning on this distribution are poorly understood. It is known that different vacuum cleaner attachments used to collect samples of dust in allergen exposure studies harvest different fractions of dust, displaying different allergen concentrations (Wickens et al., 2004). It has also been reported that the efficiency of allergen removal by dry vacuuming is dependent upon carpet type and level of wear (Lewis et al., 1998; Causer et al., 2004).

In order to better understand how allergen sampling methods and allergen avoidance measures can be applied to carpets, we examined the vertical distribution of Der p 1 present in several used household carpets before and after a standardised vacuuming procedure using either of two styles of dry vacuum cleaner. Previous studies investigating the allergen content of dust sampled from such carpets have most often expressed results using the metrics of mass of allergen per unit area ($\mu\text{g}/\text{m}^2$) or mass of allergen per mass of dust sampled ($\mu\text{g}/\text{g}$) (Carswell et al., 1991; Doull et al., 1997) with no universally accepted standard. In the present study, we sectioned the carpets into several depth layers, making the expression of Der p 1 content using an allergen per volume ratio of pg/mm^3 more appropriate, since the makeup of the carpet material that was sampled (dust, pile fibre and carpet backing) represented a different sample material than previous studies, which examined dust only.

Materials and methods

Sections of 7 domestic carpets, all of age exceeding 5 years, were obtained at the time of their being replaced. All carpets were from homes in Sydney, Australia. One carpet was of woollen loop pile construction, one was synthetic loop pile, and five were synthetic cut pile.

Areas of carpet (each $1 \times 2 \text{ m}$) having the appearance of consistent wear were selected. Since the Der p 1 content of carpets varies considerably over small distances (Mitakakis et al., 2002), a total of 30 pieces ($5 \times 10 \text{ cm}$) were cut from each carpet, in a random distribution, for subsequent testing.

Vacuum cleaning

The 30 randomised pieces from each carpet were then grouped into three sets of 10, and each of these 10 then re-assembled into a continuous plane by fixing to a board. The assembled sections were treated as follows: (a) vacuumed using an upright style household vacuum cleaner with powered brushes or (b) vacuumed using a canister style household vacuum cleaner without powered brushes or (c) left untreated (control). The three assembled test samples were then separated, and the carpet pieces within each individually analysed to determine their Der p 1 content.

The upright vacuum cleaner was a Hoover 1500 Windtunnel (Hoover Co., North Canton, OH) rated at 1500 W, while the canister vacuum cleaner was a Volta 1100 Electronic (Electrolux, Stockholm, Sweden) rated at 1100 W. Vacuuming consisted of passing the vacuum head over the surface of the carpet four times over a period of 10 s. This regime is adapted from the American Standard Test Method F608-96 (ASTM, 1996).

The dust collected by the upright and canister vacuum cleaners from each carpet in parts (a) and (b) was recovered from their filter units, weighed and assayed to measure the total amount of Der p 1 removed by vacuuming.

Sectioning of carpets and Der p 1 measurement

Carpet pieces were secured to a cutting board with double-sided carpet tape (3M, St. Paul, MN), and the carpet height was measured using vernier callipers. The carpet pieces were then sectioned to produce 3 depth layers: the top 2 mm, the remainder of the carpet pile and the carpet base (consisting of the styrene-butadiene latex plus jute and/or polypropylene backing). Sectioning was performed using veterinary clippers (Oster EW610, Oster Professional Products, McMinnville TN) and a custom-made Perspex cutting guide. The carpet remained in its normal horizontal

position during the sectioning procedure. In order to collect the severed carpet pile and associated dust released during the sectioning process, the nozzle of a small suction device was held 1 cm above the cutting blades. The device collected the fibres and dust from the carpet into a pre-weighed ‘collection sock’ made of 20 µm Nytrel mesh. Each layer of removed carpet pile, and the carpet base, was weighed before further processing.

To determine their Der p 1 content, samples were eluted in phosphate-buffered saline 0.05% Tween 1% Bovine Serum Albumin (BSA/PBST) for 2 h on a mixing wheel, using 10, 30, and 15 ml of eluant for the top, middle and base sections, respectively. The samples were then centrifuged (800*g* for 10 min) to recover the liquid eluates, which were stored at −20 °C. Analysis was performed using a two-site monoclonal antibody ELISA specific for Der p 1 (Indoor Biotechnologies Inc. Charlottesville, VA), with a lower detection limit of 2.8 ng/ml.

The concentration of Der p 1 in each layer of each carpet was expressed as picograms per cubic millimetre of carpet volume (which included carpet pile, all trapped dust, free space, and, for the base layer, backing material). Due to the carpets sampled being heterogeneous between the depth layers, the commonly used metrics of µg/m² or µg/g would introduce confounding factors, and were not appropriate for our analysis.

Statistical analysis

Differences between the Der p 1 concentration in each layer before and after cleaning with each style of vacuum cleaner were tested for each carpet individually using the Mann–Whitney *U* test.

The effect of cleaning with each style of vacuum cleaner on Der p 1 concentration in each layer was also tested for all carpets together using the Kruskal–Wallis ANOVA.

Statistical significance was set at *p* < 0.05. Statistical tests were performed using Analyse-it + General 1.68 (Analyse-It Software Ltd., UK).

Results

Der p 1 concentrations and pile height prior to vacuum cleaning

The pile height of the carpets (from the top of the backing to the top of the pile) ranged between 8 and 12 mm, with the thickness of the backing ranging from 1 to 3 mm. The median total Der p 1 content of the carpets before vacuum cleaning ranged between 252.4 and 2228.7 µg/m² (Table 1), and all carpets sampled prior to vacuuming displayed a variable distribution of allergen throughout the depth layers (Fig. 1). In 5 of the 7 carpets tested, the highest Der p 1 concentration was seen in the carpet base. Der p 1 concentrations were non-normally distributed. In the top layer, the median Der p 1 concentration per volume was 41.9 pg/mm³ (25th–75th percentiles: 28.3–92.6 pg/mm³). For the middle layer the values were similar (38.1 and 22.4–108.5 pg/mm³, respectively), but for the carpet base they were much higher (212.4 and 98.8–456.2 pg/mm³, respectively). There was no significant difference between the concentrations of Der p 1 found in the wool carpet compared to the synthetic carpets, or in the cut pile carpet compared to the loop pile carpets.

In order to check that the finding of a lower Der p 1 concentration in the top 2 mm of carpet was not an artefact due to the pile fibres being less densely packed in the upper layer, Der p 1 concentration was also calculated as nanograms per gram of the total mass in each layer. Again, a variable distribution of Der p 1 was shown in the untreated control samples, and again the top 2 mm layer contained a lower concentration of allergen than the middle layer. In the top layer, the median Der p 1 concentration, calculated with respect to the total mass of dust and carpet mass, was 533.8 ng/g (25th–75th percentiles: 325.1–893.7 ng/g). For the middle layer these values were slightly greater (568.2 and 375.2–1305.1 ng/g, respectively), but for the carpet base they were lower (244.1 and 119.1–459.1 ng/g, respectively) due to the greater mass of some the components (eg. carpet latex) found only in the backing. For example, the

Table 1. Physical description and total Der p 1 content of the untreated carpet samples

Carpet sample	Pile type	Pile material	Pile depth (mm)	Backing thickness (mm)	Total Der p 1 content (µg/m ²) median (25th–75th percentiles)
A	Cut	Synthetic	11.1	2.1	2228.7 (2018.0–2387.2)
B	Cut	Synthetic	12.0	1.6	1726.8 (1481.5–2015.8)
C	Cut	Synthetic	10.5	1.8	702.1 (572.0–1009.0)
D	Cut	Synthetic	8.0	1.0	2576.8 (2185.0–3801.3)
E	Loop	Synthetic	9.3	3.0	252.4 (178.8–306.4)
F	Cut	Synthetic	11.5	2.6	485.3 (452.8–522.4)
G	Loop	Wool	9.0	2.6	607.1 (593.0–744.4)

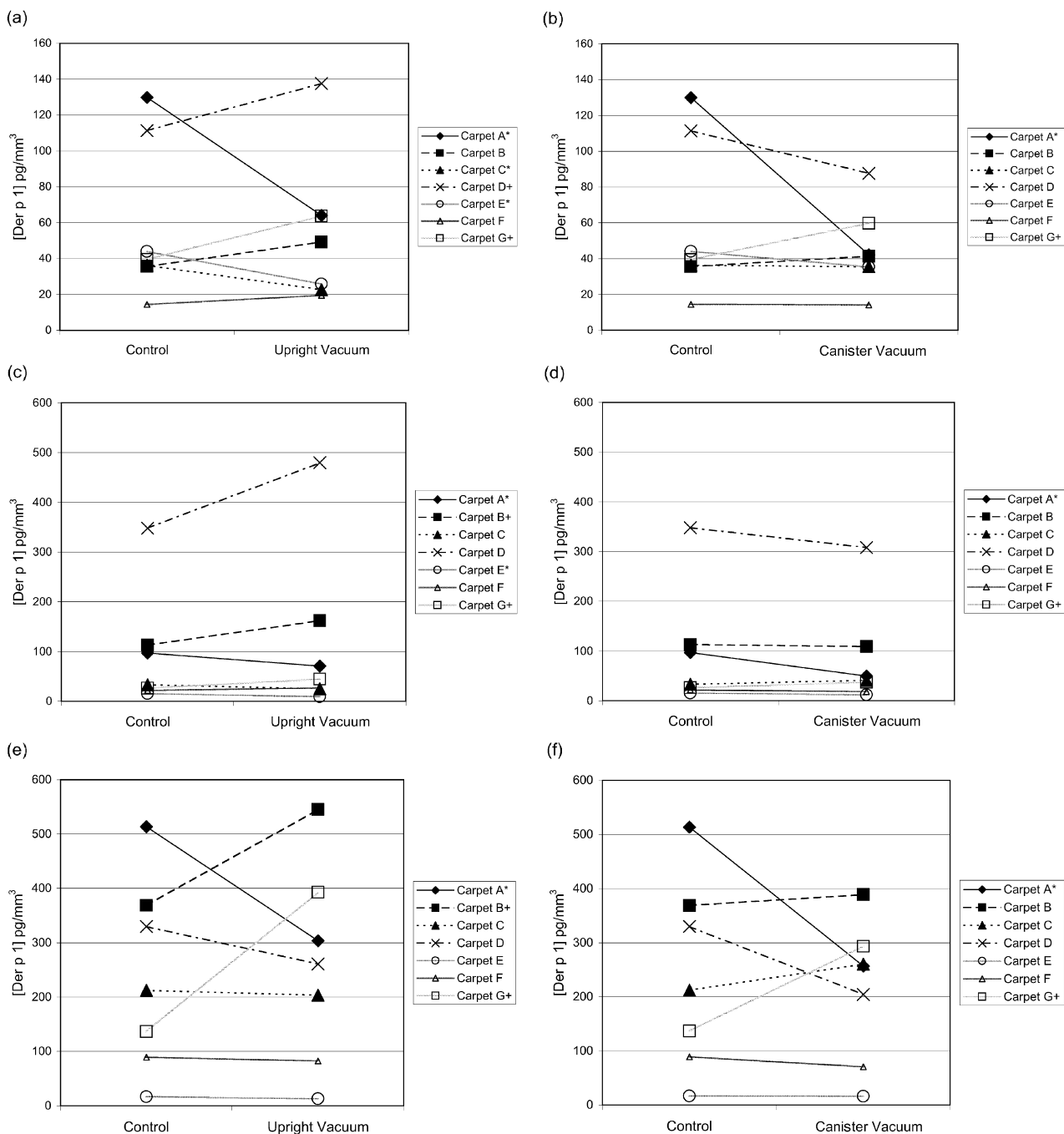


Fig. 1. Median Der p 1 concentrations with respect to volume of carpet material (pg/mm³) in the 3 depth layers of 7 carpets, before vacuum cleaning (Control) and following cleaning with 2 styles of vacuum cleaner (Upright and Canister). (a) and (b) Top 2 mm of carpet pile, (c) and (d) Middle layer and (e) and (f) Carpet base. *Indicates a significant reduction in allergen concentration in a depth layer compared to Control. + Indicates a significant increase in allergen concentration in a depth layer compared to Control.

base layers of the carpet pieces had a mean mass of 8.15 g, compared to 3.24 g for the middle layer of carpet pile.

Der p 1 concentrations after vacuum cleaning

Carpet A showed significant ($p < 0.05$) reductions in allergen across all 3 depth layers following cleaning with

both styles of vacuum cleaner (Fig. 1), while carpet G displayed a significant ($p < 0.05$) increase in allergen across all 3 depth layers following cleaning with both styles of vacuum cleaner. Generally, the remaining carpets showed no significant change in their Der p 1 loading after vacuum cleaning, but with some notable inconsistencies – where significant increases or decreases

in allergen load were observed in different depth layers of specific carpets.

The fact that dust sampled from carpet G using both vacuum cleaners contained appreciable quantities of Der p 1, yet carpet G was seen to increase in allergen content through all depth layers following vacuuming, reflects the problems expected when making pair wise comparisons from a large sample of naturally exposed used carpets – items which are known to contain an allergen loading that is highly variable over small areas.

When the effect of cleaning with each style of vacuum cleaner was tested for all carpets together using the Kruskal–Wallis ANOVA, no significant differences were seen in Der p 1 content following the use of either type of vacuum cleaner. There was no significant correlation between carpet pile material or construction and the response of the carpets to vacuum cleaning.

When calculated on a micrograms per gram of carpet and dust material (mass concentration) basis, the patterns of significant changes in allergen concentration were similar to that exhibited for results calculated as picograms per cubic millimetre (volume concentration) (data not shown).

Allergen and dust collected by vacuum cleaners

The upright vacuum cleaner was found to remove significantly greater amounts of total dust and Der p 1 than the canister vacuum (Wilcoxon ranked-sum test, $p < 0.02$), although appreciable quantities of allergenic material were removed from all carpets by both (Table 2). There were no significant differences in the concentration (nanograms of Der p 1 per gram of total dust) of the dust collected by the 2 styles of vacuum

cleaner, or in the mass of Der p 1 removed by each vacuum cleaner relative to the mass of Der p 1 remaining in the carpets.

Discussion

This was the first study to examine the effect of a standardised vacuum cleaning method on the distribution of naturally occurring Der p 1 present in carpets following domestic use.

Vacuum cleaners are the domestic devices most commonly used to remove allergens, yet little is known about the mechanisms by which they remove allergens from the structure of carpets. Previous studies have examined the effect of sequential vacuum cleaning and vacuum sampling (Adilah et al., 1997) and how different carpet characteristics such as material, construction and degree of wear affect the collection of artificially-applied cat allergen and house dust mite allergen (Lewis et al., 1998; Causer et al., 2004; Lewis and Breyse, 2000). Others have also investigated the allergen aerosolisation induced by vacuum cleaners during use (Gore et al., 2006) and the aerosolisation of fungal spores from carpet (Buttner et al., 2002). In order to better understand both the mechanisms of allergen aerosolisation from carpets and the performance of vacuum cleaners, specific information on the distribution and behaviour of allergens within carpets is required.

By separating carpet samples into 3 depth layers we demonstrated that the Der p 1 content in 7 samples of well-worn carpets followed no consistently predictable distribution according to depth, either before or after cleaning with 2 styles of vacuum cleaner. We also

Table 2. Dust and allergen removed by the upright and canister vacuum cleaners

Carpet	Dust removed (g)		Der p 1 removed (μg)		Concentration of Der p 1 in dust collected by vacuuming ($\mu\text{g/g}$)		Percentage of the total Der p 1 in the carpet that was removed by vacuuming (%)	
	Upright	Canister	Upright	Canister	Upright	Canister	Upright	Canister
A	1.60	0.89	27.1	11.5	16.9	12.9	27.9	18.2
B	2.05	0.72	25.6	19.8	12.5	27.4	16.6	17.2
C	1.55	0.77	21.7	10.1	14.0	13.2	39.9	18.0
D	7.68	2.64	54.0	39.9	7.0	15.1	23.5	24.7
E	0.85	0.30	7.6	4.7	8.9	15.7	47.1	30.1
F	0.90	0.60	5.4	2.4	6.1	3.9	17.9	10.4
G	1.05	0.66	20.6	7.3	19.6	11.1	30.0	11.4
Median	1.55	0.72	21.7	10.1	12.5	13.2	23.5	18.0
25th–75th percentile	0.97–1.92	0.63–0.75	14.1–24.6	6.0–17.4	8.0–13.6	12.0–15.6	19.9–35.8	14.3–23.0
Statistical difference between vacuum cleaner styles	$p < 0.02$		$p < 0.02$		$p = 0.81$ (n.s.)		$p = 0.078$ (n.s.)	

showed that the upright and canister vacuum cleaners used in this study removed a median of 23.5% and 18.0% (respectively) of Der p 1 from all carpets, which is consistent with our previous findings (Causer et al., 2004). Despite this finding, comparisons between control and vacuumed carpet samples showed no significant reduction in the amount of Der p 1 per cubic millimetre across all depth layers in 6 out of the 7 carpets tested – most likely reflecting the high degree of variability in allergen loading across carpets.

Despite the large number of investigations conducted using the mite allergen content of reservoir dust as a marker for aeroallergen exposure, there is no consensus on the correct metric to express the allergen concentration in such house dust samples. The bulk of studies on reservoir allergen levels have involved the sampling of dust from carpets and furnishings using several styles of modified vacuum cleaners, which collect some poorly defined fraction of the dust present in a reservoir (often called ‘fine dust’). The measures of mass of allergen per unit area ($\mu\text{g}/\text{m}^2$) or mass of allergen per mass of dust sampled ($\mu\text{g}/\text{g}$) are both regularly used (Carswell et al., 1991; Doull et al., 1997), depending on the substrate being sampled, the intervention performed, and investigator preference. In the present study, we expressed Der p 1 content using a volume ratio. Because dust and carpet fragments were combined in our case, expression of results in terms of $\mu\text{g}/\text{g}$, while still valid, would have a different meaning than for traditional dust sampling studies and would be somewhat misleading. When we did, however, calculate our results as a mass ratio in order to repeat significance tests for the effects of vacuum cleaning, we saw no obvious difference, since the masses of each carpet section were fairly consistent between replicates.

Studies aimed at reducing people’s inhaled exposure to allergens by cleaning or removal of potential allergen reservoirs within the home have had mixed success. While substantial removal or control of allergens from other domestic textiles can be achieved by high temperature laundering or use of occlusive covers on bedding, these methods cannot be applied to carpets. Wet vacuum extraction, ‘steam’ cleaning, and treatment with acaricides or allergen denaturants show variable results (de Boer, 1990; Brown and Merrett, 1991; Colloff et al., 1995; Hayden et al., 1992; Munir et al., 1993). These methods (Tovey et al., 1992; Tovey and McDonald, 1993) and even the installation of new furnishings (Custovic et al., 1996) have been shown to lead only to relatively short-lived reductions in allergen levels.

Carpets are most commonly cleaned by conventional dry vacuuming, but contradictory reports exist as to the efficacy of such cleaning in allergen reduction. To date, there are no reports on the effect of long-term vacuum cleaning on domestic airborne allergen levels. Some studies (Munir et al., 1993; Adilah et al., 1997) have

shown dry vacuuming to reduce reservoir Der p 1 levels in domestic situations, but others report no significant effect (Bischoff et al., 1989; Popplewell et al., 2000), suggesting that achieving complete cleaning of fitted carpets may be quite difficult, particularly if the pile of such carpets is worn (Causer et al., 2004; Arlian et al., 1982).

It is not known how the depth at which allergenic particles exist within a carpet contributes to the propensity of allergens to be aerosolised, and hence inhaled. Intuition would suggest that particles occurring towards the top of the carpet pile would be those most likely to be aerosolised, and therefore most likely to contribute to inhaled exposure, although there have been no relevant data published. There are, however, data indicating that artificially applied fungal spores of 1.8–3.5 μm size are aerosolised in substantially greater numbers from cut pile carpet than loop pile carpet or vinyl flooring during a simulated walking procedure (Buttner et al., 2002). These fungal spores were applied to the surfaces of the flooring materials, but the resulting depth distribution of the spores in the carpets, and how this contributed to the difference seen between carpet types, was not explored. It is likely that both the construction of a carpet and the location of allergenic particles within the carpet contribute to allergen aerosolisation.

Our finding of a lack of a clear pattern of depth distribution of allergen, while appearing to contrast with other studies by our group (Sercombe et al., 2000; Causer et al., 2006), can be appreciated in light of our previous findings that even with controlled conditions of carpet type (Sercombe et al., 2000) and history (Causer et al., 2006), the depth distribution was associated with considerable inter-replicate variation. When the much greater variation in age, wear and construction of the samples tested in the present study is considered, it is not surprising that no consistent pattern of allergen depth distribution could be seen.

Following vacuum cleaning, we found a consistent reduction in Der p 1 content throughout all depth layers in only one carpet sample. In other cases we found reductions in some depth layers, and in others, no change or even increases in Der p 1 content with no apparent pattern. In particular, we observed an increase in Der p 1 content in all layers of the wool carpet (G) compared to the control sample after vacuum cleaning (despite both vacuum cleaners recovering allergenic material during cleaning), suggesting some confounding influence. Considering the large number of samples compared in our study – 630 allergen measurements in total – and the known high variability in carpet Der p 1 concentrations in domestic carpets, it could be expected that we would encounter such an effect in a proportion of our pair wise comparisons.

For domestic use, there are two main styles of vacuum cleaners: the ‘upright’ with rotating brushes integral to the unit which function to beat the carpet, and the

‘canister’ which has a cleaning head which may or may not contain its own set of rotating brushes, separate to the main unit. The efficiency of dust extraction has been shown to differ between these two styles (ASTM 1996). We found that both the upright and canister styles of vacuum cleaner removed both bulk dust and Der p 1 from all of the carpets tested. However, we found a significant difference in the masses of bulk dust collected, and the mass of Der p 1 collected by the 2 vacuum cleaners, with the upright model proving more effective. We also found that there was no difference in the Der p 1 concentration per unit mass of the collected dust, suggesting that both cleaners collected the same sub-population of the complex mixture that constitutes dust from the carpets but that they collected different amounts of dust. There was also no significant difference seen in the percentage of Der p 1 removed by vacuuming, relative to that remaining in the carpets – this is most likely due to the generally low relative allergen removal seen (around 20% for both cleaners) which would serve to mask any differences. These findings suggest a complex, multi-factorial relationship between vacuum cleaner power and cleaning head design, carpet structure and carpet allergen distribution.

This study has demonstrated that carpets, after several years of use in domestic conditions, contain large amounts of Der p 1 allergen throughout their structure. Vacuum cleaning removes Der p 1 from such carpets in an incomplete and inconsistent manner. Our results indicate that while a single round of vacuum cleaning performed according to ASTM F608-96 has the potential to remove a portion of the Der p 1 present in heavily worn carpet, it does not provide an effective means of significantly reducing the overall Der p 1 content. Such vacuum cleaning may also lead to a redistribution of the remaining Der p 1. For worn carpets at least, allergen avoidance measures that rely solely on vacuum cleaning are likely to be of limited success unless cleaning procedures more rigorous than ASTM F608-96 are performed.

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