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Efficiency of Vacuuming for the Removal of Cat Allergen (Fel d 1) from Worn and Unworn Wool Carpets of Different Construction

Abstract Exposure to cat allergen (Fel d 1) has been associated with immune responses and exacerbation of asthma. As such allergen can accumulate in carpet, we sought to determine the influence of carpet pile conformation (loop vs. cut) and degree of wear on the levels of Fel d 1 present before and after different cleaning processes. Tufted wool carpets of different construction were loaded with house dust and artificially worn, before being either dry or wet vacuumed. Using enzyme linked immunosorbent assay to determine Fel d 1 levels at each stage, we showed the efficiency of Fel d 1 extraction from unworn (but soiled) carpets to be high, and to differ little with pile conformation or cleaning method. However, efficiency of removal decreased as the carpet became more worn, in which state wet vacuuming also proved slightly more effective than dry vacuuming. Therefore, if seeking to minimize exposure to cat allergen in a carpeted environment, in addition to established Fel d 1 avoidance techniques, implementation of a regular cleaning regime is desirable and consideration should also be given to removal of any heavily worn carpets (preferencing replacement with constructions of high wear resistance).

Key words allergen control, carpets, cleaning, Fel d 1, vacuuming

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Exposure to the major group I allergen derived from cats, Fel d 1, is a known risk factor for sensitization to that allergen [1] and for acute asthma [2, 3]. Fel d 1 is a relatively stable 36 kDa protein dimer secreted by the sebaceous glands of cats [4–6], for which carpets and other domestic textiles often provide a sink [7–9]. Fel d 1 is typically associated with 1–10 μm particles [10] and is readily transported between environments, as evidenced by its presence in cat-free buildings [11, 12], and even in locations as geographi-

cally isolated from cat populations as Antarctica [13]. Thus, avoidance of environments containing cats will not necessarily preclude a risk of exposure for Fel d 1 sensitized individuals. However, to provoke a respiratory response, cat

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allergen needs firstly to be aerosolized, and secondly, it must come into contact with the mucosal lining within the lungs or nose of a sensitized individual.

Unfortunately, how such allergen interacts with the fibrous matrices in which it accumulates, how this influences the ease of aerosolization, and how levels in textiles correlate with exposure to actual airborne allergen, are all poorly understood. Nevertheless, removal of carpets is frequently advocated as a method by which asthmatics can reduce their exposure to such allergen. In many instances, however, removal is either not possible (e.g. in rented accommodation) or it is wished to retain carpet for aesthetic or other reasons. It is, therefore, important to know how effective conventional cleaning processes are at reducing particulate pollutant loadings in carpet, and what role floorcovering structure and degree of wear play in determining the ease of its removal.

Much of the published research on allergen behavior within textile structures concerns another important biological pollutant, house-dust mite allergen, and a consideration of these results is useful background for helping understand how cat allergen might behave. For example, whilst cat and mite allergens undoubtedly have different aerodynamic characteristics [10], we know that both are removed in significant quantities by dry vacuuming of carpet [14–17], although not always completely [18]. We also know, from studies delving into the effect of fiber and carpet characteristics, that decreasing fiber surface area and the presence of fluorochemical stain-resist treatments aid the removal of Fel d 1 and the house-dust mite allergen, Der f 1 [15, 16], but that pile height and cleaning method (wet vs. dry extraction) are of lesser importance [18]. Conversely, an increased level of carpet wear appears to greatly hinder the removal of Der f 1 [18].

The present study was initiated to ascertain whether vacuum removal of Fel d 1 from carpet follows a similar pattern of behavior to that for mite allergen, and to determine how the efficiency of removal might vary depending upon the degree of wear (worn vs. unworn), pile conformation (loop- vs. cut-pile), and cleaning method (hot water extraction vs. dry vacuuming). By doing so, we hoped to develop recommendations for carpet selection and maintenance, and to provide information to assist vacuum cleaner design.

Experimental

Dust Collection and Carpet Seeding

Floor dust was collected by vacuuming a series of houses in Christchurch, New Zealand, then sieving it through a 106 μm mesh to remove larger pieces of debris. To maintain its free flowing characteristics, 1% w/w amorphous fumed silica (Sigma) was added. This dust was then applied to a series

of tufted wool carpets and the efficiency of Fel d 1 removal by different types of vacuuming determined.

To dope, wear and clean the carpets, we used a variation of a method described previously [18]. Briefly, dust was seeded onto 84 samples (each 307 mm $\times$ 216 mm) of 6.5 mm pile height carpet, manufactured on an 1/8th gauge tufter (315 needles/m), using a 2-ply yarn with a linear density of 0.6 g/m, and at a stitch rate of 350 stitches/m. Half of the samples were loop-pile carpet, half were of cut-pile construction, and all were seeded by placing them two at a time under an inclined track, down which was rolled a perforated roller that had previously been loaded with dust (65.0 cm³). This operation was performed four times, rotating the carpets in the manner described by Lewis et al. [19], but without reloading the roller between rolls. The dust was then embedded in the carpets by placing them in a template and dragging a steel rod (12.6 kg) across the surface of each 30 times, as per ASTM F608 [20]. All carpets were conditioned for 24 hours at 20 °C, 65% RH, and their masses and Fel d 1 content determined before and after dust seeding.

Wear and Cleaning of Carpets

After the dust seeding/embedding step, half of the loop-pile and half of the cut-pile carpets were artificially worn in a hexapad tumbler, according to standard textile testing protocols [21, 22], involving bouncing around of a rubber-covered hexapodal weight within a revolving carpet-lined drum for a set number of revolutions. For our study, the vacuuming step that is typically carried out midway through the wearing process was omitted, so as not to remove any allergen. The 8000 hexapad revolutions we used is widely accepted to simulate the amount of wear occurring in a four-person household over the course of 4–5 years.

Samples of worn and unworn carpet (both loop- and cut-pile) were then cleaned using an automated vacuuming apparatus (Figure 1), also described previously [18], and in accordance with standard textile testing procedures [20]. The wet extraction process was performed with a Steamvac LS (Hoover) and the extraction solution (Hoover Steamvac Carpet Upholstery Detergent, 5 oz/gal, 37 $\pm$ 5 °C) recommended by the manufacturer. Four passes were made over the surface of each carpet, where one pass consisted of a forward motion (55 cm/s) with detergent solution being simultaneously sprayed onto the carpet and sucked out again, and a return motion using suction only. A similar number of passes were used during cleaning with a dry vacuum cleaner (Dirt Devil, Royal Appliance Manufacturers). We have described the individual machines previously [18], and all test protocols were carried out at 45% RH and 23 °C.

For every replicate of pile type, wear level and cleaning method (seven per combination), eight 1195 mm² core samples (39 mm diameter discs) were taken for Fel d 1 analysis.

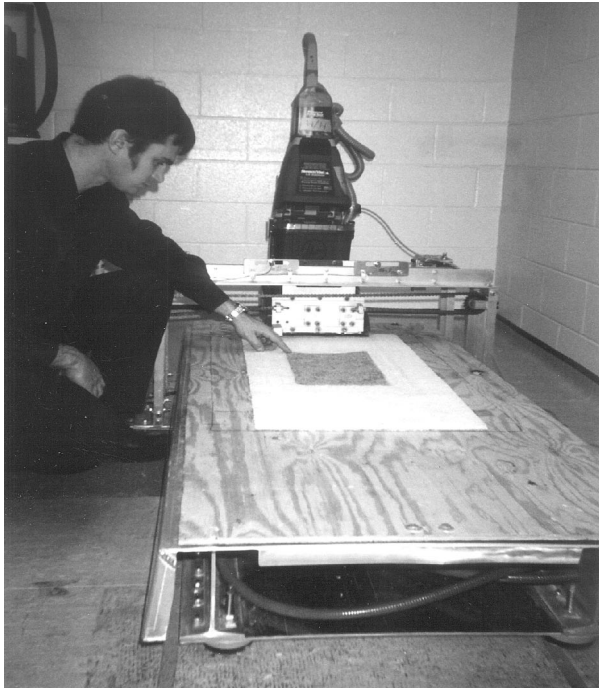


Figure 1 Automated vacuuming apparatus, showing wet vacuum cleaner mounted above sliding sample bed.

Fel d 1 Analysis

To determine the Fel d 1 content, the eight cores from each treatment were extracted in phosphate buffered saline/Tween (15 mL each) at room temperature for 24 hours, then the extracts were pooled and subjected to double monoclonal antibody enzyme linked immunosorbent assay (ELISA) [23]. Standard antibodies supplied by Indoor Biotechnologies, Cardiff, UK, were utilised for the analysis, along with appropriate negative controls.

All data were examined using analysis of variance (ANOVA) and students t-tests within Genstat 7.2 and Microsoft Excel software packages, respectively. Statistical significance was set at the 5% level.

Results

Analysis of samples of the undoped, unworn control carpet revealed a very low mean Fel d 1 concentration ($9.4 \mu\text{g}/\text{m}^2$), but analysis of the artificially soiled samples yielded readily detectable levels of Fel d 1 – both before and after cleaning. The mean mass of dust added to each carpet sample was 6.96 g (95% CI: $6.71\text{--}7.21 \text{ g}$), resulting in a mean Fel d 1 content of $2872.1 \text{ g}/\text{m}^2$ and, reassuringly, this concentration was not found to change significantly ($P > 0.05$) after

the carpets were artificially worn (Figure 2). The level of Fel d 1 initially seeded onto the carpets was relatively consistent between samples (95% CI: $2660.6\text{--}3083.6 \mu\text{g}/\text{m}^2$), with a notable reduction in variability also occurring after wear, suggesting a further evening out of dust distribution occurred during this step.

As no significant difference ($P > 0.05$) existed between Fel d 1 levels in the cut- and loop-pile carpets for any given combination of wear and cleaning, data from like-treatments were pooled. Subsequent analysis showed significantly more ($P \leq 0.001$) Fel d 1 was removed from unworn carpets (mean: 75.0% removal) than worn ones (mean: 34.9% removal), and that wet extraction was more effective than dry vacuuming ($P \leq 0.05$), but only marginally so, and only for worn carpet (Figure 2). Thus, an interaction between level of wear and cleaning method was evident ($P \leq 0.001$), although not between any other combination of factors.

Discussion

Results of the present investigation suggested the behavior of Fel d 1 in carpets was similar to that previously described for house-dust mite allergen [18], particularly in terms of the influence of degree of wear on efficiency of allergen removal by vacuuming. As much as two-thirds of Fel d 1 was removed from unworn carpet by a relatively light vacuuming, however, it became much more difficult to vacuum out as the carpet became worn. While other explanations exist for this behavior (such as changes in fiber surface structure), the most likely reason relates to compression and shear forces incident upon the pile during wear resulting in a marked flattening of the carpet tufts, and in the individual fibers assuming a more horizontal orientation. The more tortuous path for particulate extraction thus formed, coupled with a reduced propensity for air flow through the condensed pile structure, then makes particulate matter more difficult to remove during cleaning. Paradoxically, the increased level of wear found in old carpets may mean that the same allergenic material (which will undoubtedly also be present in greater quantities) is probably less likely to be aerosolized or transferred to humans via direct contact – both important routes for exposure to Fel d 1. That (for any given combination of cleaning method and wear level) we did not observe differences in Fel d 1 removal for cut- and loop-pile carpet, suggested the extraction path was equally tortuous within each – perhaps because allergen lodged primarily in the areas between tufts or within individual yarns (opportunities for which exist in loop- and cut-pile structures), rather than penetrating the voids existing between the two legs of each loop pile tuft.

The statistically significant interaction that was shown between wear and cleaning method could also be related back to fiber orientation which, in an unworn carpet, is

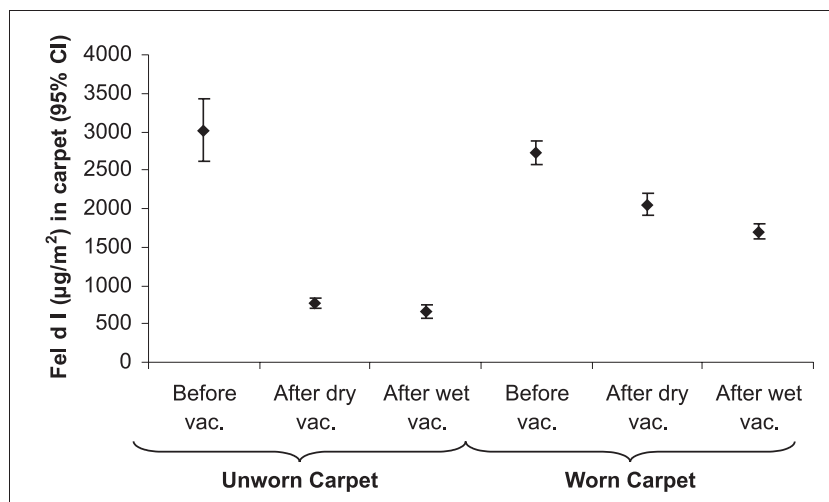


Figure 2 Fel d 1 content of carpet before and after different vacuuming processes.

most likely in the optimal configuration for efficient vacuum extraction, whatever the method used. However, because Fel d 1 is highly water soluble [24, 25], it is possible that, in a worn carpet, wet vacuuming is slightly more efficient than dry vacuuming because the liquid to volume ratio is increased (due to the pile having been flattened) and more efficient solubilization of Fel d 1 occurs. Whatever the reason, the magnitude of the difference observed was small.

That wear was so important in determining ease of removal most likely relates not only to the increased level of fiber entanglement found in older carpets, but also to the cross-sectional distribution of the allergen itself. Again, it is useful to draw comparisons with the behavior of house-dust mite allergen. Whilst such mites live within the pile of carpet, and cats above it, the allergens of both are present on particulate matter and will be subject to the same shear and compression forces as a carpet is worn, presumably forcing each deeper into the pile. The concentration of the mite allergen Der p 1, for example, has been shown to be inversely related to its distance from the carpet backing [26], and such material will be much harder to remove if located at the base of the pile than nearer the surface. It is likely that this pattern of behavior and particle distribution are also assumed by other particulate pollutants, such as Fel d 1, but it should be remembered that they arise from different sources and may have unique surface chemistries or charge and physical characteristics which could mean they behave slightly differently. Certainly, there are some major differences in how they behave in air [10], in particular in their settling rates.

The extent to which these allergens build up on differing surfaces also varies. For example, house-dust mite allergen is typically found in lower levels on hard flooring than on carpet [27–32], and cat allergen is often reported in higher concentrations in flooring than in bedding [7, 8].

Notwithstanding this, it would appear from our results that considerable merit exists in selecting carpets with constructions most resistant to wear. Generally speaking, such carpets are those of loop-pile construction, made from high twist yarns and from fibers of high bulk and strength (noting, however, that the present investigation determined no difference in the performance of cut- and loop-pile constructions made from identical yarns).

In this study, we investigated a level of dust that might be considered typical of that which would be found after several years of wear on a carpet, and that was intermediate to that which might be found on a highly worn carpet and the lower level one might expect on a typical hard flooring surface. That the dust loading level may be important in determining ease of Fel d 1 removal is suggested by studies of lead particle removal [33], where a statistically significant interaction between carpet wear and level of contamination was determined. Thus, it remains unknown whether the pattern of results observed in the current study would be repeated were a much higher rate of soiling employed, for example.

The amount of Fel d 1 aerosolized off a hard surface versus a carpeted surface, considering the surfaces are likely to contain quite different amounts of allergen, is also an important question remaining unanswered. It seems reasonable to assume that factors that hinder the cleaning of carpet (such as its fibrous nature) will also deter aerosolization. However, as previously noted, the pool of allergen that might potentially be aerosolized, for a given level of disturbance, is likely to be correspondingly higher for carpet.

Whether the nature of any particles aerosolized (e.g. their mean diameter) might be mediated by the level of loading and/or type of surface they are present on is also an interesting point to consider. This is quite possible if carpet acts as a partial filter or trap for particulate matter,

as we propose. The size of the particles aerosolized is important for several reasons: smaller particles are likely to remain in the air for much longer than larger ones; smaller particles are likely to penetrate further into the respiratory tract than larger ones; and smaller particles are likely to contain a correspondingly lower level of allergen than larger ones.

Variation in size will exist between particles associated with the same allergen, but also between those associated with different allergenic particles (e.g. cat allergen vs. mite allergen). The original intent of this study was to investigate not only the removal of Fel d 1 from carpet, but also that of bacterial endotoxin – another environmental contaminant associated with respiratory symptoms, but one found on somewhat smaller particles (typically $<1\ \mu\text{m}$ in diameter) than Fel d 1 [34]. Unfortunately, when a matching set of carpet cores to those taken for Fel d 1 analysis were subjected to testing to determine the endotoxin content (using room temperature extraction in an endotoxin-free 0.005% Tween-20 solution followed by kinetic Limulus amoebocyte lysate analysis with a kit supplied by Bio Whittaker, USA), background levels on the carpets were found to dwarf any component that might have been removed by cleaning. This made it impossible to draw any firm conclusions about endotoxin behavior or to contrast the behavior of different sized particles. However, that endotoxin was detectable in appreciable amounts on unsoiled carpets (mean = 2.08×10^7 endotoxin units/m²), and that contributions were made by both pile and backing components, are interesting observations in their own right, and merit further investigation.

Conclusions

Our results suggested that Fel d 1 levels in new or lightly worn carpet may be readily controlled by either wet or dry vacuuming. However, in heavily worn carpets, its removal is likely to be more problematic. Given that inhalation of Fel d 1 is likely to be a more important route for exposure than dermal contact, a key consideration is how tightly the particles are attached to the fibers. Also influencing the extent to which aerosolization will occur, will be the concentration of particulates in the carpet, where they are located in the carpet cross-section, and the nature of the disturbance itself (walking, vacuuming, etc.). It also follows that, for a cleaning process to efficiently remove all allergen, it would have to create sufficient agitation and air or liquid flow through the lower levels of the carpet to remove any component lodged there [26, 35].

In instances where carpet is desired for its aesthetic, sound insulating, safety and comfort properties, but at the same time it is wished to minimize levels of reservoir allergen, the present study suggests a consideration of the

degree of wear (if assessing the need for replacement) or likely wear characteristics (if specifying new carpet) should be made. Clearly, however, such decisions regarding floor-covering selection, maintenance or replacement should also be made along with a consideration of other potential allergen avoidance measures that might be implemented at the same time. The most obvious of these (for Fel d 1 at least) would be the exclusion of cats from the home.

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