

Carpet properties that affect the retention of cat allergen

Roger D Lewis, PhD, CIH* and Patrick N Breyse, PhD, CIH†

Background: Although the importance of carpeting on airborne levels of cat allergen (Fel d 1) has been demonstrated, no studies have been performed to determine specific properties of carpet that may affect its retention and removal.

Objectives: This study characterizes factors that affect the retention of cat allergen on tufted carpets. The experiments were designed to test the hypothesis that the amount of allergen-containing dust recovered from vacuum samples of tufted carpet sources was dependent on micro (fiber) or macro (construction) retention properties of carpets.

Methods: Twenty-six types of custom manufactured carpet were spiked and embedded with reference dust containing Fel d 1. A standardized vacuum surface sampler was used to recover dust from the samples. Allergen was assayed using a standard, monoclonal antibody ELISA.

Results: Carpet-surface area and fluorocarbon-fiber treatments were found to have the largest effects on retention and recovery of cat allergen. The style per se of a carpet, such as loop or cut pile, does not affect allergen retention. These results are generally in agreement with previous studies on dust mite allergen retention.

Conclusions: Carpets that are easiest to clean would have the following properties for release of cat allergen and in this order: low pile density and height, fluorocarbon coating of fibers, high denier per filament, and a fiber shape with a low surface area.

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INTRODUCTION

The importance of the major cat allergen, Fel d 1 (*Felis Domesticus* allergen 1), in the etiology of asthma is well documented and the removal of cat allergen from the homes of asthmatic patients who are sensitized to cat allergen is important in preventing or reducing clinical symptoms of asthma.^{1–3} Some investigators have described the importance of environmental factors, particularly “soft” (textile) furnishings, on airborne cat allergen.^{4,5} For example, deBlay et al reported that in a controlled setting, carpeted surfaces accumulated 100-fold more Fel d 1 than what accumulates on a polished floor. Although the importance of car-

peting on airborne levels of cat allergen has been demonstrated, no systematic studies have been performed on specific characteristics of carpet that affect the retention and removal of Fel d 1.⁵

We previously reported on factors that affected the retention of dust mite allergen on carpets.⁶ Carpets that had low surface areas and fluorocarbon coatings retained the least amount of dust and dust mite allergen. Allergen extracts prepared from these same dust samples^{6,7} were assayed for Fel d 1 and evaluated for main and interactive effects on carpet retention and recovery. Similarities and differences with dust mite allergen retention are reported.

METHODS

Carpet Specifications

The theory and mechanics of textile soiling which are the basis of the study hypothesis have been extensively reviewed. Micro-occlusion is an intrafi-

ber phenomenon and can be affected by a number of fiber related properties including denier (thickness of fiber), fiber shape, and the coating of fibers with fluorocarbon, such as with Teflon. Macro-occlusion is an interfiber or inter-yarn phenomenon where mechanical entrapment of particles occurs primarily due to carpet construction, such as pile height and density, yarn twist, and carpet style. The style of a carpet is dependent upon tufting. Carpets can be tufted into three broad categories: *loop*, uniform level loops; *cut-pile looped*, a combination of cut piles and looped piles; and *cut-pile*, all piles have been cut.^{8,9}

Four fibers were selected in the initial design of the study representing two levels of denier (16 or 19) and two levels of shape (trilobal or square-hollow). Microscopic cross-sections of these two fiber shapes are illustrated in Figure 1. One year after the project commenced, larger denier fibers were introduced into the market and a 23-dpf (denier per filament) fiber was added to the study. The addition of the 23-dpf brought the number of types of fibers to five, allowing for a three level evaluation of denier. The 23-dpf fiber, however, was only available in the trilobal shape and to minimize expense, it was tufted only into cut pile carpet. After tufting yarn into specific types of carpets, carpets were mock dyed (oil and dirt removal), backed with a latex coating, coated with Teflon as specified, and cut into 46 × 46 cm samples.

The micro-occlusion characteristic study evaluated the effects of four independent fixed factors: style, denier (dpf), shape, and Teflon (a brand of fluorocarbon coating) on the recovery of bulk dust and Fel d 1 from vacuum-sampled carpets. Carpets were tufted into a cut-pile or loop construction

* Saint Louis University School of Public Health, St. Louis, Missouri.

† Johns Hopkins University School of Hygiene and Public Health, Baltimore, Maryland.

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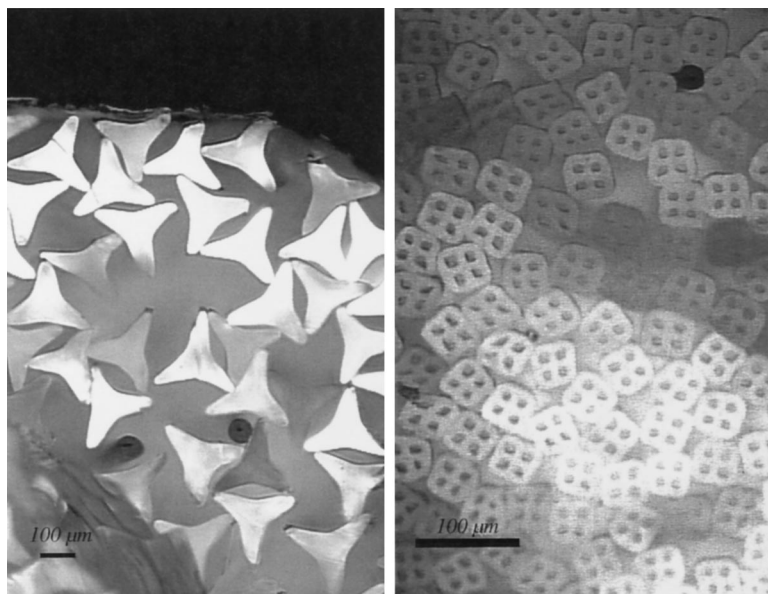


Figure 1. (Left panel) cross-section of trilobal fiber. (Right panel) cross-section of square-hollow filament fiber. Round black objects are carbon fibers used to control static electricity.

with each combination of denier (16 or 19), shape (trilobal or square-hollow), and Teflon coating (yes or no). Two levels for each factor resulted in a balanced design with 16 different carpet types. Each carpet was tested with seven replicates for a total of 112 samples. The addition of denier 23 resulted in an unbalanced design, which increased the sample size to 126. The balanced design resulted in an equal number of samples between levels of each factor, whereas the unbalanced design contained an unequal number of carpet samples for each factor, except Teflon.

The macro-occlusion characteristic study evaluated the effects of two independent construction-factors, pile height, and pile density. Two levels for each factor resulted in a balanced design with eight carpet types. Each carpet type was tested with seven replicates for a total of 56 samples. The sample size for both micro and macro-occlusions studies were based on the ability to detect a 10% difference in mean recoveries of each factor level (assuming a c.v. of 16%, $\alpha = 0.05$, and $\beta = 0.2$).

In this study, the range in height for cut pile varied by a factor of 4, as

compared with a factor of 2 for loop pile. The density range for loop pile, however, varied by a factor of 2.4, as compared with a factor of 1.9 for cut pile. The magnitude of the differences in height and density between cut pile and loop carpet in this study represented differences found in the market place. The specifications for the dichotomous levels of height and density were determined after consultation with textile experts (Personal communications: A. Luedtke, Dupont, Dalton, Ga.; R. Burnett, RBI, Dalton, Ga.; R.D. Lewis 1992 Nov 5 selection of height and density parameters for the factorial study).

Carpet Sample Preparation, Sampling, and Assay

A composite sample of house dust (dust passing through a 300- μm sieve), produced for use in all the carpet-doping procedures, was deposited and embedded on each carpet sample using a standardized method.¹⁰ The average Fel d 1 content of the dust was $70 \pm 1.5 \mu\text{g/g}$ (mean $\pm$ standard deviation). The high volume small surface sampler (HVS3) was used for vacuum sampling the carpets after doping and embedding of allergen containing

dust.^{7,11–13} Allergen was extracted from the recovered dust using borate buffered saline with 5% bovine serum albumen (BBS-BSA) from each HVS3 collection bottle. Quantitation of allergen was performed using a non-competitive microtiter plate based enzyme immunoassay that uses allergen-specific monoclonal antibodies to capture specific allergens from the aqueous extract and a second enzyme-labeled antibody to detect bound allergen.^{14,15} All of the immunoassays were performed at the Johns Hopkins University Asthma and Allergy Center's Dermatology, Allergy, and Clinical Immunology (DACI) Reference Laboratory. Based on the DACI quality assurance studies, extraction and quantitation of allergen had a coefficient of variation of approximately 15%.

Statistical Methods

Analysis of variance (ANOVA) using the Statistical Package for the Social Sciences (SPSS) was performed to assess the significance of each factor-level effect on dust and allergen recovery for each balanced and unbalanced factorial study design.

RESULTS

The recovery of bulk dust from the 126 samples in the micro-occlusion characteristic study was $802.5 \pm 176.3 \text{ mg}$ (mean $\pm$ SD) and ranged from 474.3 to 1243.6 mg. Mean Fel d 1 recovery was $7 \pm 2 \mu\text{g}$ (range: 3 to 13 μg).

The top panel of Table 1 represents the effects of micro-occlusion factors on dust and cat allergen recovery from an ANOVA of the balanced design with 112 samples. Style was not a significant factor in recovery of bulk dust or cat allergen. The cross-sectional shape of the fiber was a significant factor in recovery of both dust and cat allergen. There was a 19% and 11% higher yield of dust and allergen, respectively, for square-hollow fibers with relatively small surface areas as compared with the trilobal fibers with greater surface areas. No significant factor interactions were observed.

The effects of denier and Teflon were also evaluated from an ANOVA

Table 1. Significance of Micro-Occlusion Factors in Dust and Cat Allergen Recovery

	Dust (mg) (Mean $\pm$ SD)	Fel d 1 (μ g) (Mean $\pm$ SD)
Balanced design (n = 112)		
Style		
cut	780.5 $\pm$ 164.7	7.24 $\pm$ 2.10
loop	796.5 $\pm$ 178.7	7.42 $\pm$ 1.65
% Δ^*	+2%	+2%
P value	.653	.011
Shape		
trilobal	719.3 $\pm$ 145.6	6.97 $\pm$ 2.07
square	857.7 $\pm$ 167.9	7.77 $\pm$ 1.61
% Δ^*	+19%	+11%
P value	<.001	<.001
Unbalanced design (n = 126)		
Denier		
16	765.9 $\pm$ 178.4	7.02 $\pm$ 1.75
19	811.1 $\pm$ 162.2	7.47 $\pm$ 1.83
23	914.1 $\pm$ 182.8	7.99 $\pm$ 2.58
% $\Delta^\dagger$	+19%	+14%
P value	<.001	.04
Teflon		
no	775.8 $\pm$ 192.7	6.72 $\pm$ 1.92
yes	829.2 $\pm$ 155.1	3.88 $\pm$ 1.71
% Δ^*	+7%	+18%
P value	.28	.046

* % Δ = Percentage change in mean between two levels of factor.

† % Δ = Percentage change in mean recovery between 23 and 15/16 dpf. The 15/16 and 15 dpfs were all reclassified as 15/16 for uniformity in the ANOVA.

of the unbalanced design with 126 samples and are presented in the lower panel of Table 1. Teflon coating had the largest micro-occlusion effect on allergen recovery. The presence of Teflon in carpets accounted for a 18% higher yield of Fel d 1 than carpets without Teflon. Teflon, however, was not a significant factor in the recovery of bulk dust, accounting for only a 7% increase in recovery compared with non-Teflon coated carpets.

Denier was a highly significant factor in the recovery of bulk dust but had slightly less of an effect on the recovery of allergen. The larger the denier woven into the carpet, the higher the recovery of dust and allergen. The difference in the mean recovery of dust between the 16 and the 23 dpf carpets was 19%. The percentage difference in the mean recovery of cat allergen was 14% for 16 versus 23 dpf carpets.

The macro-occlusion study represented assays of 56 samples. Recovery of bulk dust was 994.7 $\pm$ 306.5 mg (mean $\pm$ SD) and ranged from 417.4

to 1909.1 mg. Mean Fel d 1 recovery was 8 $\pm$ 2 μ g (range: 5 to 15 μ g).

The results of an ANOVA of the effects of pile height and pile density on cut-pile carpets are presented in Table 2. Pile height was a highly significant factor in recovery of bulk dust and a significant factor in recovery of cat allergen. There was a 64% higher relative recovery of dust from low level carpets (0.25 inch) compared

with high level carpets. Low height also accounted for a 20% higher yield of Fel d 1 than high-height carpets.

The density of the carpet was also a significant factor in recovery of dust from cut-pile carpets but it had no significant effect on allergen recovery. The low-density carpets had a 32% higher yield of dust than the higher density carpets. There were no significant interaction effects on recovery between height and density among cut-pile carpets.

The results of an ANOVA of the effects of pile height and pile density on loop carpets are presented in Table 3. Height was a highly significant factor in recovery of bulk dust but was not a significant factor in the recovery of cat allergen. There was a 21% higher relative recovery of dust from low-level carpets compared with high-level carpets.

The density of the carpet was also a significant factor in recovery of dust and allergen from loop carpets. The low-density carpets had a 54% higher relative yield of dust than the larger density carpets. Low density also accounted for a 40% greater yield of Fel d 1 than the high density level. There were no significant interaction effects on recovery between height and density among loop carpets.

DISCUSSION

Results of the factorial studies support the hypothesis that carpet fiber and construction characteristics affect recovery and conversely retention of

Table 2. Significance of Macro-Occlusion Factors in Dust and Cat Allergen Recovery

	Cut Pile (n = 56) Mean $\pm$ SD	
	Dust (g)	Fel d I (μ g)
Height		
High	725.7 $\pm$ 194.5	8.01 $\pm$ 1.95
Low	1233.6 $\pm$ 244.5	9.63 $\pm$ 2.35
% Δ^*	+64%	+20%
P value	<.001	.05
Density		
High	856.1 $\pm$ 280.0	8.62 $\pm$ 2.23
Low	1130.2 $\pm$ 321.4	9.00 $\pm$ 2.40
% Δ^*	+32%	+4%
P value	<.001	.67

* % Δ = Percentage change in mean recovery between two levels.

Table 3. Significance of Macro Factors in Dust and Cat Allergen Recovery

	Loop (n = 56) Mean $\pm$ SD	
	Dust (g)	Fel d 1 (μ g)
Height		
High	900.8 $\pm$ 245.4	8.35 $\pm$ 2.38
Low	1091.7 $\pm$ 308.9	8.17 $\pm$ 2.44
% Δ^*	+21%	-2%
P value	.004	.75
Density		
High	783.2 $\pm$ 109.1	6.88 $\pm$ 0.75
Low	1209.3 $\pm$ 256.2	9.64 $\pm$ 2.65
% Δ^*	+54%	+40%
P value	<.001	.001

* % Δ = Percentage change in recovery between two levels.

both bulk dust and cat allergen. The results of the micro-occlusion characteristic study support the observations of Rivett et al that carpet soiling can be predicted by a combination of fiber surface area and fiber surface energy.¹⁶

Denier was highly significant for recovery of bulk dust but less so for cat allergen. Large deniers, with their thicker cross-sections, weigh relatively more than their lighter, more narrow, small denier counterparts. An equal weight of carpet would have more small denier fibers than large denier fibers. This results in an inverse relationship between surface area and denier, with small denier fibers accounting for larger surface areas than their large denier counterparts.

Fiber cross-sectional shape was also a highly significant factor in recovery of dust and allergen. Square-hollows fibers had a 19% and 11% higher yield of dust and cat allergen, respectively, than trilobals that have relatively greater surface areas.

The recovery of dust was greater than the recovery of allergen for each micro-occlusion factor tested with the exception of Teflon. Teflon had a very interesting micro-factor affect on allergen recovery. Recovery of Fel d 1 was 18% greater from Teflon-coated carpets than noncoated carpets. Teflon, however, has a greater affect on the release of dust mite allergen than cat allergen. Recovery of Der p1 from Teflon-coated carpets was 33% greater than noncoated carpets.⁶ Teflon, however, did not significantly effect the

recovery of bulk dust, exhibiting only a slight gain in bulk dust recovery. This apparent inconsistency may be explained by the fact that the bulk dust was composed of particles with $<300 \mu\text{m}$. Cat allergen is found in highest concentrations among particles with aerodynamic diameters <2.5 particles (Fel d 1 also is found on particles with diameters $>10 \mu\text{m}$).⁴ Dust mite allergen is found on considerably larger particles, 10 to 40 μm diameter, yet still much smaller in diameter than most of the mass of bulk reference dust.¹⁷ Air currents and mechanical forces, such as the air suction and motion of the HVS3 on carpets, are more effective in removal of large particles relative to smaller particles, as both theory and experience point out.^{18,19} As particle diameter decreases so do the effects of air and mechanical removal forces on particle adhesion.¹⁹ The non-allergen-containing particles, which comprise most of the bulk sample mass, may be sufficiently large so that mechanical or air currents alone are sufficient to remove most of them. Air currents or mechanical motion from vacuum sampling may not have sufficient force to recover the comparatively small allergen particles from carpet in the absence of a fluorocarbon coating. Cleaning of tufted carpets that rely heavily on air currents and mechanical force (including vacuuming with beater bars) may have only a small effect on allergen recovery in the absence of Teflon coating.

The results of the micro-occlusion study reveal that there is little effect on retention of soil and cat allergen based on whether a carpet is a loop or a cut pile.

Macro-occlusion characteristics had a much larger effect on recovery of dust and allergen than the micro-occlusion characteristics. The reason that the macro-occlusion factors, such as pile height and density, are so important in retention of allergen could be due to surface area considerations, much like the micro-occlusion characteristics. The range between the lowest and highest surface areas among the five fibers in this study represents a maximum of only 35% difference. Although specific surface areas of carpet types used in the macro-occlusion characteristic study were not computed, they are expected to represent much larger relative differences in surface area than those in the micro-occlusion study. The difference in surface area between a 0.25 and a 1-inch pile height carpet is approximately 275%, assuming a 0.5-inch diameter of cylindrical two-ply yarns.²⁰ Assuming a linear relationship between surface area and pile density, the difference in surface area between a loop carpet with 5 stitches/inch and one with 12 stitches/inch would be equivalent to a surface area difference of 140%. Therefore, both pile height and pile density have larger relative differences in surface area than those of the micro factors and these differences may explain why macro-occlusion characteristics rank first and second in both dust and allergen recovery.

In this study, height and density differed in their effects on dust and allergen recovery based on carpet style. The extreme dichotomous nature of the macro factor study may be responsible for these results. The range of height levels (0.25 to 0.5 inches) found in loop carpets is small, as reflected in this study and in the market place. It is not surprising, therefore, that only a minimal and non-significant difference in allergen recovery among dichotomous levels of height in loop carpets could be found. This same small range

of height in loop carpets, however, did yield a significant difference in recovery of bulk dust. Perhaps this disparity is due to the fact that the Fel d 1 allergen, which exists primarily on particles $<2.5\ \mu\text{m}$, is affected less by differences in surface area of a carpet than the larger bulk dust, which is primarily composed of particles $<300\ \mu\text{m}$. As described earlier in the discussion of the effects of Teflon on allergen recovery, smaller particles are held more tightly to carpet than larger particles. The larger range of heights used in cut-pile carpet (0.25 to 1 inch) may be the reason for its comparatively large, significant effect on allergen recovery. Loop carpets, on the other hand, have a larger range of density characteristics (7 stitches/inch) than cut pile carpets (4.7 stitches/inch) and these differences may also explain why density was a significant factor in recovery of allergen in loop carpets but not among cut pile. Further research should be performed to determine how the range of height and densities of carpet will differentially affect allergen recovery.

High-surface area and non-fluorocarbon coated carpets, which act as a kind of filter or reservoir to retain allergens could possibly be considered a superior means of allergen avoidance than low surface area and fluorocarbon-coated carpets, which retain less bulk dust and allergen. Carpets with smaller surface areas and fluorocarbon coating will be easier to clean than higher surface area and non-fluorocarbon coated carpets. The most appropriate choice for allergen avoidance, when choosing between the extremes of surface areas and fluorocarbon coating, would appear to be selection of a carpet which is easiest to clean. Carpets are warm and soft and "invite" children and adults to lay on them, initiating direct contact with possible sources of cat allergen. Hand-to-mouth or hand-to-nose contact with a carpet that has been difficult to clean, because of its high soil retentive characteristics, may expose people to higher allergen concentrations than they would other-

wise have had from lounging on a carpet with low retention characteristics.

This study examined the major characteristics of carpet that were expected to affect retention of cat allergen based on theories and mechanics of soiling. Carpet wear and dust-loading factors were not examined in this study and these factors may also affect allergen retention and release into the home environment. Research should be conducted to examine these additional carpet properties and their effects on allergen retention. Findings from this study, however, should be helpful to those considering purchase of a new carpet from which allergen removal is optimal.

CONCLUSIONS

Carpet purchasers should probably consider that carpet characteristics would affect the ease of removing dust and cat or dust mite allergen. A carpet style per se, such as cut pile or loop, did not affect allergen removal. Carpets which are the easiest to clean would have the following characteristics for release of cat allergen and in this approximate order of importance: low pile density and height, fluorocarbon coating of fibers, high denier per filament, and use of low surface area fibers such as the square-hollow fiber shape. There is no practical difference between how carpet characteristics affect dust mite or cat allergen retention. If effective allergen avoidance is based on selection of specific carpets that are easier to clean than others, then cleaning should be performed frequently to prevent the resuspension of particles carrying cat or other aeroallergens.

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- Request for reprints should be addressed to:
Roger D Lewis, PhD, CIH
Saint Louis University School of Public Health
3663 Lindell Blvd.
St Louis, MO 63108*
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