Retention and Removal of House Dust Contaminants from Carpet: Integrating our Knowledge of Source Dusts, Carpet Properties, and Carpet Cleaning for a Healthier Indoor Environment

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ABSTRACT

The purpose of this paper is to describe the state of the science in retention and removal of house dust contaminants in carpet. A brief review of the literature on carpet contaminants, its health concerns, sources and pathways, mechanics of soiling, and cleaning will be presented. The importance of lead, dust mite and cat allergen, both as serious indoor pollutants and as divergent exposure pathways, is emphasized. Data is presented on the importance of fluorocarbon coatings, surface area, and wear retention and removal of allergens and lead. Although high-suction, high-flow rate vacuum cleaners appear to have an important role in cleaning dust contaminants, many household vacuum cleaners clean with only marginal difference. Carpet cleaning systems that remove dry particulate, lead and dust mite allergen appear to be superior or equivalent to wet removal methods in new studies. The interaction of carpet types with vacuum cleaners and with dust loading, however, suggests that a systems approach be used for addressing the removal of house dust contaminants from carpet. If carpet is to remain a staple of the indoor environment, then an understanding of the source of dust-borne contaminants and of how they are retained, released, and removed may inform the debate on how to maintain a healthy indoor environment.

INTRODUCTION

As indoor air quality and its importance to public health have become household words, an increasing amount of scrutiny has been given to sources of pollutants indoors that could lead to serious health effects or diseases, such as asthma or lead poisoning. Many in the scientific community have categorized carpeting as a "reservoir," although at times a "source" of indoor pollutants.[1] A serious debate may yet emerge, however, about the role of carpet as a filter, drawing pollutants from the atmosphere into its fiber spaces. Although the scientific literature is replete with references on how carpet can capture particulates, there are few to no articles that demonstrate the protective effects of carpet on human health. On the other hand, there are a number of articles that ascribe asthma and other health conditions to carpet, though it is equally difficult to demonstrate any real evidence to support that contention. Carpet can serve an important role in the indoor environment – providing insulation to a cold floor, sound dampening, and a place to lounge. The purpose of this paper is to describe the state of the science in retention and removal of house dust contaminants in carpet. A brief review of the literature on carpet contaminants, its health concerns, sources and pathways, mechanics of soiling, and vacuum cleaning will be presented. The importance of lead, dust mite and cat allergen, both as serious indoor pollutants and as divergent exposure paths, is emphasized. If carpet is to remain a staple of the indoor environment, then an understanding of the source of dust-borne contaminants and of how they are retained, released, and removed may inform the debate on how to maintain a healthy indoor environment.

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Relationships between house dust contaminants, exposure pathways, and human health

Concerns have been raised by a number of environmental scientists, activists, and government agencies that carpet can be a reservoir for house-dust contaminants or a niche for microorganisms. House dusts are a heterogeneous mixture of inorganic and organic particles such as soil, sand, residue from volatile organic compounds used in the household, outdoor materials such as road tar, pollens, decaying vegetable matter, mammalian skin scales and hair, and a host for dust mites, bacteria, and fungi.[1]

Many references already exist about the allergenic nature and exposure pathways of many house dust contaminants.[1,2,3] A great deal of attention, however, has been given to the importance of lead, dust mites, and cat allergens in the indoor environment. Much of this attention is justified since dust mite and cat allergen sensitivity are major predictors of asthma; and many children, especially in urban neighborhoods, have high blood-lead levels with serious health consequences.[3,4] The case for an in-depth understanding of these contaminates, can also be made on other grounds, and this is largely due to the vast differences in aerodynamic behavior of the dust mite as opposed to the cat allergen and the hand-to-mouth route of exposure for lead.

Dust Mites

The dust mite allergen, a glycoprotein, is largely found on dust mite fecal particles that are between 10-40 microns in diameter.[5] Because of its large aerodynamic size and consequent high settling velocity, it has proven to be difficult to sample in the air.[5,8] Recent success has been made by measuring human exposure to dust mite allergens using a newly developed nasal filter that can be directly assayed for the allergen.[9] However, epidemiological studies supporting sensitization to dust mite allergen and subsequent development of asthma are strongly correlated to surface samples of dust mite allergens.[10] Once thought to be too large to cause asthma, the fecal particle's large volume has been theorized to produce high concentrations of allergen on the bronchial mucosa.[3] The large aerodynamic size of these particles, coupled with the strength of association of surface-sample exposures to dust mite sensitivity, suggests that sensitization and perhaps periodic asthma episodes are related to direct nasal inhalation of these allergens from surfaces, such as pillows, bedding, carpet, and hands. Short ragweed pollen, an experimental surrogate for the dust mite fecal particle, has been shown to enter the nasal pharynx in surprisingly high proportion from direct inhalation off a pillow.[11] There is also ample evidence for the link between dust mite exposure and atopic dermatitis.[12, 14] This link illustrates the importance of understanding transfer efficiency of dust mite allergen from a surface across the epidermis.

Surface characterization studies have identified different sources of dust mite contamination in homes.[2,6,15] Hung et al. found moderate to high levels of Der f 1 in office carpeting and upholstery (> 2 ug/g dust) but other investigators found little to no dust mite allergen in schools and offices. This difference is probably due to differences in moisture, temperature, and nutrients (human skin scales and fungi).[16] The importance of humidity, seasonal variation, temperature, and habitats on mite growth has been reported in several articles.[1,2,5,6,10,17-19] *Dermatophagoides pteronyssinus* thrives at 25^0 C and 80% relative humidity. *Dermatophagoides farinae* thrives at higher temperatures (30^0 C) and can survive much drier climates (as low as 33 % RH).[7] The microenvironment of a bed, where people typically sleep from 6-10 hours a day, can generate temperatures of 37^0 C due to the warmth of the human body.[7]

A review article on house dust mite ecology concluded that in addition to the free water content or the frequency of condensation in a fabric surface (such as carpet), surface characteristics of the fabric may also be an important factor of mite growth.[19] Leupen et al. found that mites and other microarthropods occupy only the boundary layer of materials with penetration no greater than 1-2 mm.[10] Van Bronswijk et al. studied the penetration of dust mite allergen through the cross-section of a mattress and found that allergen penetrated 12 mm into the center and 6 mm into the sides of the mattress.[6] This suggests that mite infestation and allergen retention may be a problem of only the top layer of a mattress, sofa or other upholstered objects.[6]

Finding correlations between dust mite allergens retained on a surface with those re-suspended in the air may suggest methods to model human exposures based on both surface retention and re-suspension variables. A limited number of studies were initiated to correlate the surface quantities of dust mite allergen found in houses to airborne concentrations. Generally, these studies showed no correlation or very limited correlation. Swanson interpreted his findings of weak correlations between surface and air concentrations of dust mite allergen by hypothesizing that the air concentrations vary as a function of house ventilation, mite production, and rate of re-suspension.[8]

A few studies have reported on the possible relationship between factors that favor mite habitation and those that favor antigen adhesion to fabric surfaces. Besides relative humidity, which positively affected mite growth, Arlian found higher levels of mites in carpet than on other surfaces in the homes.[20] High pile carpet contained significantly more mites than short pile carpet, which the authors suggested was due to the better microbiological growth potential in these carpets. It is not known, however, whether long pile carpet favors dust mites because of more room for attachment, greater moisture retention capabilities, or more accumulated house dust, which serves as a food source. Although dust mite growth is highly dependent on the temperature and water content of a micro-environment (25^0C at 80%RH is optimal), the relative humidity in the room air directly affects the house dust fauna.[19]

There are, however, significant differences between psychometric properties of room air and that within floor coverings – although there appears to be little difference between carpet types.[20,21]

In an observational study of the relationship between airborne dust mite allergen and asthma, Price et al. found that among residential home carpet with equivalent levels of dust mite allergen, some carpet styles had higher yields of airborne allergen than others.[6] These investigators reported that characteristics of different surfaces might influence the amount of mite allergen in air samples.[22] This study, however, was a very small case study of limited scope and the data in the article are not sufficient to support the hypothesis that carpet directly or indirectly affects airborne concentrations of allergens.

Cat

Cat allergen includes both *Fel d 1* (*Felis Domesticus* allergen 1) and cat serum albumin. *Fel d 1* is a glycoprotein and is the predominant allergen found in all cats.[23] This allergen is found in both the sebaceous glands of cats and in saliva, hence, cat dander and frequent licking of the fur are sources or behaviors that lead to cat allergen indoors. Over 2.3 % of the US populations have positive skin prick tests for cat dander extracts. Experiments by Lucynska et al. determined that a significant proportion of cat allergen remains airborne in undisturbed conditions, and this is largely due to its small aerodynamic size, approximately 2.5 microns.[23] The small aerodynamic size and its electrostatic properties may also be responsible for the observation by some authors that the particles stick to walls and other surfaces.[24] Cat allergen has been observed to stick to people's clothes and carried into houses exposing non-cat owners to cat allergen.[23]

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.[1,25,26] Some investigators have described the importance of environmental factors, particularly “soft” (textile) furnishings, on airborne cat allergen.[27,28] For example, deBlay et al. reported that in a controlled setting, carpet surfaces accumulated 100 fold more *Fel d 1* than what accumulates on a polished floor.[29]

Lead

Sources of lead exposure to children include paint, dust, soil, and water. Lead in gasoline has diminished as a source over time. Lanphear has summarized children’s exposures to lead and lead sources and pathways in a recent government publication. Children's blood levels are correlated to lead exposure from hand contact with dust-borne lead in and around homes.[30]

Although the literature on relation of carpet dust-contaminants to direct human exposures is scanty at best and hyper-exaggerated at worst, there have been some important studies that examine both carpet-borne contaminates and human exposure. In a study to investigate a number of environmental, social and sampling parameters on blood-lead levels of 200 children, investigators from the University of Rochester School of Medicine found that blood-lead values were correlated with flooring surface type in residences.[30] Carpet floors and non-carpet floors were both significantly related to children's blood-lead values. However, among five different sampling methods evaluated, carpet was found to be significant for each method ($p< 0.01$ - $p < 0.05$), whereas hard floors were significant in two methods used (wipe and a cyclone collection method). However, when investigators wanted to determine which surfaces should be routinely measured, a regression analysis was run adjusting for significant predictors of blood-lead and carpet surfaces were not significantly associated with blood-lead even when children with only two or more carpet floors were included in the model. Lanphear et al. concluded that more research should be performed to determine the differential effect of flooring types and cleaning techniques on blood-lead reductions.[30]

Carpet Structure and Carpet Soiling

Some soil retention studies in the textile literature may rely on methods that are inappropriate for evaluating allergen retention on carpet. These methods are used to determine the "apparent" soil on a carpet surface. Apparent soiling procedures depend on a protocol in which white light is shined onto a carpet specimen and the percentage of light that is reflected back through red, green, and blue filters is measured by a colorimeter.[31] Soiling is computed by comparing non-soiled samples to soiled samples with measurements reported as color differences. A review of the literature by Brown et al. found that most studies of carpet soiling are based on apparent or visual methods of soiling.[31] Apparent soiling, however, is not directly related to real soiling.[31] Studies which use apparent soiling as a measure of the amount of soil retained or released by carpet may be either unrelated or inversely related to the problem of dust and allergen retention and recovery. Using these methods, several investigators found differences in soil retention based on fiber type. For example, wool was found to have fewer soiling characteristics than nylon.[32] However, no actual difference in soil retention among fibers appears to exist when gravimetric experiments are used to recover soil.[31]

Micro-Occlusion Characteristics

Micro-occlusion characteristics pertain to factors that affect retention of soil to fiber surfaces in addition to the trapping of particles in a fiber's pores or crevices. Masland was one of the earliest scientists to investigate fabric soiling and micro-occlusion characteristics. Using photomicrographs of soil on rayon versus wool fiber, he concluded that two principles apply to soil retention on fibers: fiber diameter and the cross-sectional outline (shape).[33] Low soil retention depends on the combined characteristics of a smooth-round cross-section and a large diameter fiber (> 27 µm).[33] Weatherburn et al. confirmed these findings in 1957 and concluded that soiling of fibers was a linear function of gross surface area of the filaments.[34]

Carpet manufacturers define fiber diameter indirectly as a denier number. Denier numbers are expressed as the weight in grams of 9,000 meters of continuous fiber. Denier is also expressed as denier per filament or "dpf" which is defined as the denier number for a specific fiber. Deniers typically range from 15 to 19 with larger deniers recently emerging on the market.[35,36]

There are several types of fiber cross-sectional shape on the market today. One of the first "shapes" was the round fiber. A later generation of fibers was developed to diffuse light, making it more difficult to visually detect soil on carpet surfaces. This later generation of fibers has a variety of shapes, including trilobal, kidney, and "dog-bone".[35] Square-hollow shaped fibers differ from the earlier generation round fiber; not only are they square but they also have hollowed out interiors for channeling light away from the surface of the fiber. The fiber shapes often used to diffuse incoming light on a carpet are higher in surface area than less light-diffusing fibers such as the round fiber that has no angular depressions or holes in its cross-section.

Fiber finishes may also affect the extent of soil retention or soil resistance. Fiber finishes for washable textiles have chemical formulations that reduce entrapment of oily particles on fibers, reduce soiling by reducing the accumulation of electrostatic charge, and increase hydrophilicity, which allows for easier release of soils in water. Carpet fibers have finishes which also resist soiling and staining by the addition of fluorocarbons. There are over five commercially known fiber finishes that resist soiling and staining including Scotchgard®, Teflon®, and Stainmaster®, as well as several additional brands of fluorochemical finishes.

The chemical formulation for most finishes is CF_3-CF_3-$(CF_2$-$CF_2)_n$ or $(CF_3)_2$-$(CF_2$-$CF_2)_n$ where n is between 1 and 6.[34] The fluorocarbons cover the fiber surfaces with a hard film of an inert substance. This film, only a few molecules thick, sheathes the fiber, reducing the opportunity for fine particulate material to be retained by micro-occlusion.[35] The same finish prevents stains by reducing the wetability (lowering the surface energy) of the fiber.

Other finishes have been developed for dissipation or grounding of electrostatic charge accumulated on a carpet surface in addition to antimicrobial finishes used to resist molds.[35]

Macro-Occlusion Characteristics

The textile literature provides few clues about the importance of macro factors on soil retention; however, Hart et al. found macro-occlusion to be a significant factor in retention of soil on carpet.[37] Because Hart et al. based his conclusions on the use of the apparent soiling method, the relevance of these findings to allergen retention is debatable. Benisek studied the effect of increasing pile weight (defined as ounces per square meter of carpet) on soilability of wool and synthetic carpet (Acrilan). Benisek found that wool carpet retains less soil with increasing pile weight while synthetic carpet retains more soil with increasing pile weight. Benisek also found that loop carpet appears to soil more than cut pile carpet.[32] Other researchers have found that loose constructions are less prone to soiling and that loop pile retains less soil than cut pile.[35] Lewis found a direct relationship between surface area and dust retention, with high pile and high density carpet retaining more dust than their lower counterparts. [38]

The wearing of a carpet can also affect its ability to retain dirt, with worn out or matted carpet releasing more dust than less worn carpet.[35] This may no longer be the case with newer generations of carpet that do not lose fiber with wear. The wearing of a carpet is often related to the age of a carpet but not in all cases. Wear is clearly related to carpet usage, whereas age is a less direct surrogate for wear. The interaction of wearing *and* surface area on allergen retention has not been reported, but our preliminary investigations suggest that for carpet with a short pile height, a cut pile construction, when unworn, has the lowest capacity to retain dust.[39] The interaction of surface area, wear, and cleaning of lead-contaminated dust has been demonstrated.[40]

A study by a consortium of carpet fiber companies, chemical companies, and carpet mills determined that no simple relationship could be found between carpet construction characteristics (such as pile density and pile thickness) and soil retention. The authors of this study concluded that there is probably a relationship between carpet construction and soiling but more research is needed to confirm this hypothesis.[31]

The carpet manufacturing industry has described certain qualities that define the construction of carpet and that may affect macro-occlusion, including: density (the number of length-wise yarns in one-inch of carpet); pile height (the height of the carpet between the backing and the top); and twist (the number of yarn plies twisted together per stitch).[37,41] Taken together, these qualities may describe a complex surface area available to which particles adhere.

Macro-occlusion may also be affected by the specific style of a carpet. Style is dependent on tufting, which is a function of how the carpet is sewn and cut. There are three broad categories of tufted carpet styles or textures that have been classified by the carpet manufacturing industry: *loop* - uniform level loops; *cut-pile looped* - a combination of cut piles and looped piles; and *cut-pile* - all piles have been cut.[37]

Vacuum Cleaning Systems

Carpet and Upholstery Cleaning

There are essentially four ways to clean carpet and upholstery: dry vacuuming, hot water extraction, added chemical agents, and a “bonnet” method, primarily used to remove stains from carpet.[42] Since staining is irrelevant to the goals of allergen or lead removal, three broad classifications of cleaning or removal of lead can be identified: dry vacuuming, water extraction, and use of chemical agents.

Some studies of lead removal from carpet have indicated that dry vacuuming is superior to shampooing and that shampooing removed only 18% and 8% of lead, respectively, from carpet and furniture upholstery.[43,44] Traditional shampooing, which maybe effective in stain removal but not particulate removal, was not evaluated in this study. Although vacuum cleaning devices are not discussed to any great extent in referenced journals, there are a number of trade association documents and consumer magazines that delineate the features of vacuum cleaning machines. A discussion of the type of machines available and their major distinctions follows.[45]

Dry vacuuming

There is apparently little difference between residential and commercial dry vacuums. Often, the major differences between the commercial and residential machines are durability and the longer warranties for commercial vacuums.[46] Major categories of dry vacuuming that are pertinent to dust contaminant removal from carpet and upholstery are the: *Traditional upright* (unfiltered air passes through fan); *Pre-filter air upright* (unfiltered air passes through a filter before entering the fan using a one- or two-motor design); and the *canister* design (standard and power nozzle).[45]

Traditional upright

The main characteristic of the traditional upright is the path which the air travels as it moves through the cleaner. The air enters the nozzle near the floor and travels directly toward the suction-producing fan, carrying the dirt with it. It then travels through the fan and is pushed upward into the paper or cloth filter bag. The air is filtered as it passes through the bag. If the paper bag is supported by a flexible outer cloth or vinyl bag, it is the traditional design. Some of these vacuum cleaners have a fill capability at the top of the vacuum collection bag, preventing dust from being blown upward into the bag. A traditional upright can also employ a filter bag which is housed within a plastic shell. This shell is not sealed and has no pre-filter, unlike the pre-filter upright.

Examples of the traditional design include: commercial Eureka uprights, commercial and heavy duty Sanitaire (by Eureka) uprights (models SC888F and S663B), commercial and heavy duty Royal uprights (models 1040Z and 4000), and Kirby uprights. All of these use a large diameter fan. There are inexpensive traditional upright models that offer on-board attachments at relatively low prices. These often have high-powered motors driving relatively small high-speed fans. These include: Eureka Bravo I and II series (model numbers starting with either seven or nine) and low priced Dirt Devils (< $100) by Royal.

Pre-filter Air Upright

One-motor design

The main characteristic of the pre-filter design is that the air is filtered before it enters the fan. While two motor uprights usually fit this description as well, this designation typically refers to an upright using only one motor to create the suction and drive the brush roll. The air enters the nozzle near the floor and travels toward the paper or cloth filter bag, carrying the dirt with it. The bag retains most of the dirt and dust while allowing the air to pass through the filter media. The air then travels through a filter pad to be cleaned further before entering the high speed suction fan or fans.

The pre-filter uprights combine a canister type motor and filtration system in the main body. The vertical configuration of the upright is maintained while performance with the attachments is improved because the canister motor creates significantly more actual suction that the traditional upright motor design. This design can be identified by looking at the filter bag and the supporting container. If the rigid bag is sealed and a foam or fiber filter pad is at the bottom of the enclosure, it its probably the pre-filter design.

Examples of the clean air design include the Panasonic MC-V7347 and MC-V5217, the Sharp EC-TU4707 and EC-12TWT4, the Hoover U5465-900 WindTunnel, and the Eureka 4472AT and 4352DT. The higher priced Dirt Devil by Royal uses this design while the lower priced Dirt Devils use the traditional design.

Two-motor upright

The main characteristic of the two-motor upright is that it combines a canister type motor and filtration system in the main body with a power nozzle. Most, if not all, two-motor uprights give the user the option of stopping the brush roll for cleaning bare floors or when cleaning with attachments. Since its own motor drives the brush roll, if its rotation slows in thicker carpet, the suction produced by the suction motor is not affected like it would be in a one motor upright.

Depending on the brand, very little difference may be found between performance of a two-motor upright and the one-motor pre-filter upright. Some two-motor uprights use a cogged or gear-type belt to transfer power from the brush motor to the brush roll, which helps in eliminating the belt slippage for better carpet agitation.

Examples of the two-motor upright include Lindhaus DP-514 Evolution and the Eureka Excalibur Upright Series. The Dirt Devil Ultra MVP by Royal and all uprights by Electrolux are two-motor uprights.

Canister

Standard Canister

The standard canister allows air to enter a nozzle near the floor and travel through a wand and hose toward the paper filter bag carrying the dirt with it. The bag retains most of the dirt and dust while allowing the air to pass through its filter media. The air then travels through a filter pad to be cleaned further before entering the suction fan or fans. Since the air has been filtered, it is allowed to flow through the motor to cool it. After leaving the motor the air is often filtered by additional exhaust filters to remove even more fine particles before it leaves the vacuum cleaner. Examples of this design include the Sharp E.C.-7311, the Eureka 3676 Powerline Plus and the Eureka Mighty Mite.

Canister Two-Motor Power Team

The two-motor canister vacuum cleaner teams a canister-type vacuum cleaner with a motorized power nozzle. Examples of the two-motor power team include Royal 4650 Power Team, Panasonic MC-V9647 and MC-V9620 Power Teams, and the Eureka 6865B and 6826A Power Teams.

Water Extraction Vacuums

Because all hot water extraction vacuums work on the same principles of delivery of heated water, detergents, and/or surfactants to carpet or upholstery, there is not a great deal of variation among them that could differentially affect lead removal. However, there are upright hot water extractors where the tanks, suction motor, and main nozzle are built into one unit, as well as canister hot water extractors with separate hose and nozzle from the tank and suction motor that is pulled after the user. Most of the uprights have brushes mounted in the same area to agitate the carpet for better cleaning effectiveness, while some of the canister extractors do and some do not have motor-driven revolving brushes in their nozzles to aid in the cleaning process. Domestic upright extractors include the Hoover Steam Vac and domestic canisters include the Bissell Power Steamer. Commercial equipment includes the self-contained Tornado Marathon Extractor, Kent SelecTrac 18 and DuraTrac 19.

The technique of the professional with the application of the system may be more important than the differences in the types of extractors.[46] Dry vacuuming is a prerequisite before hot water extraction. No matter how elaborate or powerful they may be, hot water extraction units are not designed to efficiently remove insoluble particle and fibrous soils from carpet piles. Important factors in hot water extraction units are water lift and airflow. There is no real difference between steam (hot water) extractors and liquid-chemical delivery vacuum systems because in hot water extraction, pre-conditioners and detergents are almost always used.

Dry-Chemical Delivery Vacuums

Variations of dry-chemical delivery machines depend not on the machine itself, but on the classification of the carrier component used. The first type is the clay-based carrier that apparently has practically disappeared from the market. The second type is cellulose-based products that are the most popular. The cellulose-based product is made of highly absorbent, ground cellulose or wood that produces a fairly uniform particle size that is more readily removed from carpet of low to medium pile height. An example is the “Host” Company system. The third type is a synthetic polymer-based product, which is actually a by-product of fiber manufacture. It is comparatively expensive to produce, resulting in a higher product cost. An example is the Capture System.

Laboratory and Field Studies

Many studies have demonstrated the effects of vacuum cleaning on reducing a number of contaminants in house dust.[29, 47-49] The following section reviews several studies, many stemming from our laboratories, that demonstrate specific effects of carpet characteristics and properties on the retention and recovery of allergen using standardized surface sampling methods. These are referred to as retention studies since they determine the recovery of antigen or dust in a collection device from carpet and therefore also indicate retention of antigen or dust not released. The second section is entitled Cleaning and Acaricidal studies.

Retention Studies

We performed a study that characterized factors affecting the retention of dust mite and cat allergens on tufted carpet.[38, 50] The experiments were designed to test the hypothesis that the amount of allergen-containing dust (*Der f 1* and *Fel d* 1) recovered from vacuum samples of tufted carpet sources is dependent on micro (fiber) or macro (construction) retention characteristics of the carpet. This study comprised twenty-six types of carpet which were custom manufactured as part of a two-stage factorial experiment using 182 carpet samples. Carpet differed with respect to fiber denier, cross-sectional shape, presence of fluorocarbon treatment, carpet style, pile height, and pile density. Allergen extracts previously prepared for dust mite allergen[51] were assayed for *Fel d* 1 and evaluated for main and interactive carpet effects. Similarities and differences with dust mite allergen retention were reported. The methods for these studies have been reported in detail elsewhere.[38,52]

Results of the factorial studies supported the hypothesis that carpet fiber and construction characteristics affect recovery and, conversely, retention of bulk dust, dust mite, and cat allergen. The results of this study, are summarized in Tables 1 and 2, and support the observations of Rivett et al. that carpet soiling can be predicted by a combination of fiber surface area and fiber surface energy.[53]

Denier was highly significant for recovery of bulk dust but less so for cat allergen. The relative increase in the mean recovery of dust from the 16 to the 23 dpf was 19%. Large deniers, with their thicker cross-sections, weigh relatively more than their lighter, narrower, 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-hollow fibers had a 19 % and 11% higher yield of dust and dust mite allergen, respectively, than trilobals that have relatively greater surface areas.

Table 1. Rank Order of Effects of Carpet Characteristics on Dust Mite Allergen Recovery
Percentage Increase in Mean Recovery (% MEAN) among
Dichotomous Levels of Each Factor

Rank	**Micro and Macro Factors** (levels)	**Der f 1 & p1** (mean Δ%)[1]	**Estimate Relative difference** in surface area across factor-levels (%)
1	Density-loop, (low > high)	60**	140%
2	Height-cut pile,(low > high)	29**	275%
3	Teflon, (yes > no)	28**	not applicable
4	Denier, (23 dpf > 15/16 dpf)	14**	18%
5	Shape,(square h. > trilobal) **	14**	15%
6	Style (loop)	8	n.d.
7	Density (cut pile)	8	n.d.
8	Height (loop)	4	n.d.

1 = The mean of two values, Der f 1 mean Δ% and Der p 1 meanΔ %

* * = Highly significant , $p < 0.001$ * = Significant, $p < 0.05$; n.d.=no difference

Table 2. Rank Order of Effects of Carpet Characteristics on Cat Allergen and Bulk Dust Recovery

Rank	**Micro and Macro Factors** (levels)	**Fel d1** (meanΔ%) [A]	**Bulk Dust** (mean Δ%)[A]
1	Density-loop, (low > high)	40 **	54**
2	Height-cut pile,(low > high)	20*	64 **
3	Teflon, (yes > no)	18 *	7
4	Denier, (23 dpf > 15/16 dpf)	14 *	19**
5	Shape,(square h. > trilobal)	11 **	19**
6	Style (loop)	2	2
7	Density (cut pile)	4	32**
8	Height (loop)	-2	21**

[A] Rank determined by percentage change (Δ%) in mean recovery between levels of each factor
* * = Highly significant , $p < 0.001$ * = Significant, $p < 0.05$

The recovery of dust was greater than the recovery of dust mite 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 carpet than non-coated carpet. Teflon, however, has a greater affect on the release of dust mite allergen than cat allergen. Recovery of *Der p*1 from Teflon-coated carpet was 33 % greater than non-coated carpet.[51] Teflon, however, did not significantly affect 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 µm. Cat allergen is found in highest concentrations among particles with aerodynamic diameters < 2.5 µm particles (*Fel d* 1 also is found on particles with diameters > 10 µm).[27] Dust mite allergen is found on considerably larger particles, 10-40 µm diameter, yet still much smaller in diameter than most of the mass of bulk reference dust.[54] Air currents and mechanical forces, such as the air suction and motion of the HVS3 on carpet, are more effective in removal of large particles relative to smaller particles, as both theory and experience point out.[55,56] As particle diameter decreases, so do the effects of air and mechanical removal forces on particle adhesion.[56] The non-allergen containing particles, which comprise most of the bulk sample mass, may be sufficiently large so that mechanical motion and air currents alone are sufficient to remove most of them. However, air currents and 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 carpet 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 this 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. 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 carpet (0.25 inch) compared to high level carpet. Low pile also accounted for a 20% higher yield of *Fel d* 1 than high-pile. 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 carpet compared to high-level carpet. The density of the carpet was also a significant factor in recovery of dust from cut-pile carpet but it had no significant effect on allergen recovery. The low-density carpet had a 32% higher yield of dust than the high-density carpet. There were no significant interaction effects on recovery between height and density among cut pile carpet.

Carpet density was also a significant factor in recovery of dust and allergen from loop carpet. The low-density carpet had a 54% higher relative yield of dust than the larger density carpet. 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 carpet.

Macro-occlusion characteristics had a much larger effect on recovery of dust and allergen than the micro-occlusion characteristics. The reason that 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 a 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 would be approximately 275%, assuming a 0.5 inch diameter of cylindrical two-ply yarns.[57,58] 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") found in loop carpet 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 carpet could be found. However, this same small range of height in loop carpet 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 µm, is affected less by differences in surface area of a carpet than the larger bulk dust, which is primarily comprised of particles < 300 µm. 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. Therefore, it seems plausible that the recovery of the relatively small allergen-containing particles will be unaffected by carpet that is either extremely low in density or extremely low in pile. The larger range of heights used in cut pile (0.25 to 1") may be the reason for its comparatively large, significant effect on allergen recovery. Loop carpet, on the other hand, have a larger range of density characteristics (7 stitches/inch) than cut pile carpet (4.7 stitches/inch) and these differences may also explain why density was a significant factor in recovery of allergen in loop carpet but not among cut pile. Further research should be performed to determine how the range of height and densities of carpet would differentially affect allergen recovery.

High-surface area and non-fluorocarbon coated carpet, 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 carpet that retain less bulk dust and allergen. However, carpet with smaller surface areas and fluorocarbon coating will be easier to clean than higher surface area and non-fluorocarbon coated carpet. 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. Carpet is warm and soft and "invites" 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 otherwise have had from lounging on a carpet with low retention characteristics.

Several investigators have determined that sampler efficiency, which could be analogous to cleaning, is related to lead dust loadings, carpet pile height, air velocity through the sampler, and relative humidity.[59,60] Tufted carpet is also subject to wear or matting down, which often improves release of particulates; however, this effect has not been systematically evaluated.[35] Ewers et al. determined that the unique construction of a carpet coupled with vacuum cleaning prevents total removal of lead at the surface even after 10 minutes of vacuuming.[60] Ewers et al. also suggested that carpet surfaces can actually be loaded with more lead dust after than before cleaning.[60] However, this observation was valid only for the first two minutes of cleaning, when the greatest quantity of soil would be expected to come to the surface of a carpet.

Cleaning and Acaricidal studies

Two studies are summarized here which our laboratories led and conducted. Both studies evaluated whether wet or dry vacuuming was superior to remove lead from carpet or dust mite allergen from carpet. Also, the lead study had several additional facets: comparisons are made among nine different vacuum cleaners, representing three categories of cleaners: pile density, carpet wear, and lead loading together were evaluated; and a field study or the use of naturally soiled carpet, were used for a comparison of dry versus wet cleaning. The lead study made use of olefin, staple-tufted carpet and the dust mite allergen cleaning study made use of spun wool-tufted carpet. The methods were very similar with some differences: a standard reference dust containing lead or dust mite allergen was distributed across carpet using methods described by Lewis et al. in both studies.[52] Dust was embedded using a locked-in roller with the lead vacuum studies, similar to what had been used in the retention studies cited earlier in this paper. The dust mite allergen cleaning study made use of a "hexapod-walker" machine, which both embedded and artificially wore carpet as required. Carpet walkers wore the carpet used in the lead studies prior to deposition of lead-containing dust. Analysis of allergen or lead recoveries was computed by comparing the difference in control carpet cores, unworn or no deposits of dust, to carpet that had been spiked with dust-borne lead or allergen. Assays for lead and allergen were performed by whole carpet extraction using anodic stripping voltametery or enzyme linked immunoassays for lead and allergen respectively.[40,61]

Study design - Lead Cleaning

Nine dry-vacuuming machines that represented a range of models, commercial and residential, both high-end and inexpensive machines, were evaluated for lead removal from carpet. The machines represented three categories of dry-cleaning: traditional upright, two-motor pre-filter upright, and canister. This was a one-factor design. Seven replicates were taken for each cleaner, representing 63 test carpets. This experiment was preliminary by design and originally intended for screening vacuum cleaners to be used in subsequent experiments on lead removal with dry versus wet vacuuming and carpet variables with lead loading. Although vacuum cleaners weren't selected for their nozzle suction or airflow, it was hypothesized that cleaners with higher nozzle suction would have superior lead removal characteristics. Assignment of cleaner was generated at random. A medium-density (8.2 stitches/ inch, 37 oz/sq. yd, 0.5 inch pile height) was used throughout this experiment.

The objective of the second experiment in the lead study was to determine whether dry vacuuming procedures were just as effective as vacuum procedures that used hot water plus detergents for removal of lead from carpet. Pile density was the second independent factor in this experiment, with two levels, high (9.0 stitches/inch) and low pile density (5.3). There were a total of four factor-levels with seven replicates per level that equaled 28 samples. Preliminary experiments demonstrated the success of dry vacuuming with only marginal improvement with detergent cleaning. Each wet vacuuming was preceded by two seconds of dry vacuuming. Dwell time for liquid injected into each carpet was approximately two seconds (the time it took to dispense the liquid uniformly over the surface of the carpet). Four seconds were spent in vacuuming suspended material and detergent. The total cleaning time for both dry and wet cleaning was both 6 seconds per test carpet or 22.5 ft^2/min. The null hypothesis was there would be no difference between the two methods (dry vs. wet).

A pre-filter, two-motor upright (PreUp4) was used for all dry vacuuming trials. A residential, moderate cost, detergent-extraction, upright, vacuum machine (De-Ex), was chosen for use in this study. A commercial ("C") high surfactant solution (12.9 % total surfactant, alkyl phenol ethoxylates, a non-ionic) was used in the detergent extraction vacuum cleaner.

The objective of the third experiment in the lead study was to determine the effects of specific carpet characteristics on lead loading. The primary hypothesis was that surface area would affect lead removal. Carpet wear was also hypothesized to affect lead removal, with worn carpet predicted to hold less lead than new carpet. Loading was also predicted to affect vacuum cleaning efficiency.[59] This experiment had three fixed factors, with two levels per factor for a total of eight factor-levels. There were seven replicates per factor-level for a total of 56 samples. The factors and their levels evaluated were pile density, high (3) and low (1); lead loading, high and low; and carpet wear, worn and not worn. The pre-filter upright 4 was used throughout this experiment and carpet was vacuumed using an automated system without technicians. All carpet combinations were randomly chosen for vacuuming.

The purpose of the fourth experiment in the lead study was to field test and validate major categories of vacuum cleaner systems under actual residential conditions. Two dry methods, the traditional upright (TUP) and pre-filter two-motor upright (PreUp4), were tested against two wet methods, a hot water extraction method with a residential detergent (2.2% partially composed of sodium xylene sulfonates and alkyl phenol ethoxylates) and the commercial detergent described in experiment 2. These cleaners were designated as "De-Ex C" and "De-Ex Re" for Detergent-Extraction vacuum cleaners with commercial or residential detergent formulations. This was a one-factor analysis, cleaning technique, with the dependent variable set as lead removed. In this design, it was assumed that both dry vacuuming techniques would have essentially the same lead removal capabilities (from Experiment 1). It was also assumed that among wet methods, lead removal would not vary much.

It was thought that about 20 replicates per cleaner could identify differences between the four cleaning treatments; however, we were not certain if practical differences would be found within the two major categories of cleaning. A sample of 20 was also based on budget considerations.

Three homes were identified through a prescreening of residential dwellings with lead-contaminated carpet (courtesy of City of St. Louis Community Development Administration). Carpet in each home was divided into 18 x 36 inch strips. A total of 105 carpet samples were collected with the following breakdown:

Traditional upright – "TUP": n =27
Pre-filter, two motor upright – "PreUp4": n = 26
Detergent-Extraction vacuum cleaners, residential formulation – "De-Ex Re": n = 25
Detergent-Extraction vacuum cleaners, commercial formulation – "De-Ex C": n = 27

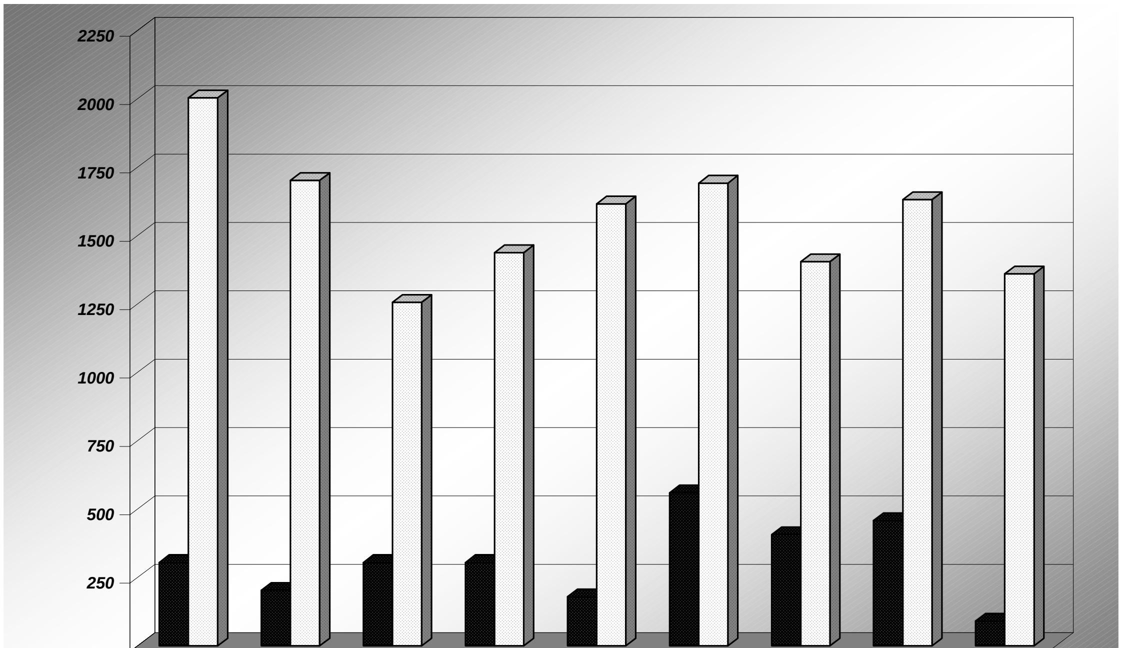
Lead Study Results

The range for lead removal using dry vacuum cleaners was 2,004 ± 752 to 1,256 ± ug/ft^2. The range for precision of recovery, represented by the coefficient of variation (C.V.), ranged from 17% to 37%. Although the TUP had the highest recovery, it also had the highest C.V. (37%). The vacuum cleaner with the best precision was the Can 3 with 17% C.V. The range of nozzle suction for the vacuum cleaners was 6.3 to 0.6 inches of water and this represented the TUP at the maximum and the Can 2 at the minimum. Although the TUP had the highest mean lead removal and highest suction, the inexpensive canister (Can 4) with the lowest mean lead removal had the second highest mean nozzle suction (2.5 inches).

An analysis of variance was performed with the data. Using an alpha level of 0.05, no significant differences were found among the nine dry-vacuum cleaners. When a covariate, the reference lead deposited before removal, was entered in the model, the vacuuming factor had a p value of 0.06, which is borderline significant. Upon closer inspection of the data, and conducting multiple comparisons among the nine-cleaners, the traditional upright (TUP) differed from one pre-filter upright, two-motor vacuum cleaner (the PreUp2), with a p value of 0.098, which is also on the borderline of significance. Therefore, the ability of the vacuum cleaners to remove lead is not based on nozzle-suction alone.

Although the TUP had the highest median value and a 50% interquartile range with the highest lead removal, the Can 1 had relatively high lead removal based on the interquartile range, with no values less than 1,500µg/ft^2 removed. The Can 1, however, is an expensive vacuum cleaner and because there were no significant differences among the vacuum cleaners, a combination of price and ability to remove lead might be considered as illustrated in Figure 1.

Figure 1. Dry Vacuum Cleaner Comparisons by Lead Removal ($\mu g/ft^2$) and Cost



	1	2	3	4	5	6	7	8	9
■ Cost $	305	203	305	305	180	560	407	458	91
□ ug/ft2	2004	1702	1256	1438	1617	1692	1405	1632	1361

<u>Legend</u>

1. TUP
2. PreUp1
3. PreUp2
4. PreUp3
5. PreUp4
6. Can 1
7. Can 2
8. Can 3
9. Can 4

The laboratory study of wet versus dry vacuuming was evaluated using an analysis of variance. Dry vacuuming was significant, $p = 0.045$, and superior to wet vacuuming for removal of lead. Controlling for the small variation in the ANOVA model by using the ratio of after to before cleaning, pile density was significant, $p = 0.002$ and vacuum method significance changed to $p = 0.009$. Using this same model, pile density was also determined to be highly significant, with a p value < 0.001. Twenty-five percent more lead was removed from low-pile density carpet than from high pile-density carpet. Dry vacuuming resulted in 38% more lead removal than wet vacuuming with the commercial detergent.

The results from the third experiment on lead cleaning, pile density, loading, and carpet wear demonstrated two significant interactions affecting lead removal ($\mu g/ft^2$): pile density and lead loading, $p = 0.016$, and wear and lead loading, $p = 0.052$. An examination of the results, illustrated in Table 3, reveals no difference in mean lead removal across high and low pile density with low lead loading. At high loading, however, pile density has a major effect on lead removal with 54% more lead removed from low-density carpet. As depicted in Table 3, wear, which has no significant effect on lead removal in low loading, has a large effect in high loading, particularly with low-density carpet. Lead removal was 39% greater in low-density new carpet than in low-density worn carpet. The effect of carpet wear with high loading is also seen in high-density carpet but to a lesser degree. The new, high-density carpet had 19% greater lead removal than the worn, high-density carpet with high loading.

Main effects are also found from pile density, $p = 0.04$, and lead loading, $p < 0.001$. The main effects, though significant, are neither surprising nor important. It is expected that the more a carpet is loaded with lead the greater the removal of lead than from a lower loading value. Of greater interest is the potential effect of loading on cleaning efficiency, as measured by the ratio of lead loading on carpet after cleaning to lead loading before cleaning. When this ratio was used as the dependent variable, loading had no effect, with the mean ratio for total cleaning efficiency at high loading equal to 0.55 ± 0.17 and low loading equal to 0.57 ± 0.14.

The hypothesis that pile density would affect lead removal was supported, implying the importance of surface area to fine particle retention, but the hypothesis that carpet wear alone would also significantly affect lead removal was rejected (p value = 0.349).

Table 3. Pile Density and Loading (Mean ± SD Pb Removal, $\mu g/ft^2$)

Lead Loading	High Pile Density		Low Pile Density	
High	1,052 ± 476		1,571 ± 488	
	971± 492	1,120 ± 490	1,314 ± 415	1,828 ± 437
Low	771 ± 445		721 ± 308	
	885 ± 572	637 ± 203	723 ± 333	719 ± 308
Wear Condition	Worn	Not Worn	Worn	Not Worn

An analysis of variance was performed on the data in the lead cleaning field validation study. The covariate, lead loading before vacuuming, was entered in the model to control for the wide variation in lead loading prior to cleaning. The home or carpet source was also entered in the model along with vacuum cleaner method. There was no significant difference in the carpet source or home factor. No significant difference was found between wet and dry methods, supporting the null hypothesis of no difference. No interaction among factors was found. Cleaning efficiency was used as a dependent variable to control for variation in the model. The most efficient vacuum cleaner for lead removal was the Traditional Upright (TUP), with a mean and standard deviation of 0.77 ± 0.26 (ratio). The least efficient vacuum cleaner was the pre-filter upright (PreUp4), with a cleaning efficiency mean and standard deviation of 1.4 ± 1.7.

The project led by Causer et al. was to further determine the effect of construction, degree of wear and type of cleaning method on ease of dust mite allergen removal from tufted wool carpet.[39] Different pile height carpet were seeded with house dust, some then subjected to artificial wear, and all were then either dry vacuumed or wet extracted.[52] The degree of wear and pile height were shown to be the two most important factors determining ease of allergen removal from carpet. For worn carpet, dry vacuuming of short pile constructions was shown to be significantly more effective ($P<0.05$) than for longer pile height constructions, while removal of allergen, using either wet or dry vacuum extraction techniques, was shown to be more efficient (>61%) from unworn carpet than from worn carpet (<30%). Only minor differences between types of cleaning method (wet vs. dry) were found. This study suggested that carpet had major differences in retention of allergen, and that carpet age, construction and cleaning regime may be important factors in carpet allergen loading.

Reducing contaminant loading in carpet, however, doesn't always mean a reduction of apparent risk to children from leaded dust. Yiin et al. in a study of HEPA (commercial) versus non-HEPA vacuum cleaners on natural-soiled carpet found significant reductions, albeit not significantly different from each other, in lead loading as measured by a vacuum sampler but note wipe sampling.[49] This suggests that even with commercial cleaners that have beater bars and volumetric flow-rates of 87 ft3/min, lead may still be available to children at the surface of a carpet after cleaning.[62]

Acaricidal and biocidal studies

In a literature evaluation of methods to control dust mites and to a lesser degree fungi, Tovey said that allergen control can be grouped as functioning either directly on the live dust mites or viable fungi or functioning on removal of dust.[63] Methods that act directly on mites are physical changes to the environment (changing humidity, heating, washing, and freezing) or chemical control. Chemical control makes use of acaricides to kill dust mites and fungicides to kill both fungi and cause mite mortality because of the close symbiotic relationship between fungi and dust mites.[63] Removal of allergen-containing dust may involve cleaning techniques such as vacuuming or wet extraction, or involve a barrier such as occlusive covers on bedding. Also, tannic acid or other agents denature the proteins responsible for the allergic reaction.[64]

Control of fungi has been successful using many clinical fungicides and even detergents. Use of Natamycin, while successful in environmental remediation, may result in development of resistant strains of fungi.[65] Inumaru et al. reported in an unpublished study that thymol and thymol with benzoate, sorbate, and ethyl cellulose could inhibit over 99% of fungal growth in carpet.[66]

Kalpakhoglu found that benzyl benzoate would effectively control mite populations, especially when applied more frequently to carpet than manufacturer's directions (at least every 3 months).[67] He also found that phenyl salicylate, a close chemical analog of benzyl benzoate, could be effective in reducing mite populations but that this chemical had not been thoroughly evaluated. Chang found that benzyl benzoate was effective in controlling mites in both mattresses and carpet but that it did not add to the effectiveness of occlusive mattress covers.[68] Schober found that *combinations* of benzyl benzoates with detergents such as those with sodium lauryl ether sulfate, alkylphenolethoxylate, and sodium salts of fatty acids were more effective than most pesticides or other chemical agents in reducing mite populations.[69]

Benzyl benzoate and plant oils, such as tea tree oil, citronella oil, spearmint oil, wintergreen oil and eucalyptus oil, have been found to be effective against *Dermatophagoides pteronyssinus* when used as laundry additives in domestic washing machines.[69,70] Similarly, Bischoff et al. found that reductions in *Dermatophagoides farinae* numbers on carpet pieces during normal domestic washing improved from 40-60% to 100% after addition of 0.03% v/v benzyl benzoate to the washing solution.[71] A follow-up study involving washing of mite-infested clothing confirmed this effect.[72] (Bischoff et al. 1998). Addition of 3.3% v/v benzyl benzoate to a carpet cleaner gave significantly improved efficacy against *Dermatophagoides farinae* (Schober et al. 1987), with two subsequent studies also returning similar results, the latter including eradication of fungi.[69,73,74]

Vacuuming alone or in combination with very hot water can kill mites and remove allergen but some investigators have found that vacuuming removes dust mites' natural predators or simply adds moisture, which produces more mites. Colloff said that use of steam cleaning could reduce 87% of dust mites in inoculated carpet cores. Colloff, however, did not validate his findings of dust mite reductions in homes (his analysis was for allergen only).[75] Vojta et al. however, found that both dry steam cleaning and intensive vacuuming together could significantly reduce mite allergen loading for up to eight weeks.[76] Physical interventions, therefore, could hold promise for abatement of dust mites as an interim measure of control.

Development and Selection of Carpet and Carpet Cleaning Regimes

It is not difficult to find information in the carpet-cleaning press on developing a systematic approach to cleaning. In fact, a systems approach to many complex phenomena is often pursued when interactions between different elements or factors exist. Protecting the indoor environment or individual from either an allergic or toxic pollutant involves consideration of a number of factors that may be independent, dependent, or interactive in nature. A number of factors or "inputs" can be tabulated that might affect indoor air quality as a result of carpet contamination. Consider the points that we try to make in the subsequent parts of this article as inputs with potential connections to other inputs. These inputs could be considered parts of a complex system that governs a "through-point," a kind of carpet or carpet-cleaning regimen that should be selected for use in the indoor environment.

At the beginning of this paper we described the concerns of many scientists, consumers, and activists about the indoor environment. The elimination of cigarette smoking in many offices and public places has raised the bar on what may be expected of products that negatively affect indoor air quality. Although the literature has a multitude of articles describing the health effects of second-hand smoke, no such data can be found that similarly relates carpet and carpet dust directly to disease. However, carpet that is loaded with contaminants, which may do harm once released, has a potential for exposure and therefore the perception that carpet can do harm is an important part of the system to be understood in choosing carpet or a carpet-cleaning regimen. The perception, if not addressed, simply means that agencies, businesses, and consumers may remove carpet from their environment in the absence of very strong evidence to the contrary.

Although perception is stated as an overarching input at the beginning of this discussion, house dust is likely the beginning of this complex system. House dust can be considered the raw material input for the end result: loaded carpet and potential exposure. House dust is a heterogeneous mixture of materials governed by geography, housing stock and building materials, individual attention to cleaning and behaviors such as setting a thermostat or opening a window.[40] The mixture is also heavily influenced by socioeconomic concerns, especially as it pertains to lead and cockroach allergen exposure.[77] Low income and urban dwellers may often have house dust signatures that are affected by where they can afford to live.[78] To simplify the model a bit requires using some index contaminants, such as dust mite allergen, cat allergen, and lead. As described earlier in this paper, these contaminants cause concern about health and their disparate exposure paths. Dust mite and cat allergen are two of the most important allergens responsible for large numbers of cases of asthma, yet they differ greatly in how they are sampled, assessed for exposure, and controlled. The different aerodynamic sizes of dust mite and cat allergen have broad implications for cleaning. Cat allergen, with a mean aerodynamic diameter (AED) of 2.5 µm will stick tenaciously to carpet and will remain aloft much longer than dust mite allergens. Dust mite allergen is found on considerably larger particles, 10-40 µm diameter, yet still much smaller in diameter than most of the mass of ordinary house dust. Assuming a mass median diameter (MMD) of 20 µm dust mite allergen and 2.5 µm for cat allergen, the settling velocity of dust mites is 64 fold greater than that of cat settling velocity.[56] As pointed out earlier in this paper, when particle diameter decreases so do the effects of air and mechanical removal forces on particle adhesion.[56] Cleaning cat allergen out of carpet is probably more difficult than cleaning dust mite allergen but exposure to airborne cat allergen in homes with cats is more likely than airborne exposures to dust mite allergen, based on aerodynamics of the particles in question.[56]

When considering possible exposure pathways for indoor allergens, consideration should be given to the fact that allergen exposure may be due to direct contact with a surface (carpet or non-carpet) and to hand contact and nasal aspiration or direct nasal aspiration from the surface of a carpet.[11] We already know that short ragweed pollen, a surrogate for dust mite allergen in a study described earlier in this paper, can be directly inhaled from the hand or from a pillow. Therefore, allergens on the surface of a carpet should be considered a pathway of exposure even in the absence of a vacuum cleaner or other disturbance.

The exposure pathway for lead is from hand contact with surfaces followed by oral ingestion. Like dust mite allergen, removal of leaded dust should consider not only the total amount of contaminant in the carpet but especially the available amount of lead from surface contact.

The textile or carpet industry has often relied on measures of soiling using apparent soiling procedures that are more indicative of the relationship between dust soiling and carpet appearance than dust soiling and health implications. The vacuum cleaning and carpet industries, while having adopted some gravimetric standards to compare vacuum cleaner performance and criteria for "green vacuum cleaner systems" should recognize that prior soiling studies, which use appearance as an outcome measure, are of little use in understanding cleaning based on health outcomes.[79] New standards need to be developed which are based on both cleaning and health-based criteria. For example, there is a great need to establish guidelines for when carpet is "clean" based on best available technology and practices and when they are "safe" based on human risk.

Studies on the importance of micro-occlusion and macro-occlusion point out the importance of fiber surface area and fluorocarbon coatings in removing small diameter allergens such as cat or dust mite allergen. However important these factors are in cleaning or in exposure, most of the surface area of a carpet is related to its pile height and density. If low densities and low piles are easier to clean than their higher counterparts, where is the line drawn between what is high and what is low? Many of the studies we performed used a range of heights and densities that were chosen to reflect the market but were also chosen to detect differences, e.g., cut piles that ranged from 0.25 to 1 inch in height.[61] Although there was significantly more allergen removed from the 0.25 than 1 inch cut pile, how does this information translate into an appropriate pile height for allergen avoidance measures? More studies should be performed to inform the debate on which characteristics of carpet form a healthy choice from the standpoint of micro-occlusion and macro-occlusion. At the same time, at what point is the selection of a carpet structure driven by its ability to trap particles or release them? If frequent vacuuming cleaning were standard practice in the home, then the ability of a carpet to release contaminants would appear to be a better choice than the selective trapping of contaminants. Moreover, since surface-to-mouth or surface-to-nose exposures could arise from carpet, a lower surface area carpet that is relatively efficient to clean makes more sense than a higher surface area carpet that could trap more and pose a greater exposure risk. These are merely conjectures, however, and need to be demonstrated with actual studies.

Wearing or matting of carpet has been thought to improve release of contaminants due to a loss of fibers and subsequent lowering of available surface area for soiling.[35] However, our own studies appear to show the opposite result, with worn carpet holding more particulate than newer carpet at higher loadings. This seems to be especially apparent with low-density carpet that may mat easier than a higher density carpet.[39,40]

Perhaps one of the most important inputs of a model that would affect indoor air quality would be the cleaning regime used. Our own studies, described earlier in this paper, showed some difference in removal of lead using dry vacuum cleaners but there was no significant difference between these. There was an indication that the traditional upright removed more lead than other vacuums and it had the highest nozzle suction (6.3 inches compared to 0.6 inches for the lowest vacuum-cleaner nozzle suction). But the second highest nozzle suction came from the Can 4, (2.5 inches) with the lowest removal of lead. Nozzle suction, although important for removal of particulates from carpet, doesn't act alone as input in the hypothetical model on indoor air quality. Clearly, other properties are important and volumetric airflow, mechanical agitation, and nozzle design are probably important factors. These parameters, cited often by industry experts, are not widely established in the literature. However, the machine that provided the best precision and therefore more predictable cleaning was a relatively expensive canister ($458), identified as Can 1 with a nozzle suction of 1.1 inches and a C.V. of 17%. What are the selection criteria for a dry vacuum cleaner? A combination of cost, performance, and precision could probably be used, as described earlier in this paper. If volumetric flow rate and perhaps nozzle suction are important parameters for removal of allergens or other dust-borne contaminants, vacuum cleaner manufacturers should consider providing gauges on these machines so consumers could more readily evaluate their performance.

Choosing an appropriate cleaning regimen often requires choosing between a dry vacuuming and a wet extraction method. As input into a hypothetical model on indoor air quality, data from the published literature either do not show an advantage using wet methods or show an advantage using dry methods for an equal amount of time expenditure.[39,40] Lead is clearly not soluble in water. Although cat and dust mite allergens, as well as many other biological contaminants of carpet are very water soluble, they are carried or mixed in with dry material. If most of the dust-borne contaminants, therefore, are carried on insoluble particles, what is the theoretical basis for using a water-based method to remove these contaminants? Clearly if oil or other sticky residues cling to the carpet, then a water-based detergent system would work best for this type of soiling. Unfortunately, there are few to no citations that actually demonstrate the value of wet extraction methods over dry vacuuming. Studies are needed to show how affordable, wet-extraction methods could be used by the health department, abatement companies, and consumers. At this point in time, the data indicates the use of dry vacuum methods for removal of dust-borne contaminants in carpet.

The interactive effects of carpet wear, loading, and carpet type (density but perhaps height as well) found in our studies of lead removal have important implications for an input into the model on cleaning. At high lead loading, cleaning was significantly different than for low loading, with low densities easier to clean, yielding 54% more lead than from higher density carpet. When worn carpet was used, however, lead removal declined from 39% -19%. This was not the case at low loading where worn actually gave up slightly more lead than unworn carpet. For the most part, abatement specialists and probably even carpet and vacuuming experts would probably overlook some of the interactive effects of carpet type, loading, wear, and contaminant removal. These findings suggest that a cleaning model should take into account both the degree of wear and loading. In addition, more studies should be performed to confirm these findings and then establish criteria for replacing carpet depending on its age and relative contamination.

Perhaps the most promising agents, as recently reported, for dust mite and fungal control in carpet, respectively, are benzoyl benzoate or steam-heat applications for dust mite and use of natural oils such as thymol, along with sorbate, and benzoate for fungi.[66] Although research will continue to explore new agents, physical or chemical, to control dust mites and fungi in carpet, very little thought has gone into designing carpet from the start to either resist infestation or minimize microbial growth without external agent application. The nature of microbes and dust mites is to establish resistance to chemicals over time. Use of a plastic barrier to cover mattresses, however, has proven to be very effective for controlling dust mites since it prevents the bodies' high moisture and temperature, two key factors in dust mite growth, from reaching dust mites. No one expects carpet to be plastic-encased anytime in the future but the carpet industry needs to explore ways to minimize or prevent mite and microbe growth by using natural or sustainable methods. Carpet was purposely designed to: reduce apparent soiling through reduced light reflection; reduce static shock by use of embedded carbon fibers; and resist staining and soiling by use of fluorocarbons. The development of trilobal or other fibers that decrease apparent soiling while increasing actual soiling and allergen retention should be re-evaluated in today's climate of healthier environments. If volumetric airflow, by way of a vacuum cleaner, improves cleaning, why cannot carpet be designed to increase air movement through them?

The carpet and vacuuming industries need to look at the problems of house dusts and surface contamination as a system in which the interactions of many factors (house dust sources, particle size and aerodynamics, carpet structures, and cleaning approaches) work together to affect indoor air quality. Carpet cleaning needs to be rigorously studied and reported in the literature, while carpet design should take into account the need for adequate airflow and resistance to microbes and dust mites.

Conclusions

This paper began with a review of the complex nature of house dust that could contain contaminants with widely ranging pathways to human exposure, including lead, dust mite and cat allergen. Cat allergen remains aloft longer and due to its particle size, should be harder to vacuum than the larger dust mite allergen. Lead is a hazard primarily from hand to mouth exposure, and reduction of lead loading after vacuuming may still leave unsafe amounts of lead on the surface of the carpet. Dry vacuum cleaners have few differences to recommend them, except that nozzle suction, combined with volumetric flow rate, cost, and perhaps precision of particulate removal, could be used as criteria to select these cleaners for use in removal of contaminated carpet. Dry vacuuming appears to be superior to wet extraction methods in a limited number of studies that we performed; however, higher water flow and higher temperatures could increase solubility of allergens in dust. The interactive nature of carpet with lead loading, density, and wear presents avenues for further study and opportunities to establish guidelines for cleaning and disposing of carpet after a period of time or an amount of soiling. The development of new detergent and biocide regimes for dust mites and fungi control in carpet should not thwart development of more innovative ways of designing carpet for maximal cleaning and microbe resistance. An integrated carpet cleaning system will take into account the many inputs or factors that may affect both human exposure to dust contaminants and their removal. A more thorough understanding of these factors, from both laboratory and field studies, will inform the debate on the influence of carpet in a healthy indoor environment.

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