

Influence of Wear, Pile Height, and Cleaning Method on Removal of Mite Allergen from Carpet

Simon M. Causer,¹ Roger D. Lewis,² Joseph M. Batek Sr.,²
and Kee-Hean Ong²

¹Wool Research Organisation of New Zealand, Christchurch, New Zealand

²Saint Louis University School of Public Health, St. Louis, Missouri

Carpet is a major sink for house dust mite allergen. Vacuum extraction methods have been shown to reduce concentrations of such allergen in dust, but the influence of carpet construction and cleaning parameters on the efficiency of extraction is poorly understood. The objective of this study was to determine the effect of construction, degree of wear, and cleaning method on ease of removal of the primary allergen (Der f I) derived from the North American house-dust mite, Dermatophagoides Farinae. Carpets of different pile heights were seeded with house dust, some were then subjected to artificial wear, and all were then either dry vacuumed or wet extracted. The Der f I content of carpet cores was measured at each stage. As a result, the degree of wear and pile height were shown to be the two most important factors determining ease of Der f I removal from carpet. For worn carpet, dry vacuuming of short pile constructions was shown to be significantly more effective ($p \leq 0.05$) than for longer pile height constructions, while removal of Der f I using either wet or dry vacuum extraction techniques was shown to be more efficient ($> 61\%$) for unworn carpet than for worn carpet ($< 30\%$). Only minor differences between types of cleaning method (wet vs. dry) were found. This study suggests that carpets differ greatly in their propensity to retain allergens, and that a consideration of carpet age, construction, and cleaning regime is important when advising the merits of different floor covering types, and on allergen avoidance techniques.

Keywords allergen, carpets, *Dermatophagoides farinae*, house dust mites, vacuuming

Address correspondence to: Simon Causer, Wool Research Organisation of New Zealand, Private Bag 4749, Christchurch, NZ; e-mail: causer@wronz.org.nz.

INTRODUCTION

Exposure to house dust mite allergen has been shown to be associated with mite sensitization⁽¹⁾ and both risk^(2,3) and exacerbation of asthma.⁽⁴⁾ A number of studies have shown that reductions in bronchial hyperreactivity can be achieved using allergen avoidance techniques,^(5,6) and that vacuum cleaning is capable of significantly reducing concentrations of mite allergen in carpet dust.^(7–10) However, neither the extent to which

this reduction needs to be made, nor the influence of carpet construction, wear, and cleaning method on the efficiency of allergen removal, are well understood.

In contrast to soft flooring surfaces, mite numbers and allergen concentrations are consistently shown to be lower on hard flooring and more easily reduced by cleaning,^(11–17) suggesting a lower exposure to allergen where such surfaces are present. Some groups contend this may not be the case if differences in ease of allergen disturbance exist between hard and soft floor coverings. This hypothesis is unproved, however. Although soft floor covering removal is frequently advocated as an allergen avoidance technique, carpet remains a popular floor covering choice and is valued for its appearance and texture, as well as insulating and sound absorbing properties.

Conflicting evidence exists from both nonintervention^(13,15,16) and intervention studies^(12,18) as to whether frequent or recent vacuuming of carpet results in lower allergen concentrations in house dust. However, it is accepted that despite the percentage of live mites removed by dry vacuuming of textiles being very low,^(11,19) intensive dry vacuuming still remains capable of significantly reducing levels of allergens in rugs^(7,8) and carpets.⁽⁹⁾ Unfortunately, while normal cleaning practices (dry vacuuming 1–2 times per week, supplemented by irregular hot water extraction) may be appropriate for dealing with soiled carpets, such studies suggest these may not be intensive or regular enough to reduce allergen levels in carpet to the point where a clinical improvement could be expected.^(9,20) In addition, it is likely that deposition and removal rates for dust/allergen will vary between carpets having different constructions but the same pile fiber type, and between similar carpets constructed with differing pile fiber types.

In previous research we found that low pile density (for loop-pile, but less so for cut-pile carpet) and low pile height (for cut-pile, but less so for loop-pile carpet) favored ease of dust and mite allergen recovery by dry vacuuming,⁽²¹⁾ as did decreasing fiber surface area and the presence of a fluorochemical stain-resistant treatment. Another important finding was that dust recovery rates were not proportional to allergen recovery rates, and that the ratio was influenced, to some extent, by

carpet construction.^(22,23) The aim of the present study was to extend this work to investigate pile fibers other than nylon, wet extraction methods, and the effect of carpet wear on ease of allergen removal from carpets.

METHODS AND MATERIALS

Samples of vacuum cleaner dust were collected from a selection of residences in St. Louis, Mo., and sieved (mesh size = 106 μm). Amorphous fumed silica (Sigma) was then added (1% w/w) to improve the free-flowing characteristics, eight subsamples (100 mg) were extracted in borate buffered saline-5% bovine serum albumin (2 mL) overnight, and the house dust mite allergen (Der p I and Der f I) content determined by monoclonal antibody enzyme-linked immunosorbent assay (ELISA).⁽²⁴⁾

Carpets were then seeded with dust, the dust was embedded, and various cleaning regimes were applied, with the carpets being sampled at each stage to ascertain the allergen content (Figure 1). Briefly, a sample of dust (650 cm^3) was transferred to a plastic cylinder, the surface of which was covered with 5-mm-diameter holes set in a 25-mm grid. Each carpet (new 7 mm and 9 mm cut-pile wool, 1/8 gauge, 7 replicates each, 920 mm $\times$ 432 mm) was cut in half widthwise and placed underneath the track, and the cylinder rolled down twice in the manner described by Lewis et al.,⁽²²⁾ rotating the carpets to give an even distribution of dust on the surface. The cylinder was then reloaded, the position of the carpets swapped, and the procedure repeated. The dust was then embedded by dragging a steel rod (12.6 kg) across each carpet surface for 30 strokes

at 540 mm/sec (1.8 ft/sec), as per procedures described by the American Society for Testing and Materials (ASTM)⁽²⁵⁾ to give a dust loading of 13.4 ± 0.6 g (95% confidence interval [CI]). A 153-mm section was cut off the end of one sample, cored four times (83 mm diameter), and the remaining 307 mm length cut in half widthwise and set aside.

The 460-mm $\times$ 432-mm sample was cut in half lengthwise and wear testing (8000 revolutions in a hexapod tumbler) was carried out according to Wools of New Zealand Test Method 247, but omitting the vacuuming step that is usually carried out midway through the wearing process. This test is generally accepted to simulate the amount of wear occurring in a four-person household over the course of 4–5 years. A section (153 mm long) was then cut off the end of each of the worn carpet strips and two cores taken from each. All four worn and unworn carpet samples (216 $\times$ 307 mm) were then subjected to either dry vacuuming or wet extraction using an automated vacuuming apparatus, according to the procedures outlined in ASTM F608.

To perform the vacuuming step consistently, each carpet sample was inlet into a similarly constructed piece of undoped carpet (920 $\times$ 432 mm), and all pieces secured to a metal plate with double-sided tape. A motor and electronic brake allowed this plate to be moved back and forth at a constant rate under a stationary mounted vacuum cleaner. For dry vacuuming, four strokes of a domestic upright vacuum cleaner (Dirt Devil MVP, Model 088305, Royal Appliance Manufacturing Co., Glenwillow, Ohio) were made, where one stroke consisted of a forward and backward passage across the top of the carpet sample at 540 mm/sec (1.8 ft/sec).

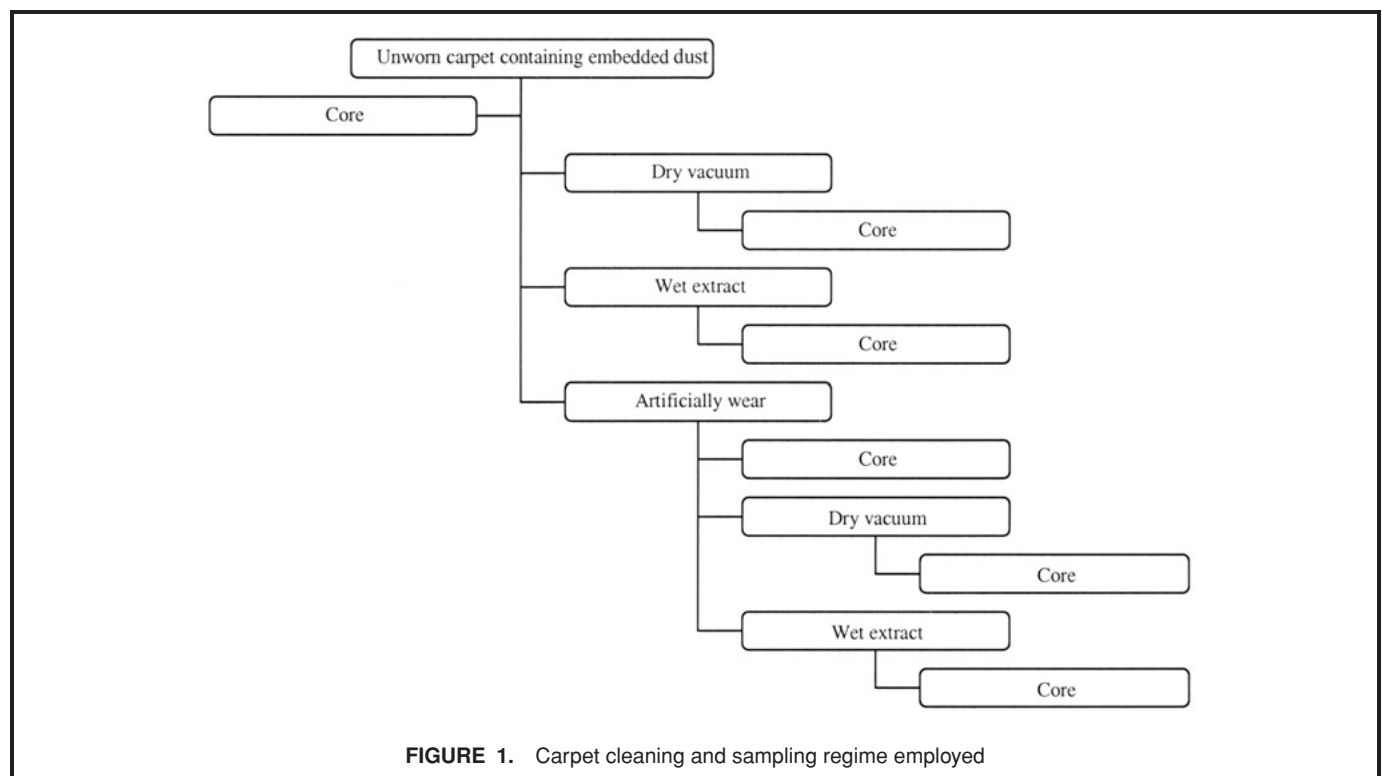


FIGURE 1. Carpet cleaning and sampling regime employed

TABLE I. Reduction in Carpet Pile Height After Wear

Nominal Pile Height	Unworn Pile Height (mm)		Worn Pile Height (mm)		Reduction (%)
	Mean	SEM	Mean	SEM	
7 mm	6.95	0.05	4.52	0.04	35.0
9 mm	9.20	0.05	7.13	0.08	22.5

Note: SEM = standard error of the mean.

For wet extraction, another domestic upright machine (SteamVac LS, Model F5892900, Hoover, North Canton, Ohio) and the same traverse speeds were used. Again, eight passages of the vacuum across the carpet were used, with the first two passages consisting of a forward motion where the detergent solution was sprayed onto the carpet (along with suction) and a return motion where the detergent solution was vacuumed out. This cycle was repeated four times to give a total of eight passages. A domestic carpet upholstery detergent (Hoover SteamVac Carpet Upholstery Detergent) was diluted with water (31.25 mL/L) at $37 \pm 3^\circ\text{C}$ and used as the extraction solution, and all carpets were cored (four replicates each) after dry or wet vacuum extraction.

The suction pressure at the carpet surface was determined for both vacuum cleaners by taking 20 readings with a Dwyer 477 digital manometer attached to the cleaner head. Between replicates all apparatus were vacuumed and wiped down with a damp cloth and the bag and filters on the dry vacuum were replaced before each series of samples (worn or unworn) was tested. Pile height measurements were also taken from worn and unworn samples using a pile height gauge that exerted a foot pressure of 20 g/cm^2 (Wools of New Zealand Test Method 20).

All carpet cores were obtained by holding samples pile-side up in a jig and coring from beneath with a handheld cutter, so as to create minimal pile disturbance. These were stored at -21°C prior to analysis, which was carried out by extracting individual cores in borate buffered saline/bovine serum albumin solution (70 mL) at room temperature for 24 hours under agitation. After centrifuging and filtration the extracts of the four samples were then pooled and the allergen content measured by double-monoclonal antibody ELISA.⁽²⁴⁾ Both Der p I and Der f I levels were quantified in the bulk dust used in this study, however only Der f I levels were determined in carpet cores. All dust seeding and vacuuming operations were carried out at 22% relative humidity and 22°C , and statistical significance was set at the 5% level.

RESULTS

Analyses of the bulk dust ascribed virtually the entire Group I mite allergen to Der f I (4750 ng/g), with only very low levels of Der p I recorded ($<20 \text{ ng/g}$), suggesting that *Dermatophagoides farinae* was the dominant mite species in houses where dust was collected. When dust was

added to carpet samples the Der f I level (mean: $16.3 \mu\text{g/m}^2$; 95% CI: $14.8\text{--}17.8 \mu\text{g/m}^2$) was not found to differ significantly ($p > 0.05$) between the 7-mm and 9-mm carpets. Similarly, there was no significant change ($p > 0.05$) in allergen levels in the carpet after wear (mean: $14.7 \mu\text{g/m}^2$; 95% CI: $13.4\text{--}16.0 \mu\text{g/m}^2$), indicating that few losses occurred during hexapodding. Reductions in values for the range ($15.6 > 7.6 \mu\text{g/m}^2$) and variability (standard error of the mean: $1.2 > 0.6 \mu\text{g/m}^2$) of data collected after hexapodding suggest this may have even resulted in an improvement in homogeneity of allergen distribution. Simulated wear was found to result in a greater reduction in pile height for the 7-mm carpet than for the 9-mm carpet (Table I).

When unworn carpets were cleaned, irrespective of whether a wet or dry vacuum extraction technique was employed, allergen levels were reduced ($>61\%$) to below the limit of detection for the ELISA test (4.0 ng/mL , equating to $5.2 \mu\text{g/m}^2$). In contrast to the relatively efficient cleaning of unworn carpets, allergen was found to be much less efficiently extracted from worn carpets ($<30\%$), leaving residual allergen levels (mean: $13.2 \mu\text{g/m}^2$; 95% CI: $11.9\text{--}14.5 \mu\text{g/m}^2$) all within ELISA detection limits.

Subsequent analysis of variance showed dry vacuuming removed significantly greater amounts of allergen ($p \leq 0.05$) from worn carpets with a lower pile compared to those with a higher pile (Figure 2). While allergen levels on worn 7-mm pile height carpets were significantly reduced ($p \leq 0.05$) using both dry and wet extraction techniques, no significant reduction ($p > 0.05$) was noted on 9-mm pile height carpets for either

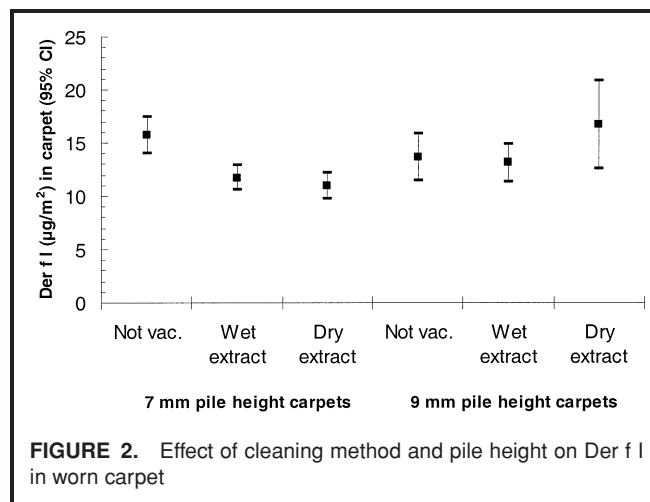


FIGURE 2. Effect of cleaning method and pile height on Der f I in worn carpet

technique. Neither were any significant differences in efficacy noted between either wet or dry vacuum extraction methods for a given pile height—although there was a slight suggestion that wet extraction may be more effective than dry vacuuming for longer pile height carpets.

A significant interaction ($p \leq 0.05$, F : 4.90, F_{critical} : 4.26) was observed between cleaning method and pile height when the initial allergen loading was used as a covariate and, as might be expected, a significant difference ($p \leq 0.05$) in static pressure at the vacuum head was noted between the Dirt Devil dry vacuum cleaner (mean = 6.7 mmHg, standard deviation [SD] = 1.3) and the Hoover SteamVac (mean = 34.0 mmHg, SD = 5.6).

DISCUSSION

Unfortunately, little data exist to quantify total dust and allergen content of carpets. Those who have attempted to derive values for mass of allergen per area have invariably measured the concentration in vacuumed dust and related this back to the area sampled—which has the major shortcoming that unless 100% removal of allergen from the carpet is achieved, the true allergen loading will be underestimated. This point aside, previous studies quote house dust mite allergen concentrations of between 0.03 and 227.7 $\mu\text{g}/\text{m}^2$,⁽⁹⁾ 0 and 10 $\mu\text{g}/\text{m}^2$,⁽²⁶⁾ and 0.2 and 1610.9 $\mu\text{g}/\text{m}^2$,⁽²⁷⁾ so the levels used in this investigation could be considered as representative of a low level allergen loading that might be encountered in a domestic residence.

Extraction efficiencies from unworn carpet (>61%) recorded were similar to those previously determined for removal of mite allergen,^(21,28) cat allergen,⁽²³⁾ bulk dust,⁽²⁹⁾ and lead,⁽³⁰⁾ while the dramatic reduction in cleaning efficiency observed after carpet wear most likely occurs because a more tortuous allergen extraction path forms as the carpet wears and the pile density increases. In addition, the motion and pressure of shoes and soil particles encountered during carpet wear may result in the formation of crevices, as well as cracking and fibrillation of the textile fibers.^(31–33) Particles trapped in such crevices and splits will undoubtedly be harder to remove than those bound loosely to fiber surfaces.

Once deposited onto carpet, a dirt or allergen particle may be thought of as being bound by one or more of four mechanisms: (1) macro-occlusion, whereby larger particles are trapped by mechanical entanglement between yarns or fibers; (2) micro-occlusion, whereby much smaller particles become trapped in irregularities on the fiber surface; (3) hydrophobic attraction; and (4) sorption by Van der Waal's or Coulombic forces at the fiber surface.^(31,34) Because of the small size of the particles involved and the strong positive electrostatic charge⁽³⁵⁾ the latter two mechanisms work concurrently—although macro- and micro-occlusion are still likely to be the most important particulate-binding mechanisms.

The ratio of oils to dry solids in carpet dust is important as oils strongly bind dirt in dry soiling⁽³⁶⁾, and likely allergen

particles also. The shape of the particles themselves is also important, with roughly spherical particles such as mite fecal pellets likely to be retained to a lesser degree than irregularly shaped particles, which work more readily into crevices. This effect is apparent during soiling of wool fibers where particulate matter concentrates in areas of surface roughness, such as along the scale edges.⁽³²⁾ Potentially, mite fecal pellets break up with carpet wear, forming smaller particles that behave in such a manner, while larger, intact particles may collect with other components of reservoir dust, nearer the base of the pile.

A number of authors have suggested that ease of particulate removal from carpets is favored by low pile height and density^(21,23) and is proportional to the total fiber surface area available for particulate bonding.^(37,38) The surface area is determined, in part, by the length of the pile (set at time of manufacture), while the flattening that occurs during wear increases the density of carpet pile, so the finding that allergen is less easily removed with both increasing pile height and carpet wear essentially agrees with that of previous authors. It is also worth noting that in our previous study⁽²¹⁾ a four-fold difference in pile height existed between the carpets tested, whereas in the present study more typical constructions were used, with closer to a 30% difference in pile height, yet this effect was still observed.

Given that thorough dry vacuuming appears to have the capacity to significantly reduce allergen levels in carpet, it is not surprising that efficient removal of the water-soluble Group I allergens has also been shown using spray extraction techniques.^(7,20,28) Disagreement exists as to which, if either, is more effective. Some studies conclude that wet extraction is better at removing allergen than dry vacuuming,⁽²⁸⁾ while others, including the present study, contend little difference exists.⁽⁷⁾ It has even been speculated⁽³⁹⁾ that despite being shown to reduce allergen levels, dry vacuuming may increase house dust mite numbers by reducing predator mite numbers, while spray extraction may improve the microclimatic conditions in such a way that mite eggs hatch more rapidly.

In this study, dry and wet vacuum extraction methods were carried out separately, but not sequentially, to permit an easy comparison of efficacy. However, it is not uncommon for wet extraction processes to be preceded by dry vacuuming, and such a combined process might be expected to result in greater removal of allergen than either process employed separately. Unfortunately it is difficult to compute the total removal rate accurately for such a combined process, as simple summation of the removal rates determined for the respective processes is likely to overestimate the extraction efficiency.

A possible explanation for our observation of an interaction between pile height and cleaning method ($p \leq 0.05$) is that, irrespective of vacuum extraction technique, the airstreams and vibration created during cleaning (particularly for longer pile height carpets) are simply not vigorous enough to reach and/or remove allergen from the lower regions of the carpet pile, where the majority has been shown to reside.⁽⁴⁰⁾ To draw an

analogy, studies on lead⁽³⁰⁾ suggest that during dry vacuuming a proportion of particulate matter is drawn up from the base of the pile but not actually removed. This vertical redistribution of particulate matter undoubtedly happens with allergen also, and is equally likely to occur horizontally across the carpet. The latter is evidenced by the observation that the spread of the data for allergen concentrations after cleaning was much greater for higher pile height carpets than lower ones. In contrast to dry vacuuming, wet extraction machines typically operate at a higher suction pressure (a five-fold difference in this case) and water is likely to penetrate the pile quite deeply, solubilizing any allergen present, and thus facilitating more ready removal.

The design of the heads of the two cleaners tested was also quite different, with the Dirt Devil comprising a single bristle brush roller with a 45 mm × 355 mm suction slot, and the SteamVac with a 6.5 mm × 280 mm suction slot with five revolving circular brushes mounted side by side, with a detergent spray nozzle incorporated in the center of each. Nozzles with rotating bars or bristles, such as were used on the two machines here, have been found to be more effective at extracting dust, dead mites, and allergens from carpet than those without.⁽⁴¹⁾ Low-humidity environments, such as the one in this study, are also likely to favor allergen removal by dry vacuuming, which may be another reason why wet extraction did not prove much more effective than dry vacuuming.

While the results obtained using both dry and wet extraction techniques applied to short pile height carpets appear encouraging, it should also be remembered that mean domestic allergen levels in countries such as Australia and New Zealand are often in the range of 20–50 $\mu\text{g/g}$,^(16,20,42) so a reduction in allergen levels of at least one order of magnitude would be required to attain the 2 $\mu\text{g/g}$ level proposed as the threshold for allergen sensitization.⁽⁴³⁾ It is almost certain this would not be achieved using a single passage of a vacuum cleaner over a carpeted surface; however, the potential for repeated cleaning episodes to reduce mite allergen concentrations to below this level is less clear. Adilah et al.⁽⁹⁾ showed it was possible to reduce mean allergen levels of 4.47 $\mu\text{g/g}$ Der p I (corresponding to 6.35 $\mu\text{g/m}^2$) to 1.83 $\mu\text{g/g}$ by vacuuming 5 times per week over a 5-week period, while an even greater reduction in the allergen per unit area figure (68.5% c.f. 48.0%) was observed. It would be interesting to determine whether similar results could be achieved (or the lower level of allergen maintained) using a less frequent cleaning regime, particularly in light of recent results demonstrating that vacuuming is capable of enhancing other allergen avoidance techniques.⁽¹⁰⁾

Unfortunately, although easy and inexpensive, dry vacuuming has a number of drawbacks that limit its value as a control technique, particularly when used in isolation. Most importantly, even if carried out intensively, it is ineffective at removing live mites and does not remove all allergens.^(7,12,41) Vacuuming procedures must also be carried out on a regular

basis, and techniques employed to avoid the increased exposure to airborne allergen that occurs during vacuuming.^(44–46) Another shortcoming is that allergen levels have been found to quickly recover to baseline values after dry vacuuming.⁽⁹⁾ In a similar study on hot spray extraction, Tovey and McDonald⁽²⁰⁾ also showed that, after an initial 3.3-fold reduction, allergen levels recovered to within 85% of their initial values within 4 weeks.

CONCLUSION

Both wet and dry vacuuming of unworn carpets are reasonably effective at removing allergen, but this efficacy is considerably reduced once the carpet becomes worn. Pile height is also important, with shorter pile height carpets appearing to be more efficiently cleaned than longer ones, irrespective of the cleaning method. While allergen reductions obtained in this study after cleaning appear promising (especially for unworn carpet), the reduction in levels achieved as a proportion of the total allergen content was quite small, particularly for worn carpet. Thus, it appears that dry or wet extraction methods are likely to be of only limited value if used in isolation, and of greatest benefit in reducing allergen exposure when used intensively and regularly, where low to medium allergen levels are present, alongside other allergen avoidance techniques, and in conjunction with a consideration of carpet type and condition.

ACKNOWLEDGMENTS

The authors wish to thank Dr. Robert Hamilton and the staff of the Dermatology, Allergy and Clinical Immunology Laboratory of the John Hopkins University, Asthma and Allergy Center, Baltimore, Maryland, who performed the allergen analyses.

Research was supported by grants from the Royal Society of New Zealand and the New Zealand Public Good Science Fund, Wellington, New Zealand.

REFERENCES

1. Kuehr, J., T. Frischer, R. Meinert, et al.: Mite allergen exposure is a risk for the incidence of specific sensitization. *J. Allergy Clin. Immunol.* 94:44–52 (1994).
2. Pollart, S.M., M.D. Chapman, P. Fiocco, G. Rose, and T.A.E. Platts-Mills: Epidemiology of acute asthma: IgE antibodies to common inhalant allergens as a risk factor for emergency room visits. *J. Allergy Clin. Immunol.* 83:875–882 (1989).
3. Burrows, B., M.R. Sears, E.M. Flannery, G.P. Herbison, and M.D. Holdaway: Relations of bronchial responsiveness to allergy skin test reactivity, lung function, respiratory symptoms, and diagnoses in thirteen-year-old New Zealand children. *J. Allergy Clin. Immunol.* 95:548–556 (1995).
4. Peat, J.K., E.R. Tovey, B.G. Toelle, et al.: House dust mite allergens: A major risk factor for childhood asthma in Australia. *Am. J. Respir. Crit. Care Med.* 153:141–146 (1996).

5. **Platts-Mills, T.A.E., E.R. Tovey, E.B. Mitchell, H. Moszoro, P. Nock, and S.R. Wilkins:** Reduction of bronchial hyperreactivity during prolonged allergen avoidance. *Lancet* 319:675–680 (1982).
6. **Ehnert, B., S. Lau-Schadendorf, A. Weber, P. Buettner, C. Schou, and U. Whan:** Reducing domestic exposure to dust mite allergen reduces bronchial hyperreactivity in sensitive children with asthma. *J. Allergy Clin. Immunol.* 90:135–138 (1992).
7. **de Boer, R.:** The control of house dust mite allergens in rugs. *J. Allergy Clin. Immunol.* 86:808–814 (1990).
8. **Munir, A.K.M., R. Einarsson, and S.K.G. Dreborg:** Vacuum cleaning decreases the levels of mite allergens in house dust. *Pediatr. Allergy Immunol.* 4:136–143 (1993).
9. **Adilah, N., P. Fitzharris, J. Crane, and R.W. Siebers:** The effect of frequent vacuum cleaning on the house dust mite allergen, Der p I in carpets: A pilot study. *New Zeal. Med. J.* 110:438–439 (1997).
10. **Warner, J.A., J.M. Frederick, T.N. Bryant, et al.:** Mechanical ventilation and high efficiency vacuum cleaning: A combined strategy of mite and mite allergen reduction in the control of mite-sensitive asthma. *J. Allergy Clin. Immunol.* 105(1 Part 1):75–82 (2000).
11. **Mulla, M.S., J.R. Harkrider, S.P. Galant, and L. Amin:** Some house dust control measures and the abundance of *Dermatophagoides pteronyssinus* in Southern California. *J. Med. Entomol.* 12:5–9 (1975).
12. **Arlian, L.G., L.L. Bernstein, and J.S. Gallagher:** The prevalence of house dust mites, *Dermatophagoides pteronyssinus* spp., and associated environmental conditions in homes in Ohio. *J. Allergy Clin. Immunol.* 69:527–532 (1982).
13. **van Strien, R.T., A.P. Verhoeff, B. Brunekreef, and J.H. van Wijnen:** Mite antigen in house dust: Relationship with different housing characteristics in The Netherlands. *Clin. Exp. Allergy* 24:843–853 (1994).
14. **Meijer, G.G., S. van der Heide, D.S. Postma, D.M. de Reus, G.H. Koeter, and W.M.C. van Aalderen:** House dust mite exposure in asthmatic and healthy children: The difference is carpeting. *Pediatr. Allergy Immunol.* 6:187–191 (1995).
15. **Wickens, K., I. Martin, N. Pearce, et al.:** House dust mite allergen levels in public places in New Zealand. *J. Allergy Clin. Immunol.* 99:587–593 (1997).
16. **Wickens, K., R. Siebers, I. Ellis, et al.:** Determinants of house dust mite allergen in homes in Wellington, New Zealand. *Clin. Exp. Allergy* 27:1077–1085 (1997).
17. **Dharmage, S., M. Bailey, J. Raven, et al.:** Residential characteristics influence Der p I levels in homes in Melbourne, Australia. *Clin. Exp. Allergy* 29:461–469 (1999).
18. **Massey, J.E., and D.G. Massey:** Effect of vacuum cleaning on house dust mites. *Hawaii Med. J.* 43:404–406 (1984).
19. **Hay, D.B.:** An 'in situ' coring technique for estimating the population size of house dust mites in their natural habitat. *Acarologia* 36:341–345 (1995).
20. **Tovey E.R., and L.G. McDonald:** Carpet cleaning. *Med. J. Australia* 158:579 (1993).
21. **Lewis, R.D., P.N. Breyse, P.S.J. Lees, M. Dienar-West, R.G. Hamilton, and P. Eggleston:** Factors affecting the retention of dust mite allergen on carpet. *Am. Ind. Hyg. Assoc. J.* 59:606–613 (1998).
22. **Lewis, R.D., P.N. Breyse, D.A. Sterling, and B. King:** A soiling system for evaluation of house dust mite allergens and lead retention on carpets and other surfaces. *Appl. Occup. Environ. Hyg.* 14:845–851 (1999).
23. **Lewis, R.D., and P.N. Breyse:** Carpet properties that affect the retention of cat allergen. *Ann. Allergy Asthma Immunol.* 84:31–36 (2000).
24. **Luczynska, C.M., L.K. Arruda, T.A.E. Platts-Mills, J.D. Miller, M. Lopez, and M.D. Chapman:** A two-site monoclonal antibody ELISA for the quantification of the major *Dermatophagoides* spp. Allergens Der p I and Der f I. *J. Immunol. Methods* 118:227–235 (1989).
25. **American Society for Testing and Materials (ASTM):** Committee on vacuum cleaners F-11: Standard laboratory test method for evaluation of carpet embedded removal effectiveness of household vacuum cleaners, F 608-89. In *Annual Book of ASTM Standards A.02*, pp. 295–311. West Conshohocken, Pa.: ASTM, 1989.
26. **Couper, D., A.-L. Ponsonby, and T. Dwyer:** Determinants of dust mite allergen concentrations in infant bedrooms in Tasmania. *Clin. Exp. Allergy* 28:715–723 (1998).
27. **Wickens, K., K. Mason, P. Fitzharris, et al.:** The importance of housing characteristics in determining Der p I levels in carpets in New Zealand homes. *Clin. Exp. Allergy* 31:827–835 (2001).
28. **Fell, P., B. Mitchell, and J. Brostoff:** Wet vacuum cleaning and house dust mite allergen. *Lancet* 340:788–789 (1992).
29. **Jerrim, K.L., J.F. Hughes, and M.T. McKechnie:** Electrostatic enhancement of dust and allergen removal from carpets. *J. Electrostatics* 53:39–51 (2001).
30. **Ewers, L., S. Clark, W. Menrath, P. Succop, and R. Bornschein:** Clean-up of lead in household carpet and floor dust. *Am. Ind. Hyg. Assoc. J.* 55:650–657 (1994).
31. **Florio, P.A., and E.P. Mersereau:** Control of appearance changes due to soiling: The mechanism, measurement and reduction of soiling changes in carpet during use. *Textil. Res. J.* 25:641–649 (1955).
32. **Salsbury, J.M., T.F. Cooke, E.S. Pierce, and P.B. Roth:** Soil-resistant treatment of fabrics. *American Dyestuff Reporter* 45:190–202 (1956).
33. **Hearle, J.W.S.:** SEM study of wear on wool stair-carpet. *J. Textil. Inst.* 91:616–627 (2000).
34. **Brown, E.M.:** *Fundamentals of Carpet Maintenance*. Leeds, UK, P. A. Brown and Associates, 1985.
35. **Gaynor, P.T., and J.F. Hughes:** Electrostatic charge characteristics of Der p I allergen-carrying particles and the house dust mite *Dermatophagoides pteronyssinus*. *Med. Biol. Eng. Comput.* 36:351–354 (1998).
36. **Snell, F.T., C.T. Snell, and I. Reich:** The nature of soil to be deterged and its bonding to the surface. *J. Am. Oil Chem. Soc.* 27:62–68 (1950).
37. **Schappel, J.W.:** Performance characteristics of synthetic fiber, wool, viscose, and blended fibers in Axminster carpets. *Textil. Res. J.* 26:211–226 (1956).
38. **Weatherburn, A.S., and C.H. Bayley:** The soiling characteristics of textile fibres. Part II: The influence of fibre geometry on soil retention. *Textil. Res. J.* 27:199–208 (1957).
39. **Wassenaar, D.P.J.:** Effectiveness of vacuum cleaning and wet cleaning in reducing house dust mites, fungi and mite allergen in a cotton carpet: A case study. *Exp. Appl. Acarol.* 4:53–62 (1988).
40. **Sercombe, J., D. Liu-Brennan, and E.R. Tovey:** The vertical distribution of Der p I allergen in carpets and the effect of vacuum cleaning. *J. Allergy Clin. Immunol.* 109:S110 (2002).
41. **Wassenaar, D.P.J.:** Reducing house dust mites by vacuuming. *Exp. Appl. Acarol.* 4:167–171 (1988).
42. **Martin, I.R., J.L. Henwood, F. Wilson, et al.:** House dust mite and cat allergen levels in domestic dwellings in Christchurch. *New Zeal. Med. J.* 110:229–231 (1997).
43. **Platts-Mills, T.A.E., and A.L. de Weck:** Report of an international workshop. Dust mite allergens and asthma: A worldwide problem. *J. Allergy Clin. Immunol.* 8:416–427 (1989).
44. **Murray, A.B., and A.C. Fergusson:** Dust-free bedrooms in the treatment of asthmatic children with house dust or house dust mite allergy. A controlled trial. *Pediatrics* 71:418–422 (1983).
45. **Sly, R.M., S.H. Josephs, and D.M. Eby:** Dissemination of dust by central and portable vacuum cleaners. *Ann. Allergy* 54:209–212 (1985).
46. **Kalra, S., S.J. Owen, J. Hepworth, and A. Woodcock:** Airborne house dust mite antigen after vacuum cleaning. *Lancet* 336:449 (1990).