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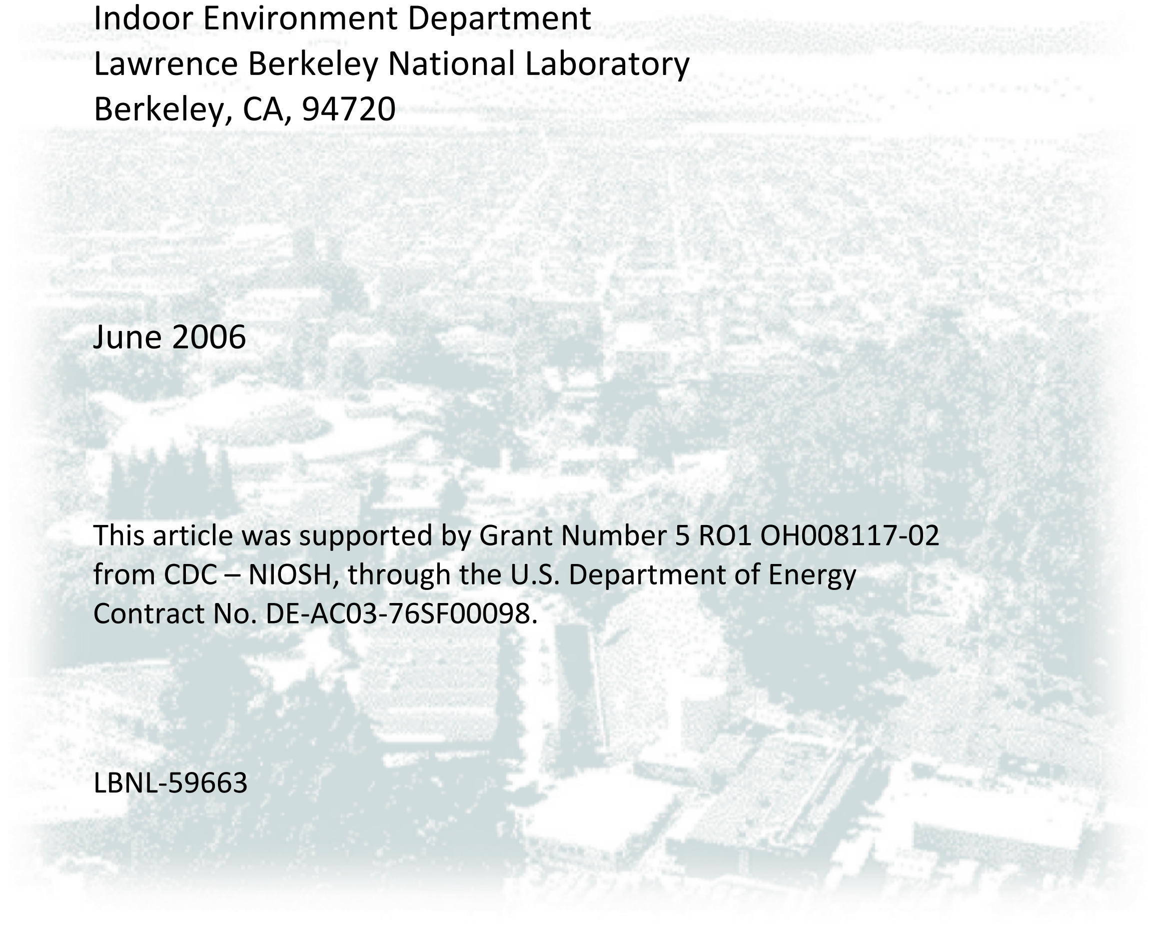
I.S. Buchanan and M.G. Apte

Environmental Energy Technologies Division
Indoor Environment Department
Lawrence Berkeley National Laboratory
Berkeley, CA, 94720



June 2006

This article was supported by Grant Number 5 RO1 OH008117-02 from CDC – NIOSH, through the U.S. Department of Energy Contract No. DE-AC03-76SF00098.

LBNL-59663

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I.S. Buchanan[1] and M.G. Apte[1]

[1]Lawrence Berkeley National Lab, Indoor Environment Dept., 1 Cyclotron Rd, Berkeley, CA, 94720, USA
email: ISBuchanan@lbl.gov http://eetd.lbl.gov/IED

Summary: ***Mechanical ventilation of buildings is a risk factor for building related symptoms (BRS). This analysis examines air filters within mechanical ventilation systems to determine their effect on BRS. We hypothesize that certain ventilation filter materials will contribute more than others to the burden of building related headaches, mucous membrane (MM) and lower respiratory (LR) BRS within a building. This hypothesis was tested using the USEPA Building Assessment, Survey and Evaluation (BASE) study. Logistic regression models constructed to control for personal, workplace, and environmental factors reveled statistically significant ($p<0.05$) associations between the increased prevalence of building related headaches, certain MM and LR BRS and polyester or synthetic containing air filters in a ventilation system, relative to fiberglass or cotton air filters.***

Keywords: ***air filters, building related symptoms, logistic regression***
Category: ***epidemiological study***

1 Introduction

Building related symptoms (BRS), more commonly known as sick building syndrome, are a collection of health symptoms with unknown etiology that building occupants report when they are in a building, but that lessen or disappear when they leave the building. BRS include mucosal, skin and respiratory symptoms along with others such as headache and fatigue.

Although these are relatively minor health effects, BRS affect a large population and have a great overall impact. It is estimated [1] that BRS are responsible for a 2% reduction in office work productivity, which leads to a $2 billion annual loss in economic productivity in the United States alone.

A major focus of BRS research has been on risk factors related to the ventilation systems of buildings. In an extensive review of studies including a total of 460 buildings and 24,000 occupants, Seppänen et al. [2] concluded that the presence of air conditioning was consistently associated with increased BRS prevalence within the building.

Recent studies have examined specific components of a building's mechanical ventilation system, e.g. air filters, as causes of poor indoor air quality and occupant discomfort. Several laboratory studies have shown that ventilation air filters can affect occupants' perceived indoor air quality and act as sources of perceived pollution instead of pollution sinks [3, 4, 5, 6].

Of particular interest are two studies that looked at the effects of used air filters in the ventilation systems on human comfort and performance. Clausen et al. [6] demonstrated that human subjects could detect the presence of a used filter in the study environment and that certain health symptoms (intensity of headaches and dizziness) increased in those subject exposed to air passing through a used filter.

Wargocki et al. [7] studied the effects of used ventilation filters on call-center employees. They discovered that performance (as measured by talk-time) increased (i.e. talk time decreased) when a new filter replaced a used filter, and that irritation of the nose and eyes decreased in the presence of a new filter relative to an old filter. These studies suggest that not only can air filters play a role in perceived indoor environmental quality, but they may also contribute to BRS within a building.

This analysis uses existing data on U.S. office buildings, collected in the US Environmental Protection Agency's Building Assessment, Survey and Evaluation (BASE) study to investigate in greater detail the effects of air filters on BRS: specifically, the possibility that certain air filter materials contribute more than others to the burden of BRS among building occupants. This analysis investigates the association between the material type of supply air filters (i.e., filters containing fiberglass, polyester or synthetic, or cotton or cellulose materials) and two groups of BRS: mucous membrane (MM, e.g. dry eyes, sore throat, runny or congested nose/sinus and sneeze) and lower respiratory (LR, e.g. tight chest, shortness of breath, cough and wheeze). In addition, because of Clausen et al.'s findings that headaches were associated with used air filters, the relationship between filter materials and building related headaches was also investigated.

2 Methods

The BASE Study

The BASE study examined 100 randomly selected US office buildings for one week in either the summer or the winter between 1994 and 1998 [8, 9]. Mechanical ventilation was the dominant form of ventilation within the 100 buildings. The full BASE protocol including the building selection protocol has been described elsewhere in more detail [10, 11].

During the one-week period that each building was studied, confidential self-administered questionnaires were used to collect personal information about the building occupants such as age, sex, smoking status, workspace cleanliness and the presence of several specific health symptoms. A self reported health symptom was classified as building related if it occurred at least 1-3 days per week for the four-weeks prior to the study week and the symptom lessened when the occupant was away from the building. The BASE questionnaire also asked about other pre-existing health and environmental sensitivities.

A detailed inspection of all of the mechanical ventilation air filters was conducted as a part of the BASE study. The inspection recorded the filter material, as well as other factors affecting filter condition.

Analysis variables

The minimum efficiency reporting value (MERV) for filters was obtained through the manufacturer, or estimated based on available data provided by the manufacturer after the completion of the BASE study.

In order to assess if certain air filter material put occupants at greater risk for BRS than other filter materials, a 2-part categorical filter material variable, FILTER, was constructed from the filter materials recorded in the mechanical ventilation system inspections during the BASE study. The filter variable was defined in the following manner: FILTER equaled 1 when a building study space had at least one filter containing polyester or synthetic materials, and FILTER equaled 0 when that study space had no filters containing polyester or synthetic materials. All filter material classifications were based on the recorded data during the BASE study inspection.

In order to see the differential effects between air filters containing polyester or synthetic materials and fiberglass or cotton/cellulose filters, we created two additional binary filter material variables, FILTER_FIB and FILTER_COT. FILTER_FIB equaled 1 when the building had at least one filter containing polyester or synthetic materials and 0 when the building had at least one fiberglass filter but no polyester or synthetic containing filters. Buildings with neither fiberglass nor polyester or synthetic containing filters were excluded from this variable. FILTER_COT equaled 1 when the building had at least one filter containing polyester or synthetic materials and 0 when the building had at least one cotton or cellulose filter but no polyester or synthetic containing filters. Buildings that had neither cotton or cellulose filters nor polyester or synthetic containing filters were excluded from this variable.

Erdmann and Apte [12] discovered that having allergies, frequent/regular headaches or environmental sensitivities put building occupants at increased risk of mucous membrane and lower respiratory BRS. Therefore, an at risk population variable, RISK, was used as a covariate to specify respondents with at least one of the following self-reported sensitivities: dust or mold allergies, hay fever, migraines, sensitivities to tobacco smoke or sensitivities to chemicals such as cleaners.

Environmental variables that were calculated from BASE data included: an estimate per person outdoor air ventilation (dCO_2: based on average indoor minus average outdoor workday CO_2 concentrations), workday thermal exposure (the integrated difference between 20^o C and 5 minute averages of indoor temperature), relative humidity (indoor workday average), and heating and cooling degree-days (^{o}C-days) as an indicator on climate severity. See Erdmann and Apte [12] for more details on how these variables were calculated.

The 24 hour ambient ozone concentration, OZONE, on the day when the occupants answered the questionnaire was calculated from data obtained blindly from a third party contractor for the EPA. This was necessary because ozone measurement were not obtained during the BASE study itself.

Statistical analyses

Logistic regression models were constructed for dependent variables that included each individual health symptom and two aggregate symptom categories, MM and LR. The MM category required the presence of least one mucous membrane BRS and the LR category required the presence of at least one lower respiratory BRS. The explanatory variables were FILTER, FILTER_FIB and FILTER_COT. Each explanatory variable was analyzed in a separate set of models (both crude and adjusted) for each individual health symptom and MM and LR.

All statistical analyses were conducted using SAS version 8.2 for Windows PC. Prevalence odds ratios (ORs) and Wald Maximum Likelihoods were calculated using logistic regression. Crude (unadjusted bivariate logistic regression) and adjusted (multivariate logistic regression) models were constructed for headache and each individual mucous membrane and lower respiratory BRS as well as for the aggregate MM and LR variables. Multivariate logistic regression (MLR) models were adjusted for personal risk factors (age, sex, tobacco use and RISK), workplace risk factors (presence of workplace carpet and building ventilation rates) and environmental risk factors (thermal exposure, relative humidity, heating and cooling degree days, the season that the building was studied, 1,2,4-trimethylbenzene (a proxy for automobile exhaust) and OZONE). MLR models were based on Erdmann and Apte's analyses [12].

To estimate the amount of BRS that could be reduced through filter replacement interventions, the percent risk reduction (PRR) was calculated for statistically significant adjusted ORs. The PRR is similar to the attributable risk, in that it estimates the possible reduction of ill-health if the exposure to the ill-health causing agent never occurred. In this case, the exposure is to filters containing polyester or synthetic materials relative to fiberglass filters or to cotton or cellulose filters.

The PRR is calculated as follows:

$$\boldsymbol{PRR} = \frac{(\boldsymbol{RR} - 1)}{\boldsymbol{RR}} \cdot 100$$

where RR is the increased risk of illness in the exposed group relative to a reference group. Although we have not calculated RR, ORs are an approximation of RR when the prevalence of the disease is low (<5%). When the prevalence is greater than 5%, adjustments must be made to the PRR to correct for errors in approximation. Adjustments include a maximum 10% reduction of the PRR if prevalence is 5-10% and a maximum reduction of 20% if the prevalence is 10-30%. For further details on this procedure see Apte et al. 2000 [13].

3 Results

Summaries of the covariates used in this analysis can be found in Erdmann and Apte [12]. Prevalence for individual and aggregate BRS dependent variables, listed in Table 1, ranged from 2-29%.

Table 1: Individual and aggregate BRS prevalence.

BRS Symptom	Prevalence
Headache	15.2%
MM	29.2%
Dry eyes	18.6%
Sore throat	6.6%
Nose/sinus	13.1%
Sneeze	11.4%
LR	7.9%
Tight chest	2.2%
Short breath	1.8%
Cough	5.1%
Wheeze	1.8%

Five buildings were missing air filter material data and were excluded from the study. Of the remaining 95 buildings, 48 had at least one filter containing polyester or synthetic materials, 31 had at least one fiberglass filter and no filters containing polyester or synthetic materials, and 14 had at least one cotton filter and no filters containing polyester or synthetic materials.

The median, interquartile range (IQR), min and max MERV values for filter materials are presented in Table 2.

Table 2: Air filter MERV values for filters containing polyester or synthetic materials (poly/synth), not containing polyester or synthetic materials (no poly/synth), fiberglass filters and cotton and cellulose filters.

Filter Type	Median	IQR	Min	Max
Poly/synth	7	6.5-8	1	14
No poly/synth	7	6-11	1	14
Fiberglass	7	5-12.5	1	14
Cotton/cellulose	6.5	6.5-7	5	11

Results from the logistic regression analyses are presented in Table 3. Crude ORs showed statistically significant ($p<0.05$) associations of symptoms with polyester or synthetic filter materials, ORs ranging from 1.23-2.08, for headache, dry eyes, nose/sinus, sneeze, shortness of breath, cough, wheeze, aggregate MM symptoms, and aggregate LR symptoms. After adjusting for personal, workplace and environmental factors all relationships that were statistically significant in the crude analyses remained so with the exception of shortness of breath. The adjusted odds ratios for the statistically significant associations ranged from 1.27-2.01. Although the associations of filter material variables with the other three symptom variables were not statistically significant at the 95% confidence level, none of them had odds ratios below unity, suggesting a systematic relationship between the polyester or synthetic filter materials and increased symptom reporting.

Table 4 presents the results of models comparing BRS in buildings with at least one filter containing polyester or synthetic materials relative to BRS in buildings with at least one fiberglass filter and no polyester or synthetic containing filters. Sample sizes for each model were reduced compared with the first set of models due to the exclusion of buildings with no fiberglass filters and no filters containing polyester or synthetic materials. Statistically significant ($p<0.05$) crude ORs for symptoms in occupants of buildings containing filters with polyester or synthetic material relative to occupants of buildings with fiberglass and no polyester or synthetic containing filters ranged from 1.26-1.96 for headache, dry eyes, nose/sinus, sneeze, cough, wheeze, MM and LR. In the adjusted models, the OR for wheeze became non-significant while significant ORs for headache, dry eyes, nose/sinus, sneeze, cough, MM and LR ranged from 1.24-1.67.

Results from the third set of logistic regression models assessing BRS in occupants of buildings with at least one filter containing polyester or synthetic materials relative to symptoms in occupants of buildings with at least one cotton or cellulose filter and no filters containing polyester or synthetic materials are presented in Table 5. The sample sizes for these models were drastically reduced from the

Table 3: Crude and Adjusted ORs (95% Confidence Intervals) for the associations of headache, MM and LR BRS with the presence vs. the absence of air filters containing polyester or synthetic materials.

BRS Symptom	Crude models		Adjusted models	
	OR (95% CI)	n*	OR (95% CI)	n*
Headache	**1.23 (1.03-1.46)**	4103	**1.27 (1.06-1.53)**	4011
MM	**1.32 (1.15-1.51)**	4169	**1.36 (1.18-1.58)**	4076
Dry eyes	**1.33 (1.14-1.56)**	4100	**1.35 (1.14-1.60)**	4008
Sore throat	1.04 (0.81-1.33)	4112	1.10 (0.85-1.44)	4022
Nose/sinus	**1.74 (1.43-2.10)**	4052	**1.73 (1.41-2.12)**	3964
Sneeze	**1.46 (1.20-1.79)**	4059	**1.56 (1.26-1.92)**	3969
LR	**1.66 (1.31-2.10)**	4173	**1.72 (1.34-2.21)**	4080
Tight chest	1.31 (0.86-1.99)	4156	1.23 (0.79-1.92)	4065
Short breath	**1.67 (1.04-2.69)**	4143	1.68 (1.00-2.82)	4051
Cough	**1.69 (1.26-2.26)**	4114	**1.94 (1.41-2.67)**	4024
Wheeze	**2.08 (1.28-3.40)**	4156	**2.01 (1.19-3.37)**	4063

*number of respondents in model

Table 4: Crude and Adjusted ORs (95% Confidence Intervals) for the association of headache, MM and LR BRS with the presence of air filters containing polyester or synthetic materials relative to the presence of filters containing fiberglass and no filters containing polyester or synthetic materials.

BRS Symptom	Crude models		Adjusted models	
	OR (95% CI)	n*	OR (95% CI)	n*
Headache	**1.26 (1.03-1.54)**	3454	**1.30 (1.05-1.62)**	3454
MM	**1.30 (1.11-1.51)**	3508	**1.29 (1.09-1.52)**	3508
Dry eyes	**1.31 (1.09-1.57)**	3448	**1.24 (1.02-1.51)**	3448
Sore throat	1.03 (0.78-1.36)	3460	0.96 (0.71-1.30)	3460
Nose/sinus	**1.73 (1.39-2.16)**	3413	**1.67 (1.32-2.12)**	3413
Sneeze	**1.42 (1.13-1.78)**	3413	**1.53 (1.19-1.96)**	3413
LR	**1.51 (1.16-1.96)**	3512	**1.44 (1.08-1.91)**	3512
Tight chest	1.27 (0.79-2.04)	3498	0.93 (0.56-1.54)	3498
Short breath	1.35 (0.81-2.26)	3489	1.24 (0.70-2.19)	3489
Cough	**1.46 (1.06-2.02)**	3460	**1.61 (1.13-2.29)**	3460
Wheeze	**1.96 (1.12-3.43)**	3498	1.60 (0.88-2.89)	3498

*number of respondents in model

Table 5: Crude and Adjusted ORs (95% Confidence Intervals) for the association of headache, MM and LR BRS with the presence of air filters containing polyester or synthetic materials relative to the presence of cotton or cellulose filters and no filters containing polyester or synthetic materials.

BRS Symptom	Crude models		Adjusted models	
	OR (95% CI)	n*	OR (95% CI)	n*
Headache	1.08 (0.84-1.38)	2820	2.25 (0.94-5.37)	2758
MM	**1.42 (1.16-1.74)**	2860	**1.58 (1.23-2.02)**	2797
Dry eyes	**1.43 (1.12-1.83)**	2811	**1.62 (1.21-2.18)**	2749
Sore throat	1.09 (0.75-1.57)	2818	1.25 (0.80-1.94)	2757
Nose/sinus	**1.64 (1.23-2.20)**	2777	**1.53 (1.09-2.15)**	2718
Sneeze	**1.40 (1.04-1.89)**	2778	**1.48 (1.04-2.10)**	2716
LR	**1.97 (1.34-2.90)**	2862	**1.94 (1.25-3.03)**	2799
Tight chest	1.27 (0.67-2.37)	2851	1.01 (0.49-2.09)	2789
Short breath	**2.74 (1.09-6.89)**	2841	2.43 (0.89-6.65)	2778
Cough	**2.03 (1.25-3.31)**	2822	**2.52 (1.41-4.47)**	2760
Wheeze	2.15 (0.98-4.75)	2851	2.25 (0.94-5.37)	2788

*number of respondents in model

previous two sets of models due to the scarcity of cotton and cellulose filters within building ventilation systems. The decline in sample size reduced the power of the analysis; however, several significant relationships were still present. Significant ($p<0.05$) crude ORs ranged from 1.40-2.74 for dry eyes, nose/sinus, sneeze, shortness of breath, cough, MM and LR, while significant adjusted ORs ranged form 1.48-2.52 for dry eyes, nose/sinus, sneeze, cough, MM and LR.

Assuming that filters containing polyester or synthetic material are causal agents for BRS and all other parameters are held constant, the PRR analyses indicated that if all filters containing polyester or synthetic materials were replaced with fiberglass filters, there could be 18%, 15%, 32%, 28%, 34% reductions of headache, dry eyes, nose/sinus, sneeze and cough BRS, respectively. If all filters containing polyester or synthetic materials were replaced with cotton or cellulose filters the estimated reduction of dry eyes, nose/sinus, sneeze and cough would be 31%, 28%, 26% and 54% respectively.

4 Discussion

The results of these analyses indicate that there exists a positive association between the presence of at least one air filter containing polyester or synthetic materials in building ventilation system and increases in headache and certain MM and LR BRS. These findings were present in crude, un-adjusted analyses, and persisted in the results of adjusted multivariate logistic regression models that controlled for personal, workplace and environmental factors.

These results are consistent with previous studies which demonstrated that air filters can affect the indoor air quality and the health of building occupants [3, 4, 5, 6, 7]. However, this study is unique in that it examined the differential effects of filter materials on occupant BRS. The analyses presented here, give the first indication that particular air filter materials are associated with higher levels of headache and certain MM and LR BRS in the BASE study.

It is important to remember that these relationships are only associations and correlations and do not form the basis for a conclusion about causation at this time. Before a conclusion is made, replication of these findings in additional cross sectional studies is necessary, findings should be documented in an intervention study, and the mechanism by which filters containing polyester or synthetic materials increase a building occupant’s odds of having BRS should be discovered and understood.

Investigation into the physical properties of filters containing polyester or synthetic materials may lead to a plausible mechanistic explanation for BRS causation. The chemical composition of the filters and how they react/interact with gas and particle phase air contaminants may prove valuable. Determination of the inertial and electrostatic conditions affecting loading patterns on different filter materials may also play a crucial role. Quantification of the types of surface chemical reactions that take place on and in filters and how they differ between filter materials will also be an important component to understanding a plausible causal mechanism. In addition, when the variable OZONE was added to the models, the majority of the ORs point estimates changed indicating possible confounding. Ozone mediated or influenced reactions may play a role in a plausible causal mechanism.

Given that previous studies have demonstrated that older filters can degrade the air quality, one should check to see if the frequency of filter change is correlated to filter materials. In addition, this study applies building wide averages for environmental and filter parameters to all occupants within that building. Future studies should try and classify environmental and filter parameter by smaller units within a building. This will be more precise and will allow for better and more detailed analyses of filter types and BRS.

Although the MERV values for the filters were not included in the MLR models, it is unlikely that they would have a significant effect on the BRS filter materials relationships that were found. There was great similarity in the distributions of MERV values for the different filter material categories indicating that MERV values should not influence the BRS filter materials relationship.

A more refined analysis would compare BRS in buildings with polyester or synthetic containing filters and at least one fiberglass filter to BRS in buildings with no polyester or synthetic containing filters and at least one fiberglass filters. The same would be true for cotton and cellulose filters analysis. This would help to eliminate difference between the two groups that are being compared. This more refined analysis was not performed here because the sample size reductions in the models would have been tremendous and would have reduced the power of the models considerably.

The results of these analyses should be taken in perspective, and the work should be replicated and causal mechanisms should be identified before any major changes to building operation practices are made. However, if polyester or synthetic air filter materials are causing a greater burden of BRS than other filters, this offers a very practical and hopeful solution for reducing the overall BRS burden. Filter replacement is a realistic intervention that could have dramatic effects if widely implemented. The PRR analyses indicate that filter replacement could be responsible for a reduction of BRS illness ranging from 15%-54% for headache, dry eyes, nose/sinus, sneeze and cough BRS. The statistics suggest that other MM and LR BRS would be similarly reduced as well. Filters must be replaced on an ongoing basis, so the costs incurred in switching filter types would only be associated with the price differential between the different filter types. Such an intervention is very practical; thus, it seems likely that building managers would be willing to implement it.

Conclusion

After adjusting for personal, environmental and workplace factors significantly higher prevalences of headache and certain MM and LR BRS were present in buildings with air filters containing polyester or synthetic materials. Our results indicate that 15%-54% of the current BRS could be avoided if exposure to polyester or synthetic containing air filters was eliminated through the use of fiberglass, cotton or cellulose filters. Such elimination would be possible through the replacement or exchange of current filters containing polyester or synthetic materials. This study is the first to report increase risk for headache, MM and LR BRS in the presence of polyester or synthetic materials in a building's ventilation system. However, before conclusions are drawn, the findings presented here need to be replicated and the underlying mechanism by which polyester or synthetic materials affect human health must be determined.

Acknowledgments

This article was supported by Grant Number 5 RO1 OH008117-02 from CDC - NIOSH. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of CDC - NIOSH. We would like to thank William Fisk, Mark Mendell and Q. Lei-Gomez at Lawrence Berkeley National Laboratory for their input and reviews. We would also like to extend thanks to John Girman and Greg Brunner of the U.S. EPA for their input and the U.S. EPA for providing the data used in these analyses.

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