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HEALTH BENEFITS OF PARTICLE FILTRATION

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ABSTRACT

The evidence of health benefits of particle filtration in homes and commercial buildings is reviewed. Prior reviews of papers published before 2000 are summarized. The results of 16 more recent intervention studies are compiled and analyzed. Also reviewed are four studies that modeled health benefits of using filtration to reduce indoor exposures to particles from outdoors. Prior reviews generally concluded that particle filtration is, at best, a source of small improvements in allergy and asthma health effects; however, many early studies had weak designs. A majority of recent intervention studies employed strong designs and more of these studies report statistically significant improvements in health symptoms or objective health outcomes, particularly for subjects with allergies or asthma. The percentage improvement in health outcomes is typically modest, e.g., 7% to 25%. Delivery of filtered air to the breathing zone of sleeping allergic or asthmatic persons may be more consistently effective in improving health than room air filtration. Notable are two studies that report statistically significant improvements, with filtration, in markers that predict future adverse coronary events. From modeling, the largest potential benefits of indoor particle filtration may be reductions in morbidity and mortality from reducing indoor exposures to particles from outdoor air.

Key words: air cleaning, allergy, asthma, filtration, particle, health

PRACTICAL IMPLICATIONS

People with allergy and asthma symptoms who reside in homes with strong sources of allergens may reduce their symptoms moderately through use of particle filtration systems in their home. Particle filtration may also help to reduce the substantial morbidity and mortality associated with indoor exposures to outdoor air particles.

INTRODUCTION

Particles in indoor air derive from outdoor air and from a variety of indoor sources including cooking, tobacco smoking, office equipment, chemical reactions, and various biological sources including molds, pets, house dust mites, and people. The adverse health effects of higher concentrations of outdoor air particles are well documented, e.g., (Brunekreef and Forsberg 2005; Delfino et al. 2005; Pope and Dockery 2006; Pope et al. 2009). Less is known about the health effects of indoor-generated particles except for the allergens and inflammatory agents of bioaerosols that are known or suspected to be associated with allergic sensitization, allergy and asthma symptoms, and asthma development (IOM 1993; IOM 2000; IOM 2004). Also, indoor aerosols emitted by people may contain infectious organisms that can transmit communicable respiratory diseases (Li et al. 2007).

One review (Schneider et al. 2003) concluded from an examination of eight studies that existing evidence was insufficient to conclude that indoor airborne particle concentrations were indicators of health risks. Two risk analyses found that indoor particle exposures were a large or dominant source of chronic health risks from indoor pollutant exposures (de Oliveira Fernandez et al. 2009; Logue et al. 2012).

Particle filtration systems are widely used to protect equipment within forced air heating, ventilating, and air conditioning (HVAC) systems and to reduce concentrations of particles in indoor air. In the HVAC systems of many U.S. commercial buildings, both the incoming outdoor air and recirculated indoor air are filtered. In large commercial buildings, HVAC system's fans usually operate continuously during occupancy, providing continuous filtration, while in smaller commercial buildings fan operation and filtration may be discontinuous. In Europe, commercial HVAC systems more often omit air recirculation, thus, only the incoming outdoor air is filtered. Most U.S. homes with forced air HVAC have no mechanical supply of outdoor air. Recirculated indoor air is filtered; however, filtration in U.S. residential systems is not continuous because the HVAC system's fans cycle on and off based on the need for heating or cooling. The efficiency at which particles are removed by the filters in HVAC systems varies widely depending on the type of filter used and particle size. Particle removal efficiency tends to be lowest for particles with aerodynamic diameters of 0.2 to 0.3 μm, and higher for both larger and smaller particles (Hanley et al. 1994). The filters used in many home HVAC systems provide minimal removal of particles smaller than 1 μm, but medium and high efficiency filters are available and used in some houses.

Stand–alone portable fan-filter air cleaning systems are also widely available and used in buildings, particularly in homes of people with allergies. The rate of air flow filtered by these systems varies widely, and particle removal efficiency also varies, but many units use high efficiency particulate air (HEPA) filters that are nearly 100% efficient in removing particles of all sizes, although air leakage around the filter can reduce the system's particle removal efficiency to a level significantly below 100%.

Most often particle filtration systems employ mechanical filters in which layers of small closely spaced fibers catch and collect particles. Various types of electronic air filtration systems are also used, often these generate ions that attach to and electrically charge particles and then collect the charged particles on a cleanable metal plates. Most of the subsequently described research employed mechanical filters. A review by the U.S. Environmental Protection Agency provides further background on residential air cleaners (EPA 2009).

Many published documents, e.g., (Fisk et al. 2002; Jamriska et al. 2003; EPA 2009; Batterman et al. 2011; Zhang et al. 2011) and papers discussed subsequently, provide information on the extent to which indoor particle concentrations are reduced by filtration systems, either installed in HVAC systems or stand-alone devices. Key factors are the rate and duration of air flow through the filter system, the particle removal efficiency rating of the filters, and particle size. Reductions in indoor particle concentrations via filtration can be substantial – in the subsequently cited studies reductions in concentrations in homes averaged more than 50%. People's indoor exposures to particles will generally be higher than indicated by measured indoor air particle concentrations as a result of the particle-generating activities of people (Ozkaynak et al. 1996). Consequently, measured and predicted reductions in indoor air particle concentrations from filtration may overestimate actual reductions in people's exposures to particles.

A smaller but still substantial number of published documents provide information on the extent to which particle filtration reduces adverse health effects. Most of the prior studies employed stand-alone portable air filters in homes, often with subjects that had allergies or asthma. This literature has been reviewed, e.g., (IOM 2000; Wood 2002; Sublett 2011) but no identified review included the results of 16 more recently published studies, most with high quality study designs. In addition, none of the prior reviews included a compilation and analysis of the modeled health benefits of using filtration to reduce exposures to particles from outdoor air. Consequently, the purpose of this current paper is to provide a more up to date critical review of the state of knowledge about health benefits of particle filtration.

METHODS

This review includes only research on particle filtration in non-industrial buildings such as homes, schools, and offices. Studies from health care buildings, in which much of the research has focused on patients with compromised immune systems, were excluded, except one of the prior reviews considered included three studies from hospital wards or patient rooms. Studies of controlled exposures to particles in chambers were not considered. The scope was further restricted to exclude studies of filtration technologies that remove only gaseous pollutants from indoor air. Studies that employed ion generators without particle collection systems were excluded. Studies performed in developing-country settings with unvented solid-fuel indoor cooking or heating were also excluded. Otherwise, there were no geographical constraints on the inputs.

Many relevant papers on the associations of particle filtration with health outcomes have been published over a several-decade period. Rather than review every paper published over this extended time period, the findings published in 2000 by the Institute of Medicine (IOM) of the National Academy of Sciences (IOM 2000) were used as a starting point. The IOM document considered papers published from as early as 1927. For the current paper, the findings from the IOM were considered together with the findings of more recently published qualitative reviews, the results of a more recent quantitative meta analysis (McDonald et al. 2002) based largely on papers considered by the IOM, and the results of more-recently published journal articles not considered by the IOM. The IOM review was selected as a starting point because it was the most comprehensive prior review and it was subjected to a rigorous independently-managed external peer review.

Papers were identified via searches using the Pub Med and Web of Science on-line bibliographic search tools with various combinations of the following search terms: building, home, office, school, classroom, work place, particle, filtration, air cleaning, health, illness, disease, allergy, asthma, respiratory infection, health symptom. Additional papers were identified from examination of the reference lists of papers identified via the computerized searches and suggested by reviewers.

To assure the high quality of input data, the review consider as eligible for inclusion only papers published in refereed archival journals and documents produced by authoritative organizations (e.g., National Academy Committees, World Health Organization) known to implement rigorous external reviews. Results of intervention studies were utilized only if the studies evaluated changes in health within a set of subjects subjected to the filtration intervention during some time periods, and subjected to a reference condition without the intervention in other time periods, or employed a control group in which no intervention was implemented with control group selection accounting for potential sources of confounding including subject age, gender, and health status, and presence or absence of tobacco smoking. Papers from cross-sectional studies were considered eligible only if the study controlled via study design or analysis methods for age, gender, subject health status, socio-economic status, and indoor tobacco smoking; however, no identified cross sectional studies met these criteria. Papers that modeled the health benefits of using filtration to reduce exposures to particles from outdoor air were reviewed if they were published in refereed archival journals.

Health outcomes considered in this review included: subjectively reported health symptoms (primarily associated with allergies or asthma); objectively measured indicators of allergy, asthma, inflammation, respiratory system performance, lung function, blood pressure, heart rate, and future cardiac events; and asthma medication use. Additional health outcomes were premature death, hospital admissions, and various types of morbidity commonly associated with higher levels of outdoor air particles. The effects of air filtration on satisfaction with indoor air quality, odor perceptions, and work performance were not considered.

From the accepted new papers, key study information, data, and findings were extracted and organized in tables. Tabulated information included study features such as type and number of subjects, key study design features, and study strengths and weaknesses. Because the benefits to health may depend on the duration of the intervention, lengths of intervention periods were included in the tables. Many studies had multiple intervention and placebo periods of this length and some assessed health multiple times within each period. Study findings tabulated, or in some cases calculated from the published data, included absolute and percentage changes in indoor particle concentrations (mass concentrations or counts) or other exposures, and the changes in subjective and objective health outcomes and their statistical significance. A 95% confidence intervals excluding the null (no effect) or a p value less than 0.05 was the criterion for a statistically significant finding. The authors' main conclusions were also included in the tables. Conclusions were drawn based on the consistency and strength of findings after considering study strengths and weaknesses.

RESULTS

Within a broader review on indoor air quality and asthma, the Institute of Medicine (IOM 2000) reviewed the scientific literature addressing the effects of particle filtration on health outcomes of asthma and allergy. Thirteen studies were reviewed that assessed effects of particle air cleaning on allergy or asthma symptoms in subjects with perennial allergic disease, often associated with allergens from indoor sources. Seven studies were reviewed that assessed effects of particle filtration on symptoms of allergy and asthma in subjects with seasonal allergic disease, associated with seasonally variable outdoor air allergens. Studies reviewed by the IOM used portable air cleaners with fibrous filters or electrostatic precipitators, except for one study that employed an ionizer. Several studies took place before 1960. All but three of the studies were performed in homes. Two studies took place in hospital wards and one study in hospital rooms plus homes. Many of the studies had substantial weaknesses such as a small number of subjects (< 15), short study periods, and a sole reliance on self-reported health symptoms. Many studies provided almost no information on home characteristics. More than half of the studies failed to assess or report reductions in airborne particles or allergens, and many of the papers failed to characterize the flow rates and particle removal performance of the air cleaners. Three of 13 studies of subjects with perennial allergic disease failed to blind the subjects or use placebo air cleaners. Four of seven studies of subjects with seasonal allergic disease failed to employ blinding or placebo air cleaners and, in a fifth study, it was unclear if subjects were blinded. Several of the older studies failed to include statistical tests of the significance of findings.

The thirteen studies of subjects with perennial allergic disease included three studies with particle-filtered air supplied at the subjects' breathing zones when in bed. All three studies reported improvements in some of the assessed health outcomes, but one of these studies performed no statistical tests of study results. Within the ten remaining studies:

- Two studies reported statistically significant improvements in at least one health outcome; however, in one of these two studies the improvement occurred only during weeks without respiratory illnesses and in the second of the two studies the improvement occurred with simultaneous use of impermeable mattress covers designed to protect against dust mite exposures.

- Two studies reported substantial health improvements but included no statistical tests.
- The remaining six studies reported no statistically significant improvements in any health outcome.

All seven of the studies of subjects with seasonal allergic disease reported some improvements in health but in four of these studies there were no tests of the statistical significance of findings.

The Institute of Medicine (IOM 2000) concluded that “overall these studies suggest that air cleaners are probably helpful in some situations in reducing allergy and asthma symptoms, but air cleaning, as applied in these studies, is not consistently and highly effective in reducing symptoms”.

Subsequent to the review by the Institute of Medicine, Wood (2002) published a review of a subset of the same set of papers. He concluded that air cleaners “have relatively little value in the control of dust mite allergens” and “they make the most sense for animal allergy”. He characterized the benefits as “far from definitive” but suggested that use of air cleaners makes sense to “allergic pet owners who refuse to remove the offending pet from their homes”. Reisman (2001) reviewed four of the studies considered by the Institute of Medicine and concluded that the studies “show minimal, if any, effectiveness in treatment of allergic respiratory disease.” A more recent pair of articles (Sublett et al. 2010; Sublett 2011) reviewed many of the studies considered by the Institute of Medicine plus a few newer studies. No definitive conclusions were stated about the health benefits of filtration; however, these papers concluded that “filtration reduces indoor levels of ambient particulates that might trigger disease processes.” One of these papers suggested that the preferred option may be use of efficient filters in forced air heating and air conditioning systems together with room air cleaners or filters that deliver filtered air to the breathing zone during sleep.

In 2002, McDonald et al. (2002) published the results of a statistical meta-analysis of ten randomized trials of the use of stand-alone residential air filtration systems in homes of subjects with asthma. Nine of ten studies in the meta-analysis were a subset of the studies reviewed by the Institute of Medicine (IOM 2000). Nine of ten studies had subjects with perennial allergic disease. Overall, the analysis indicated that particle filtration was associated with statistically significant improvements in total symptoms and sleep disturbance. On average, when filters were employed symptom scores decreased by approximately 5% to 8% and sleep disturbance scores decreased by approximately 10%. There were no overall statistically significant improvements in nasal symptoms, medication use, or peak expiratory flow. The improvements in total symptoms and sleep disturbance were not statistically significant when a more conservative statistical model was employed for the analysis.

Tables 1 through 3 provide key features and results of 16 additional intervention studies of the health benefits of particle filtration published since 2003 in refereed archival journals. Studies included in the previously-discussed review by the Institute of Medicine (IOM 2000) and in the meta-analyses by McDonald et al. (2002) were excluded from these tables. Also excluded were several studies that employed ion generators for particle control. [A review of the effectiveness of ion generators is provided by Siegel et al. (2008)]. Thirteen of the 16 studies were performed in homes, two in office buildings, and one in a classroom. Most studies had multiple strong design elements such as control groups, crossovers (control group becomes intervention group), use of placebo filters, random assignment of subjects to intervention group versus control group, and balancing of the order of treatment (intervention versus placebo). Many of the studies included both objective (measured) and subjective (reported) health outcomes.

Table 1 summarizes five new intervention studies performed in homes with subjects that had allergies or asthma. In four of the studies, the homes contained pets or tobacco smoking, which are known risk factors for allergies or asthma. The fifth study took place in homes with high pet allergen levels. In two studies, the air cleaners also contained sorbents for removing some gas-phase chemicals as well as filters for removing particles. From these five studies, there were seven reported statistically significant improvements in health outcomes (reported symptoms and objectively measured outcomes) out of 28 total reported results. Only 1.4 statistically significant improvements in health outcomes would have been expected by pure chance with 95% confidence intervals. There were no reported cases of a statistically significant worsening of health outcomes. In some studies, health outcomes improved but not by a statistically significant amount. All but one statistically significant improvement in health outcomes occurred in the homes with pets or high levels of pet allergens; hence the evidence of health benefits in homes with tobacco smoking was limited.

Table 2 details four intervention studies performed in homes with allergic or asthmatic subjects and with air cleaners providing particle-filtered air to the breathing zones of subjects when sleeping in their beds. Two of these studies (Pedroletti et al. 2009; Boyle et al. 2012) employed the same filter system. All four studies reported statistically significant improvements in health outcomes and the overall rate of improvement was much higher than expected by chance. However, one study (Morris et al. 2006) had a weak design, the results were not fully analyzed, and the un-analyzed portion of the data appear to indicate that there were no health benefits. Three of the studies were supported by the manufacturer of the air filter systems, a potential source of bias. Some authors of the fourth study had received support from the filter system manufacturer.

Table 3 summarizes five intervention studies that did not specifically target subjects with allergies or asthma. The building types varied. In three of these studies, there were known strong health risk factors (wood smoke, environmental tobacco smoke) and all of these studies reported improvements in markers of health. Allen et al. (2011) found that filtration in homes with exposure to wood smoke was associated with statistically significant improvement in markers of inflammation and markers of future coronary events, but a marker of oxidative stress was not affected by filtration. Brauner et al. (2008) performed a similar study but in homes without special strong sources of particles. They reported statistically significant improvement in a predictor of coronary events and slightly increased hemoglobin levels, but no changes in biomarkers of inflammation or blood coagulation. The study of Weichenthal et al.

(2012) in First Nation homes, most with tobacco smoking and high particle levels, found filtration associated with statistically significant improvements in lung function and blood pressure, but no statistically significant improvements in a predictor of coronary events. Lin et al. (2011) found reductions in blood pressure and heart rate with filtration, but the study is highly subject to confounding error because the intervention periods always followed the periods without intervention. This study also reported a statistically significant association of blood pressure and heart rate with PM2.5 levels only during the period without filtration, despite the fact that PM2.5 levels were only about 20% lower during the filtration intervention period. One study in two floors of a large office building (Mendell et al. 2002) found no statistically significant reductions in acute health symptoms despite a very large 94% decrease in concentrations of small particles. A second study in offices (Skulberg et al. 2005) reported some statistically significant improvements in objective health measures (nasal cross section, nasal volume, peak expiratory flow) but no significant improvements in health symptoms. The final study (Wargocki et al. 2008), performed in classrooms, found no consistent and statistically significant improvements in health symptoms with operation of electrostatic precipitators. The study reported two cases of a statistically significant worsening of a health outcome.

Tables 1-3 provide the percentage improvements in statistically-significantly improved health outcomes, when it was possible to calculate the percentages. In most cases, these percentages could not be calculated. The calculated percentage improvement in symptoms ranged from 8% to 42% with a mean and median of approximately 22%. The calculated percentage improvements in objective outcomes ranged from 1% to 33% with a mean of 11% and median of 8%.

Many of the studies provided percentage reductions in airborne particle concentrations in one or more size ranges or provided data enabling calculations of percentage reductions in concentrations. Excluding results from studies that provided filtered air to the breathing zone of sleeping subjects, the reductions in particle concentrations ranged from 16% to 94% with mean and median values of approximately 54%. Percentage reductions in particle concentrations tended to be larger for smaller size particles. Two of four studies with filtered air provided to the breathing zone of sleeping subjects reported reductions in breathing-zone concentrations of particles. In both cases, the reduction in particle counts was greater than 99%, but the supporting measurements appeared to be limited.

Another set of papers included in this review addressed the effects of filters on the health effects of particles with an outdoor-air origin. An extensive body of research indicates that death rates, hospital admissions, asthma exacerbations and other adverse health effects increase with increased concentrations of particles in outdoor air, e.g., (Brunekreef and Forsberg 2005; Delfino et al. 2005; Pope and Dockery 2006). Since a large fraction of people's exposures to these outdoor air particles occurs indoors, and because these exposures can be reduced by filtration, it is reasonable to expect associated health benefits from particle filtration. However, many of the health or health-related outcomes associated with outdoor particles (death, hospital admission, chronic bronchitis) are infrequent. Consequently, very large studies would be necessary to empirically document reductions in these health effects with improved filtration, and these large studies have not been performed. However, the associated health benefits have been estimated with models and Table 4 summarizes four papers that employed this approach. The specific scenarios and populations considered varied. Three papers (Zuraimi 2007; Beko et al. 2008; Macintosh et al. 2009) employed mass balance modeling to estimate reductions in exposures to particles by comparing either particle filtration to no filtration or more efficient to less efficient filtration. The fourth paper (Hanninen et al. 2005) used measured data from buildings with and without filters to project how more widespread use of filtration would affect exposures. All papers employed published relationships of particle concentrations with health outcomes to estimate the health benefits of filtration. In all cases, it was assumed that there was no threshold (concentration below which particles do not affect health). Each paper projected substantial health benefits of filtration, e.g., 7% to 21% reductions in a variety of adverse health outcomes associated with particle exposures. One paper (Hanninen et al. 2005) projected that filtration upgrades in Europe would annually prevent 27,000 to 100,000 premature deaths. One paper (Beko et al. 2008) compared filtration costs in an office building with the economic benefits of avoided health effects. The predicted annual filtration operating cost was $2.6 per person, which included filter material, maintenance, and energy costs. Predicted annual mortality-related economic benefits were $37 to $144 per person and predicted annual morbidity-related economic benefits were $8 to $30 per person, thus, predicted health-related economic benefits far exceeded costs. While the modeled health benefits have not been demonstrated empirically, there is little doubt that filtration can substantially reduce indoor exposures to particles from outdoor air and there is broad evidence that these particle exposures adversely affect health.

DISCUSSION

Authors of prior reviews have generally concluded that particle filtration is, at best, a source of small improvements in health effects of allergy and asthma. Many of the early studies had weak designs. The more recent intervention studies, summarized in Tables 1 - 3, generally have strong designs, and typically have larger study populations than the older studies. The intervention studies included in Tables 1 and 2 provide persuasive evidence that filtration systems in homes can sometimes improve health symptom outcomes in subjects with allergies and asthma, particularly when strong sources of allergens are present. Several of these studies also report statistically significant improvements in objectively measured health outcomes. However, only a fraction of health symptom outcomes and objective health outcomes had statistically significant improvements and adverse effects were typically improved only moderately. The intervention studies targeting the general population (Table 3), as opposed to targeting subjects with allergies and asthma, less often reported changes in health symptoms. In these studies, symptoms generally did not improve when filtration was implemented. Thus, the limited available evidence suggests that particle filtration is not very effective in reducing acute health symptoms in subjects without allergies and asthma. However, all three of the studies targeting the general population that measured objective health outcomes reported statistically significant improvements in some of these outcomes. Perhaps most notable are the two intervention studies that reported statistically significant improvements in markers that predict future adverse coronary events. The results of these two studies provide empirical support for the modeled reductions in morbidity and mortality (Table 4) associated with outdoor air particles when particle filtration is employed or upgraded to reduce indoor exposures to particles from outdoor air. The projected reductions in morbidity and mortality are substantial from a societal perspective. Additionally, one of these papers estimates that the associated economic benefits far exceed the costs of filtration.

Very few studies provided more than a rudimentary description of the air filters and buildings. It would be beneficial if future studies provided sufficient information to enable a comparison of predicted and measured reductions in indoor particle concentrations. For that purpose, it would be necessary to specify, at a minimum, filtration air flow rates and efficiencies or filter system clean air delivery rates, filter system operation times, indoor air volumes, building HVAC types and the types of filters in the HVAC systems, and building air exchange rates. These factors and others influence the extent to which air filter systems are able to reduce indoor particle concentrations. A system that is not effective in reducing particle exposures would not be expected to improve health.

The review has several limitations. The number of new studies (16) was modest and many of the studies have small populations. A statistical meta-analysis of study results was judged inappropriate because of the large diversity in filtration technologies, background exposure conditions, subject types, and health outcomes. Findings may have been subject to publication bias, e.g., the preferential publication of studies with statistically significant positive findings.

Many studies failed to provide important background information, as summarized in the prior paragraph.

In summary, the currently available evidence indicates two main health benefits of particle filtration. Filtration can be modestly effective in reducing adverse allergy and asthma outcomes, particularly in homes with pets. Compared to use of filtration systems, removal of the pets and tobacco smoking from the home should be more effective and hence preferred as remedial actions. Unlike the prior research (IOM 2000), the more recent research has not targeted the use of filtration to reduce dust mite allergen exposures and associated health effects. Thus, the evidence that filtration is effective with respect to dust mite allergies continues to be very weak. The results of this new review (Table 2) suggest that filtration of air in the breathing zone of sleeping allergic or asthmatic persons may be more consistently effective in improving health than use of room or whole-house filtration systems. The review by the Institute of Medicine (IOM 2000) also pointed out prior evidence of benefits of such filtration systems.

From a societal perspective, the largest potential benefits of particle filtration may be reductions in morbidity and mortality associated with indoor exposures to particles from outdoor air; however, these benefits are projected with models. Unfortunately, it would be very challenging to implement sufficiently large studies for empirical verification of many of the predicted reductions in morbidity and mortality because the outcomes (e.g., death, hospital admission) affect a small portion of the population at any given time. Three sets of empirical findings should increase our confidence in the modeled estimates of benefits. First, the empirical data compiled in Tables 1-3, and in other studies, e.g., (Batterman et al. 2005; Hacker and Sparrow 2005; Macintosh et al. 2008; Zuraimi and Tham 2009; Batterman et al. 2011; Zhang et al. 2011), demonstrate that filtration can substantially reduce indoor particle concentrations. Second, the adverse health consequences of increased exposures to outdoor air particles are documented in a large number of studies and the resulting body of research has been subjected to critical reviews and meta analysis, e.g., (Brunekreef and Forsberg 2005; Delfino et al. 2005; Pope and Dockery 2006; Pope et al. 2009). Third, we now have two studies (Brauner et al. 2008; Allen et al. 2011) reporting that filtration improves markers that predict future adverse coronary events. These three categories of empirical evidence increase our confidence in the model predictions of health benefits of using filtration to reduce indoor exposures to particles from outdoor air.

CONCLUSIONS

The main conclusions of this review are as follows:

- Particle filtration can be modestly effective in reducing adverse allergy and asthma outcomes, particularly in homes with pets.
- Particle filtration systems that deliver filtered air to the breathing zone of sleeping allergic or asthmatic persons may be more consistently effective in improving health than use of room or whole-house filtration systems.
- The limited available evidence suggests that particle filtration in buildings is not very effective in reducing acute health symptoms in subjects without allergies and asthma.

- The largest potential benefits of particle filtration may be reductions in morbidity and mortality associated with reducing indoor exposures to particles from outdoor air.

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Table 1. Intervention studies in homes of subjects with allergies or asthma.

Study	(Brehler et al. 2003)	(Butz et al. 2011)	(Francis et al. 2003)	(Lanphear et al. 2011)	(Sulser et al. 2009)
Subjects	44 adults with allergies and/or asthma	85 children with asthma**	30 adults allergic to cats or dog allergen	215 children with asthma	30 asthmatic children sensitive to pet allergen
Type of building	Homes (24 rural, 20 urban)	homes with smokers	homes with cats or dogs	homes with smokers	homes with high cat or dog allergen levels in dust
Exposures focus	general particles, pollens	environmental tobacco smoke	pet allergen	environmental tobacco smoke	pet allergen
1st filter location	bedroom outdoor air supply	bedroom	bedroom	bedroom	bedroom
2nd filter location		living room	living room	main activity room	living room
Gas phase filtration	no	yes (activated carbon)	no	yes (activated carbon and potassium permanganate zeolite)	no
Intervention period	2 week	6 month	12 month	12 month	12 month
Reduction in exposures	not reported	intervention group: SS 19.9 and 8.7 μg/m^3 (59% and 46%) decreases in PM2.5 and PM2.5-10, respectively versus control group: 3.5 and 2.4 μg/m^3 (9% and 14%) increases in PM2.5 and PM2.5-10, respectively no SS changes in air nicotine	SS and substantial reductions in airborne cat and dog allergen in both groups, reductions in intervention group not SS relative to reductions in control group	SS 25% reduction in particles counts > 0.3 micrometer in intervention group relative to 5% reduction in control group; no SS reductions in particle counts > 5 micrometers or in airborne nicotine	no SS change in cat and dog allergen concentration in dust
Change in allergy and asthma symptoms	subjects with seasonal allergy: nose* ↓ (30%) ↔ eyes* ↓ (42%) ↔ lung ↔ subjects with perennial allergy: nose ↔ eyes ↔ lung ↔	symptom free days*** ↔ slow activity days ↔ nocturnal cough ↔ wheeze ↔ tight chest ↔		asthma symptoms ↔	nasal ↓ nocturnal ↓ pediatric quality of life score ↔
Change in objective health outcomes	peak expiratory flow in morning ↓ (5%) peak expiratory flo**w in daytime** ↔		bronchial hyper-reactivity or reduced asthma treatment ↓ forced expiratory volume ↔ forced vital capacity ↔	unscheduled asthma-related visits to a health care provider ↓ (25%) exhaled nitric oxide (inflammation indicator) ↔ medication use ↔	forced expiratory volume ↔ eosinophil cationic protein (inflammation marker) ↔ bronchial hyper-responsiveness ↔ non-SS trend toward improved bronchial hyper-responsiveness
Assessment of study strength	strong (crossover, placebo, randomized order of exposure)	moderate (random assignment to intervention vs. control group, no placebo)	moderate (random assignment to intervention vs. control group, no placebo)	strong (control group with placebo, random assignment to groups)	strong (control group with placebo, random assignment to groups)
Author(s) main conclusion(s)	recommends fresh air filtration systems in bedrooms	air cleaners reduce particles and symptom free days but don't prevent exposure to second hand smoke	"small but significant improvement in combined asthma outcome"	air cleaners promising "as part of multi-faceted strategy to reduce asthma morbidity"	"although HEPA air cleaners retained airborne pet allergens, no effect on disease activity…was observed"

*improved in morning log but not subsequently in daytime log **excluding subjects in group with air cleaners plus health coach SS = statistically significant

***SS improvement on symptom free days when subjects with air cleaners, both with and without a health coach, were compared to controls

↓ statistically significant improvement in health outcome, e.g. reduction in adverse effect or improvement in lung function ↓(n%) statistically significant improvement in health outcome by "n"%

↔ no statistically significant change in health outcome ↓↔ statistically significant improvement in health outcome in some cases and no statistically significant change in health outcome in other cases

Table 2. Intervention studies in homes of allergic or asthmatic subjects with filtered air supplied to the subjects' breathing zones when sleeping in their beds.

Study	(Boyle et al. 2012)*	(Morris et al. 2006)*	(Pedroletti et al. 2009)**	(Stillerman et al. 2010)***
Subjects	282 asthmatic adults and children sensitive to pet or mite allergen	13 adults and children with ragweed allergy	22 asthmatic adults and children allergic to dog or cat allergen	35 adults with perennial allergic symptoms of nose and eyes; excluded subjects with seasonal allergy
Type of building	homes	homes	homes	homes
Exposures focus	general particles, allergens	general particles, allergens		allergens, general particles
Filtration system	HEPA filtered slightly cooled air released above head when sleeping	HEPA-filtered air supplied horizontally over subjects' heads when sleeping	HEPA filtered slightly cooled air released above head when sleeping	HEPA filtered air supplied to special pillow system used by subjects
Included gas phase air cleaning	no	no	no	no
Intervention period	12 month	1 week	10 weeks	12 weeks
Reduction in exposures	99% reduction in median count of particles > 0.5 μm in the breathing zone (from limited measurements) no SS decrease in cat or dust mite allergens aspirated from mattress dust	not reported	not reported	based on limited measurements 99.99% reduction in particles > 0.3 μm in breathing zone versus 7% reduction in placebo, no SS change in allergens in dust sampled from floor
Change in allergy and asthma symptoms	14.8% more subjects had clinically significant improvements in asthma quality of life score with air cleaning ↓	morning symptoms ↓ (25%) evening symptoms ↓ (23%) sleepiness score ↓ (29%) rhinitis quality of life score ↓ (33%) improvements reported using week 1 data with filter system off as the reference; **important - if week 3 data with filter system off had been used as the reference, there would have been no improvements in health**	asthma quality of life score ↓ (9%)	relative to placebo case that was also associated with improvements: overnight total symptom score ↓ (8%) upon waking total symptom score ↓ **(12%)** daytime total symptom score ↔ before bed total symptom score ↔ upon waking nasal: congestion ↓; itching ↓; rhinorrhea ↓; sneezing ↔ upon waking eye itching/watering ↓ composite nocturnal rhinoconjunctivitis quality of life score ↓ (10%)
Change in objective health outcomes	exhaled nitric oxide (inflammation marker) ↓ blood eosinophil counts (inflammation marker) ↔ IgE levels (allergic response marker) ↔ asthma medication ↔ asthma exacerbation ↔ forced expiratory volume ↔ peak expiratory flow ↔		exhaled nitric oxide (inflammation marker) ↓ (22%) forced expiratory volume ↔ peak expiratory flow ↔	
Assessment of study strength	strong (control group with placebo, random assignment to groups)	weak (one group intervention, no placebo or blinding; no balancing of order of treatment, incomplete analysis)	strong (crossover with placebo, randomized order of treatment)	strong (crossover with placebo, randomized order of treatment)
Author(s) main conclusion(s)	"improves quality of life, airway inflammation, and systemic allergy in patients with persistent asthma"	"significant improvement of allergic symptoms during ragweed hay fever season"	"positive effect on bronchial inflammation and quality of life"	"provided effective nighttime allergen exposure reductions and clinical benefits"

*study support came from the manufacturer of the filter system **some of the authors have received support from the manufacturer of the filtration device
*** study support came from the manufacturer of the filter system and most authors were employees of or have received support from the manufacturer of the filter system SS = statistically significant
↓ statistically significant improvement in health outcome ↓(n%) statistically significant improvement in health outcome by "n"% ↔ no statistically significant change in health outcome
↓↔ statistically significant improvement in health outcome in some cases and no statistically significant change in health outcome in other cases

Table 3. Intervention studies not targeting subjects with allergies or asthma

Study	(Allen et al. 2011)	(Brauner et al. 2008)*	(Lin et al. 2011)	(Mendell et al. 2002)	(Skulberg et al. 2005)	(Wargocki et al. 2008)	(Weichenthal et al. 2012)
Subjects	45 adults	41 healthy non-smoking adults age 60-75	60 healthy non-smoking young adults	396 adults	72 adults	190 children	37 adults and children, 6 with asthma
Type of building	25 homes in small city	urban homes within 350 m of a major road	homes in Taiwan	2 office floors in urban area	6 office buildings in urban area	10 classrooms	first nation homes most with smoking
Exposures focus	wood smoke	general particles	general particles	general particles	general particles	general particles	general particles, tobacco smoke
Filtration site (filter type)	bedrooms (HEPA)	bedroom and living room of each home (HEPA)	air conditioner (3M Filtrete)	HVAC System (high efficiency fibrous filters)	offices (electrostatic precipitators)	classrooms (electrostatic precipitators)	main living area (high efficiency stand alone air filter)
Gas phase air cleaning	no	no	no	no	yes (coarse activated carbon filter)	no	no
Intervention period	1 week	2 day	4 weeks	4 weeks	3 weeks	1 week	1 week
Reduction in exposures	60% PM2.5 74% wood smoke marker	63% (PM2.5 geometric mean 51% (PM2.5-10 geometric mean) 68% (count 10 to 700 nm particles)	~20% reduction in PM2.5	94% (0.3 - 0.5 µm particles) 55% (1 to 2 µm particles) 16% for > 2 µm particles	intervention group: 46% particle mass control group: 14% particle mass	particle counts decrease 40% to 80% for smallest particles, less for larger particles	54% (PM10) 61% (PM2.5 62% (PM1.0)
Change in objective health outcomes	coronary event predictor ↓ (9.4%) inflammation marker ↓ (33%) oxidative stress ↔	coronary event predictor ↓ (8.1%) hemoglobin ↓ (0.9%) inflammation biomarker ↔ biomarker of coagulation ↔	systolic BP*** ↓ (~11%) diastolic BP ↓ (~7%) heart rate ↓ (~11%)		min. nasal cross section ↓ ↔ nasal volume ↓ ↔ peak expiratory flow ↓ peak expiratory flow variability↓		systolic BP ↓ (~7%) diastolic BP ↓ (~6%) forced expiratory flow ↓ (~6%) forced vital capacity ↔ (~4%) peak expiratory flow ↓ (~8%) coronary event predictor ↔
Change in sick building syndrome symptoms				eye ↔ nose ↔ throat ↔ chest ↔ headache ↔ fatigue ↔ skin ↔	mucosal ↔ skin ↔ general = fatigue, nausea headache, concentration ↔ ↓	nose ↔ ↑** throat ↔ skin ↔ ↑** fatigue ↔ headache ↔ ↓	
Assessment of study strength	strong (crossover, placebo, randomized order of exposure)	strong (blinded, placebo controlled intervention, within-subject, randomized order of exposure)	weak (intervention periods always followed periods without intervention)	strong (multiple crossovers, blinding of subjects)	strong (control group with placebo; random subject allocation to groups)	strong (placebo-controlled crossovers, balanced order of treatment)	strong (randomized double blind crossover)
Author(s) main conclusion(s)	predictors of cardiovascular morbidity, can be favorably influenced by reducing particles	"filtration of recirculated air…… may be a feasible way of reducing the risk of cardiovascular disease"	"effects of PM2.5 on BP heart rate were greatest during visits without filtration"	"benefits of enhanced filtration require assessment in buildings with higher particulate contaminant levels"	reduced total airborne dust; nasal congestion decreased by small amount, peak expiratory flow increased by small amount	"considerably reduced particles no consistent effects … on symptom intensity"	"reducing indoor PM may contribute to improved lung function in First nation communities"

*Study employed filter system designed to deliver filtered air above breathing zone of subject when sleeping, and installed systems in both the bedroom and living room. The paper did not indicate if, during the study, the bedroom filter delivered air above the breathing zone when sleeping. **in only one of five pairs of classrooms, there was a statistically significant worsening of outcome ***BP = blood pressure ↓ statistically significant improvement in health outcome ↓(n%) statistically significant improvement in health outcome by "n"% ↑ statistically significant worsening of outcome ↔ no statistically significant change in health outcome ↓↔ statistically significant improvement in health outcome in some cases and no statistically significant change in health outcome in other cases

Table 4. Modeled health benefits of filtration.

Reference	Buildings	Description of Analysis	Predicted concentration or exposure reductions	Predicted Health Benefits
(Beko et al. 2008)	hypothetical office building with mechanical outdoor air supply but no air recirculation	relied on mass balance model (Jamriska et al. 2003) to estimate particle exposures without filters in outdoor air supply and assumed 30%, to 80% further reduction with F7 (~MERV 13) filters in outdoor air supply; estimated filtration operating costs for filters, labor, energy; estimated economic benefits of reduced premature mortality and morbidity	performed analyses for 30%, 60%, and 80% reduction in office air PM10 with filtration**; with 22.8% of time in office, corresponds with 7, 14% and 18% reduction in total PM10 exposure	health benefits not reported, but with linear models can estimate that PM10-related health effects in office are reduced by 7%, 14%, and 18%; predicted annual mortality-related economic benefits of $37 to $144 per person, annual morbidity-related economic benefits of $8 to $30 per person, annual operating costs of $2.6 per person
(Hanninen et al. 2005)	residential and occupational buildings in Helsinki, extrapolated to Europe	estimated reductions in total (indoor and outdoor) exposures to outdoor air PM2.5 and total PM2.5 and estimated associated health effects for future scenario in which all buildings have F7 (~ MERV 13) or F8 filters relative to current situation with filtration (unknown efficiency) in 78% of workplaces and in < 1% of homes; utilized measured PM2.5 and elemental sulfur in newer and older buildings and outdoors to estimate effects of filtration	27% reduction in total exposure to PM2.5 from outdoor air; 20% reduction in total exposures to PM2.5 from indoor sources plus outdoor air	with typical assumption that health effects of outdoor air PM are linearly related to exposure, predicted a 27% reduction in PM-caused health effects; for Europe the associated reduction in PM-related deaths per year is 27,000 to 100,000
(Macintosh et al. 2009)	homes in three metropolitan areas of Ohio	applied mass balance model to evaluate changes in indoor concentrations of PM 2.5 with high efficiency filtration in HVAC with continuous airflow when windows are closed relative to homes with standard low-efficiency filters in HVAC and homes with no forced air HVAC or air cleaning; estimated associated changes in exposures to PM2.5; projected health impacts using existing concentration-response functions	predicted median indoor-outdoor ratios of outdoor air PM2.5 were 0.57 for homes without forced air HVAC, 0.35 for homes with forced-air HVAC and conventional filters, and 0.1 for homes with forced air HVAC and high efficiency filters	for total population of approximately 2.7 million in homes with forced air HVAC***: a) converting from standard filtration to high efficiency filtration was projected to annually prevent 700 premature deaths, 220 respiratory hospital admissions, 160 cardiovascular hospital admissions, 560 asthma-related emergency room visits , and 130,000 asthma exacerbations; b) similar size benefits projected from converting from no forced air HVAC/no filtration to forced air HVAC with standard filtration
(Zuraimi 2007)	Office buildings in Singapore	applied mass balance models to estimate particle exposure reduction from increasing filter efficiency from 40% to 85% for PM10 in the population of Singapore offices; used existing concentration –health response functions to estimate associated reduction in health effects; used unit costs for health outcomes to estimate financial implications	approximately 14% decrease in total PM10 exposures in Singapore adult population (percentage read from chart is approximate)	projected 14% decrease in mortality in adults with age >30, 8% reduction in chronic bronchitis in adults age >27; 11% reduction in hospital admissions; 14% reduction in emergency room admissions for age < 65, 14% decrease in asthma exacerbations for age >15, 14% reduction in restricted activity days for age >20; 14% reduction in work loss days for age 18-65

*F7, F8, and MERV 13 refer to ratings of filter efficiency (European Union 1993; ASHRAE 1999)

**assumes indoor PM10 concentrations without any filtration are 65% to 95% of outdoor PM10 concentrations.

***estimated population of residents in Cleveland, Cincinnati, and Columbus metropolitan areas who reside in single family homes with forced air heating or cooling systems

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