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Improving indoor air quality, health and performance within environments where people live, travel, learn and work

Frank J. Kelly, Julia C. Fussell

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1 Improving indoor air quality, health and performance within environments
2 where people live, travel, learn and work

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4 Frank J Kelly* and Julia C Fussell

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7 ^aMRC-PHE Centre for Environment and Health

8 Department of Analytical, Environmental & Forensic Sciences

9 School of Population Health & Environmental Sciences

10 Facility of Life Sciences and Medicine

11 King's College London

12 150 Stamford Street

13 London SE1 9NH

14 UK

15 Tel: +44 20 7848 4004

16

17

18 *Corresponding Author Email: frank.kelly@kcl.ac.uk

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1.0 Introduction

The dramatic episodes of excess mortality arising from the air pollution disasters in the Meuse Valley in 1930¹, Donora in 1948² and London in 1952³ were pivotal drivers in motivating epidemiological research into this insidious environmental threat. Originating in the UK in the 1950s, such work extended to the United States and Canada and fed into the landmark Harvard Six Cities Study⁴ correlating daily incidents of cardiopulmonary mortality with ambient particulate matter (PM). As a result of the subsequent extensive research effort, the associations between short-term and chronic exposure to modern-day outdoor air pollutants (comprising a heterogeneous mix of PM, nitrogen oxides [NO_x] and ozone [O₃]) and mortality and morbidity from cardiovascular (CV) and respiratory disease are well documented⁵. Furthermore, emerging epidemiological and experimental data from a growing number of studies suggest a negative influence on a broader number of diseases including adverse birth outcomes⁶, diabetes⁷, neurodevelopment deficits⁸ and dementia⁹. Conversely and crucially important, “natural experiments”¹⁰⁻¹², country-wide changes in air pollution levels¹³ and temporary control measures¹⁴ have all provided evidence that reductions in air pollutants can yield observable health benefits – both within a short period of time and over the longer term depending upon the timeframe of the intervention.

Despite heightened awareness of the associated health risks of air pollution, it is invariably deemed to be solely an outdoor issue, in the general belief that the confines of an inside space, and particularly ones home, offers protection. Owing to marked changes in the lifestyle and working conditions of modern society, particularly in the industrialized nations, individuals spend on average about 90% of their time indoors¹⁵. It follows therefore that the most important environment in relation to our health and

wellbeing is the indoor environment. Concentrations and sources of indoor air pollutants vary considerably in different parts of the world. In rural homes of developing countries, unvented combustion of solid fuel for household cooking and heating has severe health effects and the greatest impact on mortality¹⁶. In the megacities of Asia, rapid urbanization and population growth has led to severe indoor air pollution from outdoor sources. These comprise some of the most toxic components of ambient PM, emitted from coal power generation, industry and vehicle exhaust, which dominates a risk to health through an impact on CV disease¹⁷. In developed countries of the western world, chemicals from cleaning and consumer products, furniture and construction materials, as well as pets and inadequate maintenance of ventilation and air conditioning (AC) systems can deteriorate indoor air quality (IAQ) and lead to a high prevalence of allergies, airway infections and sick building syndrome (SBS)¹⁸⁻²⁰.

As a consequence of the increased amount of personal time spent indoors, mounting evidence that exposure to poor IAQ is the cause of excessive morbidity/mortality and confirmation from research into ambient air quality that reductions in air pollutant exposures improve health outcomes, there has been a long standing interest in evaluating the effectiveness of measures to reduce indoor air pollution and improve public health. The objective of this review is to appraise such research on the efficacy of air purification technologies to remove/reduce indoor air pollutants in order to influence health and performance in non-industrial indoor environments where people live, learn, work and travel (homes, schools, offices, cars). Passive purification materials such as paint catalysts are not included. The studies selected for inclusion were collected through searches using PubMed, Embase and Web Science for articles published up until April 2018 (Figure 1). The titles and abstracts of 578 original research and review articles were screened (including studies identified from reference lists of relevant review articles

stemming from the primary search results). Those that were not relevant to the focus of this review were discarded, leaving 483 articles that were then appraised in detail. Of these, the studies that have been included in this review are limited to those deemed to be have produced results of special interest, thereby adding to our understanding of how to improve air quality in the most important indoor environments in relation to health, productivity and wellbeing.

Figure 1: Search terms and strategy

2.0 Indoor air pollution

Owing to a dramatic change in pollution sources, indoor pollutants that we are exposed to today are markedly different and chemically more diverse from those experienced 40 years ago²¹. Older, relatively inert construction materials have been replaced with new, technologically complex products (e.g. polymers, high performance paints). In addition, the development of new building techniques and designs devoted to effective energy saving can result in airtight indoor spaces with inadequate ventilation. The continuous

increase in the number and type of compounds identified indoors is also a consequence of the emergence of more sophisticated and sensitive analytical instruments and an improvement in sampling strategies^{21,22}.

2.1 Sources of indoor air pollution

Sources of indoor air pollution can be categorized into endogenous contamination, reaction products within the indoor environment and penetration of outdoor pollutants. Endogenous pollutants constitute emissions from building and DIY materials, cleaning and personal products, cooking, environmental tobacco smoke (ETS), human metabolism and other biological sources such as mold, pets and house dust mites. The direct emission of primary pollutants from indoor sources is complicated by a wealth of predominantly uncharacterized indoor chemical transformations through which ambient pollutants can be degraded²³ and secondary pollutants can be formed from indoor gas-phase reactions²⁴. Recent findings of indoor multi-phase chemistry include diffuse oxidation with possible reactive radical production when using chlorine bleach to wash work surfaces²⁵ and the oxidative ability of human occupancy to reduce O₃ concentrations²⁶ and at the same time rapidly increase carbonyl compounds²⁷. Pollutants of particular concern that infiltrate from outdoors include PM, and nitrogen dioxide (NO₂) produced from industry, road traffic, power stations as a consequence of the combustion of fossil fuels, and O₃ generated at ground level by atmospheric reactions of UV light with NO_x and hydrocarbons.

2.2 Factors governing indoor air quality

Factors governing pollutant concentrations, exposures and public health consequences in occupied indoor environments are complex in number and diversity. In simple terms they are categorized as follows: (a) attributes of the pollutants including their chemical

structure, dynamic properties (e.g. reactivity of gases, size of particulates) and outdoor air concentration that in turn are influenced by ambient environmental conditions (e.g. temperature, wind speed/direction); (b) the design, construction and state of repair of the building such as the types and condition of materials that comprise surfaces, floors and furnishings, the air-exchange rate (ventilation) and presence/effectiveness of air cleaning processes; (c) the timing of presence within the indoor space, occupant density, lifestyle, habits and behaviors. The three widely recommended basic strategies to enhance IAQ are source control to avoid indoor and outdoor emissions, provision of adequate ventilation and air cleaning technologies to achieve further improvements when warranted. Whilst reducing the pollution source is the universally preferred approach, often this is not possible and ventilation increasingly presents challenges in terms of building energy use and because clean outdoor air is far from a given in many areas around the world. The use of air cleaners that do not involve the energy costs of moving and conditioning outdoor air are therefore receiving increasing attention as a strategy to remove unwanted particles and gases.

2.3 What is acceptable indoor air quality?

In 2010, the World health Organization (WHO) issued guidelines on protecting the public from health risks associated with exposure to chemicals commonly present in indoor spaces^{28,29}. Other organizations have also adopted guidelines such as the US Environmental Protection Agency's (EPA) voluntary IAQ guidance for multifamily building upgrades³⁰ and schools³¹. In England, guidance on IAQ at home is currently under consultation and development³². Regulatory controls on indoor air pollution are limited to ventilation standards of building regulations that are widely believed to be inadequate in relation to health³³. They are designed to meet acceptable air quality and

comfort requirements, specified by a percentage that does not express dissatisfaction with IAQ and/or the intensity of odor. This is a subjective response that results in a measure of perceived air quality. Whilst comfort is an important parameter, some argue that it does not fully reflect serious health impacts (e.g. asthma, allergies, COPD, CV diseases) that are associated with exposures to pollutants present in indoor air³⁴. Indeed, the link between comfort and health is not clearly established and it is not certain whether ensuring comfort requirements will abate health risks and vice versa. On the other hand and as discussed by Ole Fanger³⁵, “the perceived air quality ... may in many cases also provide a first indication of a possible health risk”. Defining an IAQ target is further complicated by limited data on the relationship between the multitude of indoor pollutants (as well as reaction products and transformations) and health²⁹, large differences among individuals’ susceptibility and preferences and the challenge of ensuring energy performance goals are met without jeopardizing the quality of our indoor environment, life and health. Whilst data is limited on measured ventilation rates in European countries³⁶, a review of domestic ventilation in 12 European countries concluded that an air exchange rate (air changes per hour) of 0.5h^{-1} - the minimum requirement in many European standards - might not satisfy health criteria³⁷.

3.0 Air cleaners

An air purification plant may be a component of the ventilation and AC system that addresses multiple spaces in a building, or a stand-alone, portable or fixed (wall, window or ceiling mounted) device that purifies a room or a portion thereof. Factors to be taken into consideration in selecting the most effective air cleaning system include the target pollutant phase, long-term performance, energy consumption and the formation of unwanted by-products. Air purification technologies are briefly described below. For more detailed information on working principles, target pollutants, performance and

problems that may occur during their application, the reader is directed to several comprehensive reviews that have been published in recent years³⁸⁻⁴².

3.1 Mechanical ventilation

Mechanical filtration is a simple and extensively utilized technique to substantially capture and retain particulate air pollutants⁴³. Performance depends on the type of filter (flat, pleated, HEPA), filter media material and coatings, airflow through the system, size of particle contaminant and filter age^{43,44}. The most commonly used HEPA filters are over 95% efficient in removing particles of all sizes⁴⁵. Owing to particle saturation and associated pressure loss, filters must be replaced to maintain removal efficiency, guard against sensory pollution and new sources of contamination in the form of harmful microorganisms⁴⁶.

3.2 Electronic air filtration

Electronic air filtration systems fall into 2 types. Electrostatic precipitators (ESP) are medium cost devices, generating ions that attach to and electrically charge particulate pollutants as they pass through the device. Once charged, the particles are deflected by an electric field onto on a series of positive and negative charged cleanable plates. The second type constitutes high cost air ionizers or ion generators that disperse positive and negative ions into the atmosphere that attach airborne particles. In that these devices do not possess collector plates, the charged particles attach to nearby surfaces or to one another forming heavier particles that promote deposition. Electronic air filtration is efficient at removing particles (90% and 95% for 0.3 - 6 μm particles for electrostatic filters and ion generators respectively) and results in slower pressure loss than mechanical filters, however a high relative humidity can negatively affect removal efficiency, plus they can generate hazardous charged particles and unwanted oxidation

188 by-products^{47,48}

189

190 3.3 Adsorption

191 Adsorption is a high performance technique (> 90% removal efficiency) that removes
192 gaseous pollutants (VOCs, O₃, NO₂, SO₂ and hydrogen sulfide)^{49,50} using an appropriate
193 adsorbent, such as activated carbon and hydrophobic zeolites^{51,52}. Disadvantages include
194 a compromised efficiency at a high relative humidity⁵⁰, the need to regularly replace the
195 adsorbents to prevent waste pollutants re-entering the atmosphere and the potential of
196 airborne bacteria to thrive on carbon sorbents⁵³.

197 3.4 Ozone generators

198 Ozone generators use UV radiation or a corona discharge to produce O₃ from oxygen to
199 eliminate microbial agents and odours⁵⁴. However, O₃ concentrations that do not exceed
200 typical exposure limits (50-100 ppb) cannot guarantee efficient removal of indoor air
201 contaminants^{49,54}, and moreover reactions with terpenes can produce potentially harmful
202 secondary organic aerosol, carbonyls, carboxylic acids and free radicals⁵⁵. For these
203 reasons, O₃ generators are not recommended by public health agencies as a safe and
204 effective way to control indoor air pollutants⁵⁶.

205 3.5 Ultraviolet germicidal irradiation

206 Ultraviolet germicidal irradiation (GI) uses UV radiation from photoreactor lamps to
207 destroy bioaerosols such as airborne viruses, bacteria, dust mites, animal dander and
208 mould (or such contaminants growing on HVAC surfaces) through photolysis oxidation
209 or UV photolysis⁵⁷. It can be configured within HVAC surfaces or independently as a

unit installed on the wall or suspended from ceilings thereby disinfecting infectious bioaerosols in upper environments, while maintaining occupant safety below. A limited application is a consequence of a propensity to produce O_3 and radicals³⁸.

3.6 Photocatalytic oxidation

Photocatalytic oxidation (PCO) promotes, at ambient temperatures, the destruction of many organic compounds in a stepwise reaction into water and CO_2 using UV light and a semiconductor as the nano-catalyst^{41,58-60}. Devices employing this technique are cost effective, require little maintenance⁶¹ and can be incorporated into new and existing HVAC systems⁵⁸. Reaction rates are influenced by many factors including the pollutant type and concentration, relative humidity, air-flow rate, residence time, UV radiation wavelength and intensity and a number of catalyst features^{58,59}. Drawbacks that currently prevent widespread commercial application include moderate performance and short lifetime of the catalyst. Furthermore, the process can generate intermediates and by-products that (a) are toxic to human health and (b) can deactivate the active sites of the catalyst⁶². As an example, 20 VOCs reaction intermediates have been identified when investigating the PCO of limonene (750 ppbv; dry air conditions) – the naturally occurring hydrocarbon used to infuse lemon scent into household cleaners and fragrances⁶³.

3.7 Cold plasma or cold thermal plasma

Cold plasma or non-thermal plasma based cleaning techniques utilize a high voltage electrical discharge to eliminate PM and biological pollution through precipitation and oxidation³⁹. In addition, the production of free radicals and oxidant species transform VOCs into CO_2 and water⁶⁴. Efficiencies in eliminating bacterial and fungal species of over 95% and 85-98% have been reported⁶⁵. Since electron density and that of reactive

radicals are modified by water vapor, efficacy of decomposition can be either enhanced or suppressed, depending on the pollutant and the dominant pathway of destruction. For example, increasing relative humidity has been shown to enhance removal of toluene, n-butane and formaldehyde, this negatively affects the degradation of tetrachloromethane, methanol and dimethyl sulfide^{66,67}. Drawbacks that currently preclude the application of this technology into commercial devices include poor energy efficiency⁶⁸ as well as the formation of O₃, NO_x, and other hazardous organic by-products^{69,70}.

3.8 Air cleaner performance

The single-pass removal efficiency (generally within a 0-100% range) is the most commonly used performance metric to describe an air cleaner and is defined as the fraction of the pollutant entering an air cleaner that is subsequently removed by the cleaner⁷¹. For particulate pollutants, removal is a strong function of particle size - lowest for particles with aerodynamic diameters of 0.2– 0.3 µm and higher for both larger and smaller ones⁷². Removal efficiency will also vary according to rate and duration of airflow through the device, filtration media loading^{72,73}, fouling of corona wires⁷⁴, UV lights⁷⁵ and activated carbon⁷⁶ and the way in which the air cleaner is installed and maintained⁷⁷. A more relevant performance parameter when comparing air cleaning devices is therefore the product of single-pass removal efficiency and the airflow rate through the cleaning device. This is termed the clean air delivery rate (CADR) and is equivalent to the volume of clean air provided to the space by an air cleaner. There are several standard laboratory test methods to measure efficiency of particle filtration (ASHRAE 52 [minimum efficiency reporting value – MERV 1-16] and European EN 779 [G1 – F9]) and gas cleaning devices (ASHRAE 145.2 and ISO 10121-2). It should be borne in mind that these tests, conducted in controlled environments over a few minutes

or hours, may not directly reflect the effectiveness in a real living conditions characterized by time- and space-varying indoor emissions, outdoor infiltration of particles, ventilation, and airflow patterns.

5.0 Effects of air cleaners on health outcomes in homes

Reviews of intervention studies using standalone air purifiers and conducted amongst free-living participants residing in their own homes to evaluate the potential health benefits began with a report by the Institute of Medicine⁷⁸. Others followed⁷⁹⁻⁸², including a meta-analysis by McDonald et al⁸³, all generally assessing a subset of the same studies appraised by the IOM. On the whole, the evaluated studies were deemed to have weak designs and the reviews generally conclude that filtration devices led to only small improvements in allergy and asthma outcomes. The meta-analysis indicated that particle filtration was associated with statistically significant improvements in total symptoms (5-8%) and sleep disturbance (10%). The review by Fisk⁸⁴ included previously reviewed studies, plus 16 additional intervention studies (published from 2003 to 2012) that featured much stronger designs. This review of the literature concluded that:

- particle filtration can modestly (7–25%) reduce allergy and asthma outcomes, especially in homes with pets;
- more consistent improvements in health may be achieved by delivering filtered air to the breathing zone of sleeping individuals with asthma/allergic diseases;
- although limited evidence indicates that particle filtration is not very effective in reducing acute health outcomes outside of asthma and allergy, statistically significant improvements in microvascular function (MVF), a marker that predict future adverse coronary events, have been cited;

- modeling studies suggest that the largest potential benefits of particle filtration may be reductions in morbidity and mortality as a consequence of lessening indoor exposures to particles from outdoor air.

Studies published from 2013, investigating the health benefits of air cleaners in homes (a) characterized by unremarkable ambient air pollution (Table 1), (b) impacted by wood smoke (Table 2) and (c) within industrial cities of developing countries with particularly poor outdoor air quality (Table 3) are discussed below.

5.1 Homes characterized by relatively low baseline air pollution (Table 1)

Three studies conducted in urban areas close to major roads all adopted randomized, double-blinded crossover interventions in which older adults were exposed to consecutive periods of filtered and non-filtered air by HEPA filters built into AC units⁸⁵⁻⁸⁷. Despite reductions in particle number concentrations ranging from 30 to 75%, no improvement in health outcomes - primarily markers of CV disease risk - were observed. In fact Padró-Martínez et al reported significantly higher interleukin-6 (IL-6) concentrations after a 21-day HEPA filtration⁸⁶. Another study by the same researchers found no benefit in terms of reduced inflammation among adults in homes receiving HEPA filtration despite reducing PNC by 50-85% and findings were not appreciably altered upon pooling the 2 datasets⁸⁷. Factors that may explain the inability to detect improvements in health outcome measures include relatively low baseline pollution concentrations and small exposure gradients, carry-over effects in the absence of washout periods and questionable compliance in keeping windows shut and/or HEPA devices running at all times. In fact Karottki et al⁸⁵ did report highly variable filtration efficacy in both the living rooms and bedrooms where the true/sham interventions took place. Exposure misclassification (owing to lack of time-activity information), uncontrolled confounding and unsuccessful

randomization (with respect to baseline IL-6 concentrations and use of anti-inflammatory drugs) are additional factors that may have contributed to the general lack of health benefit as well as the unexpected negative IL-6 association⁸⁶. That is to say, the effects of changes in PM concentrations on CV disease markers might be masked by medication per se or more difficult to detect because of the existing disease they are taken for. In contrast to the earlier tranche of air purifier intervention studies, very few recent investigations have focused on respiratory outcomes. One exception demonstrated that the introduction of portable HEPA air purifiers into living rooms and bedrooms were effective in significantly reducing indoor PM_{2.5} concentrations and nasal symptom scores in asthmatic children⁸⁸. A trend towards an improvement in childhood asthma control test scores and mean evening peak flow rates was also reported. Investigations focusing on the effectiveness of air purifiers to remove secondhand smoke (SHS) has begun with a pilot study deploying HEPA air purifiers in conjunction with SHS education into the homes of nonsmoking pregnant women or post-partum mothers (any smoking status) with infants (0-12 months)⁸⁹. The homes had at least one smoker and the study reported significantly decreased indoor PM_{2.5} concentrations and salivary cotinine levels in non-smoking women (but not infants) but no change in air nicotine concentrations. The latter is consistent with previous studies addressing SHS^{90,91} and may be attributed to the inability of carbon filters to remove many of the carcinogenic gas phase pollutants from tobacco smoke⁴⁴.

A number of modeling studies have evaluated scenarios of improved home filtration by integrating mass balance models, epidemiological functions and monetary valuations to estimate health and economic impacts of reducing mortality associated with indoor particle concentrations⁹²⁻⁹⁴. Zhao et al⁹² projected that the use of filters (MERV 5 to

HEPA) in HVAC systems of homes in 22 US cities would reduce premature mortality by 0.002–2.5% and increase life expectancy by 0.02–1.6 months, equating to annual economic benefits ranging from \$1 to \$1348 per person. Another study modeled the reductions in mortality in Toronto from replacing standard furnace filters with MERV 15 rated filters in homes constructed to the latest energy efficiency standards (R2000). Use of mechanical HVAC systems, improved filtration and tighter building envelopes were identified as the key factors influencing predicted PM_{2.5} exposure reductions (29% in summer and 28% in winter) and a 26% reduction in non-accidental mortality. The citywide residential retrofitting was predicted to save US\$2.3 billion/year in health care costs. In modeling scenarios adopted by Fisk & Chen⁹⁴, the largest predicted mortality reductions, at approximately 2 per year per 10 000 population, resulted from interventions with continuously operating PAC with HEPA filters in homes. Economic benefits always exceeded costs (in most cases by more than a factor of 10), whilst larger increases in the mortality reductions per unit population and the benefit-to-cost ratios were achieved by restricting interventions to homes of older people. A model has also been developed to evaluate potential benefits of O₃ control by in-duct AC filtration in homes in 12 US cities in 5 different climate zones⁹⁵. Average indoor O₃ removal effectiveness ranged from 4 to 20% and the mean predicted benefit/cost ratios were for >1.0 in 10 of the 12 cities. That benefits of residential AC filtration were greatest in homes with high HVAC use located in cities with high seasonal O₃ suggests an important contribution from secondary atmospheric chemistry in eliciting health effects within the studied localities.

358 **Table 1. Summary of studies investigating health effects of air filtration in homes characterised by relatively low baseline air pollution**
 359

Study	Study design, purifier type, filtration site, intervention duration	Exposure focus, health outcomes, location, study population	Indoor pollutant reduction & health outcome	Author conclusion
Karottki et al 2013	Double-blind, crossover randomized to true/sham filtration HEPA filter in AC units Living room & bedroom 2 x 14 d; no washout	UFP, PM _{2.5} , UVPM, BC, PAH MVF, lung function (FEV ₁ /FVC), BP, inflammation (CRP, WBC), markers of lung cell & monocyte surface damage Greater Copenhagen, Denmark 48 non-smoking elderly adults; mean age 67 years	PM _{2.5} 46% (4.3 µg/m ³ with filtration & 8.0 µg/m ³ without filtration) in living room, 51% (3.7 µg/m ³ with filtration & 7.6 µg/m ³ without filtration) in bedroom; PNC 30%; UVPM 44%; BC 54%; PAH: 48% ↔ MVF, BP, lung function, biomarkers	No improvement in MVF or lung function or detectable reduction in systemic inflammation, monocyte activation or lung cell damage in this elderly population, including people taking vasoactive medication, but with relatively low initial exposure levels.
Padro-Martinez et al 2015	Double-blind, crossover randomized to true/sham filtration Window mounted HEPA Living room 2 x 21 d; no washout	UFP Inflammation (IL-6, CRP, TNF-RII), coagulation (fibrinogen), BP Somerville, Massachusetts, USA 20 adults; mean age 53 years	PNC: 21-68% ↑IL-6 (49.6%) ↔ CRP, fibrinogen, TNF-RII, BP	There is a need for more effective filtration to reduce UFP & to increase sample sizes to see biological effects.
Brugge et al 2017	Double-blind, crossover randomized to true/sham filtration Window mounted HEPA Living room or bedroom 2 x 21 d; no washout	UFP Inflammation (IL-6, CRP, TNF-RII) Boston & Chelsea, Massachusetts, USA 24 adults; mean age 64 years	PNC: 75% ↔ Inflammation	No benefits were found on blood biomarkers for CVD risk, however valuable lessons were learned that could inform future trials.
Park et al 2017	Randomized to no or 2 air purifiers Portable HEPA Living room & bedroom 12 weeks	PM _{2.5} cACT, peak flow rate, nasal symptoms (congestion, rhinorrhea, nasal itching, sneezing) Fresno, California, USA 17 children with asthma/allergic rhinitis (control group n = 8, mean age 14 years; active group n = 9, mean age 10 years)	PM _{2.5} 43% (4.3 µg/m ³ with filtration & 7.4 µg/m ³ without filtration) ↓total (27%) & daytime (30%) nasal symptoms ↔ cACT, peak flow rate	Indoor PM _{2.5} levels can be reduced in homes by using air purifiers with HEPA filters & these improvements in indoor air quality can improve nasal symptoms scores.
Rice et al 2018	Pilot single arm study to evaluate feasibility of deploying 2 PACs in the homes of pregnant women & children	PM _{2.5} , air nicotine Salivary cotinine	↓ 45% PM _{2.5} (17 µg/m ³ with filtration & 31 µg/m ³ without filtration) ↔ Air nicotine	Air purifiers with SHS education is a feasible intervention in homes of women & infants, achieving reductions in indoor PM _{2.5} & salivary cotinine in

	Portable HEPA & SHS education Living area & adult/child bedroom 28 days	Baltimore, USA 50 women; mean age 27 years (pregnant non smokers n = 18; or post-partum any smoking status n = 32) with an infant age 0–12 months	↓ 35% non smoking women salivary cotinine ↔ Child salivary cotinine	non-smoking adults.
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↔; no statistically significant change; ↓ or ↑ statistically different change

BC: black carbon; BP: blood pressure; cACT: childhood asthma control test; CRP: C-reactive protein; FEV₁: forced expiratory volume in 1 second; FVC: forced vital capacity; HEPA: high efficiency particle arresting; IL-6: interleukin-6; MVF: microvascular function; PAH: polycyclic aromatic hydrocarbon; PM_{2.5}: particulate matter < 2.5 µm in diameter; PNC: particle number count; TNF-RII: tumor necrosis factor receptor type II; UFP: ultrafine particle; UVPM: UV absorbing PM; WBC: white blood cell count

5.2 Homes afflicted by landscape or residential wood smoke

The use of air cleaners in homes of smoke impacted communities to either reduce exposure⁹⁶⁻¹⁰¹ or mitigate health effects¹⁰²⁻¹⁰⁴ has and continues to attract interest. Regional-scale smoke pollution stems from wildfires, large-scale biomass burning to clear land for agriculture and in/outdoor residential wood burning and is associated with mortality and cardiorespiratory morbidity¹⁰⁵, declines in lung function/respiratory symptoms in children and hospital visits^{106,107}. The research into effectiveness of PACs in smoke impacted communities is particularly relevant since to mitigate exposures to smoke during prescribed burns and wildfires, a common public health recommendation includes remaining indoors with doors and windows shut. An earlier study by Allen et al¹⁰² already reviewed by Fisk et al⁸⁴, reporting a 9.4% increase in endothelial function and 33% decrease in the C-reactive protein (CRP) in healthy adults following one-week filtration in wood burning homes, has been included in this discussion to add context to the more recent investigations (Table 2). Despite using a very similar randomized crossover study design and population in wood smoke-impacted community, and reporting significant reductions in PM_{2.5} and the wood smoke marker levoglucosan, the same group of workers subsequently found no relationship between PM_{2.5} exposure and endothelial function or markers of inflammation and oxidative stress¹⁰³. This may be explained by lack of woodstove use among participants and lower outdoor levoglucosan concentrations in the latter (13-20 ng/m³) versus the earlier (530-613 ng/m³) study. In addition, compliance in operating the air cleaners at the highest comfortable speed may have been a factor since indoor PM_{2.5} concentrations did not decrease in seven of 44 homes during the week with HEPA filters in place. In rural areas of Montana, Idaho, and Alaska, where residential wood combustion is a major source of ambient and indoor PM_{2.5} and the primarily means of heating, the impact of either improved technology

wood burning stoves or portable electret filtering devices (over one winter period) in improving health measures in asthmatic children has been investigated¹⁰⁴. Whilst neither intervention improved the subjective pediatric asthma quality-of-life measures, the air-filtration device brought about a 11.8% improvement diurnal peak flow variability (a measure of airway hyperactivity). Fisk et al¹⁰⁸ have modeled potential health benefits and costs associated with 6 air filtration interventions in homes during a 10-day wildfire smoke event that substantially elevated particle concentrations and hence smoke exposure in a six-county region in southern California in 2003. Three out of six intervention scenarios involved the use of PACs as (a) a stand-alone intervention or (b) in conjunction with low or (c) high efficiency in duct filtration and brought out reductions in indoor PM_{2.5} concentrations by 45, 51 and 62% respectively. Results estimated that targeted PAC use alone would have reduced smoke-related deaths and hospital admissions in the general population by 30 and 45% respectively and in the elderly by 50 and 78% respectively. Mortality-related economic benefits for interventions incorporating PAC use exceeded intervention expenditure and this cost effectiveness (intervention costs: US\$368 million; health-related benefits: US\$445 million) increased by intervening in the homes of older people.

Table 2. Summary of studies investigating health effects of air filtration in homes of woodsmoke impacted communities

Study	Study design, purifier type, filtration site, intervention duration	Exposure focus, health outcomes, location, study population	Indoor pollutant reduction & health outcome	Author conclusion
Allen et al 2011	Single-blind, crossover randomized to true/sham filtration Portable HEPA Main activity room & bedroom 2 x 7 d; no washout	PM _{2.5} , levoglucosan (wood smoke marker) Endothelial function, inflammation (CRP, IL-6; band cells), oxidative stress (MDA, 8-iso-PGF ₂ α) Smithers, British Columbia, Canada 45 healthy adults; mean age 43 years	PM _{2.5} : 59% (4.6 µg/m ³ with filtration & 11.2 µg/m ³ without filtration); levoglucosan: 74% (33 ng/m ³ with filtration & 127 ng/m ³ without filtration) ↑endothelial function (9.4%); ↓CRP (33%) ↔ IL-6; oxidative stress markers	Predictors of cardiovascular morbidity, can be favourably influenced by reducing indoor particle concentrations.
Kajbafzadeh et al 2015	Single-blind, crossover randomized to true/sham filtration Portable HEPA Living room & bedroom 2 x 7 d; no washout	PM _{2.5} , levoglucosan Endothelial function, inflammation (CRP, IL-6, band cells) Vancouver, British Columbia, Canada 20 healthy adults; mean age 51 years	PM _{2.5} : 48% (3.4 µg/m ³ with filtration & 6.5 µg/m ³ without); 60% LG (11.8 ng/m ³ during filtration & 29.3 ng/m ³ during control periods) ↔ endothelial function, CRP, IL-6, band cells	No evidence of an association between cardiovascular effects and indoor PM _{2.5} among healthy adults in wood smoke-impacted locations.
Noonan et al 2017	Single-blind, crossover randomized to true/sham filtration Portable electret filter Living room & bedroom 2 x one winter period; no washout	PM _{2.5} , UFP PAQLQ scores, PEF, dPVF Montana, Idaho & Alaska, USA in homes impacted by residential wood smoke 92 asthmatic children, mean age 12 years	PM _{2.5} : 67% ↓dPVF (11.8%); ↔ PAQLQ, PEF	Among children with asthma and chronic exposure to wood smoke, an air-filter intervention that improved indoor air quality did not affect quality-of-life measures but was efficacious for improving an indirect measure of airway hyper-responsiveness.

↔; no statistically significant change; ↓ or ↑ statistically different change

CRP: C-reactive protein; dPVF: diurnal peak flow variability; HEPA: high efficiency particle arresting; IL-6: interleukin-6; MDA: malondialdehyde; PAQLQ: Pediatric Asthma Quality of Life Questionnaire; PEF: peak expiry flow; PM_{2.5}: particulate matter < 2.5 µm in diameter; UFP: ultrafine particles

5.3 Homes afflicted by exceptionally high ambient air pollution

The global public health burden of ambient PM_{2.5} is disproportionately felt in developing countries undergoing enormous industrialization and urbanization¹⁰⁹. Population weighted PM_{2.5} exposures average 74.3 and 58.4 µg/m³ in India and China respectively and together account for >50% of global PM_{2.5} mortality¹¹⁰. As a consequence of infiltration of outdoor air and emissions from indoor sources such as cooking oil fumes, smoking and human activities^{111,112}, indoor PM_{2.5} concentrations in Chinese cities can average 80 - 124 µg/m³^{113,114}. Improving outdoor air quality in Asia is proving a gargantuan task, with the risk of any short-term improvements being undone as a result of the ongoing appetite for cheap power and automobile use¹¹⁵. Indeed, according to the forecasts of demographic and epidemiological transitions, average PM_{2.5} levels would need to decrease approximately 20–30% over the next 15 years to offset the increase in mortality attributable to PM_{2.5} levels among aging populations in China¹¹⁶. Solving the problem constitutes a long-term goal for generations to come. In the interim, hundreds of millions of individuals will continue to be exposed to hazardous ambient PM_{2.5} concentrations far exceeding WHO Air Quality Guidelines. It is not surprising therefore that investigations into the impact of short-term solutions in the form of indoor air filtration devices has been actively investigated (Table 3). Chen et al conducted a double-blind, randomized, crossover study, incorporating a 14 day washout period, among healthy university students living in dormitories in a central urban area of Shanghai¹¹⁷. Confining the young adults to their dormitories, equipped with a portable electret filtration device, for 48 hours reduced indoor PM_{2.5} concentration, systolic and diastolic blood pressure, a marker of coagulation and some measured metrics of inflammation and platelet activation. Whilst fractional exhaled nitric oxide, an established marker of respiratory inflammation, was reduced, lung function did not change. A subsequent study

of near identical design other than increasing the active/sham intervention to 9 days brought about significant reductions in indoor PM_{2.5} concentrations (as well as personal exposure), blood pressure and biomarkers of oxidative stress and inflammation¹¹⁸. In contrast to the aforementioned studies, Cui et al¹¹⁹ examined the cardiorespiratory impact, of a single overnight HEPA air filtration intervention, better approximating the real-world scenario where people only have indoor air filtration for part of the day when they are home. Compared to sham filtration, active purification within student dormitories substantially decreased indoor particle concentrations and significantly improved airway mechanics. No significant improvements in CV function were observed but filtration also lowered von Willebrand factor (26.9%) reflecting reduced risk for thrombosis. Chuang et al¹²⁰ investigated whether long-term improvements in IAQ, using electret filtration added to window mounted air conditioners, are beneficial for CV health among adult housewives and househusbands in Taipei. The one-year filtration intervention reduced personal exposure to PM_{2.5}, which was associated with improved CV health as evidenced by reduced systolic and diastolic BP and 8-hydroxy-2'-deoxyguanosine, a marker of oxidative stress. An associated reduction in personal VOC exposure was unexpected since the air purifier was not designed to remove gaseous pollutants leading the authors to speculate that aerosolized VOCs could be adsorbed into the filter media. The cardiorespiratory effects of in-home HEPA air filtration for a 2-week period have also been examined in a more susceptible population, namely 23 non-smoking elderly individuals, with and without COPD, residing in Beijing and under instructions to spend much of their time indoors¹²¹. Following active filtration, significant reductions in indoor PM_{2.5} were not associated with detectable improvements in lung function, blood pressure or HRV, suggesting that short-term interventions can be of limited health benefit with exposure to extreme high outdoor air pollution levels. In another susceptible population,

Barn et al¹²² investigated the impact of HEPA filter air cleaner use for 5 months during pregnancy on indoor residential PM_{2.5} and blood cadmium concentrations (as an indicator of SHS exposure) among non-smoking women in Ulaanbaatar, Mongolia's capital city. Air cleaners lowered indoor PM_{2.5} by 29% and blood cadmium by 14% from a geometric mean of 0.23 µg/L to 0.20 µg/L. Whilst these are relatively low concentrations compared with those previously reported for pregnant women, reductions, even from low levels, could have important public health implications. Cadmium is a known carcinogen and in pregnancy has been linked too small for gestational age infants and reduced infant birth weight¹²³⁻¹²⁵. Air cleaner effectiveness was reduced by 50% after approximately 5 months of use and participants reported using air cleaners for 64% of the study period possibly owing to concerns about noise and electricity.

It is unlikely that every component within the overall ambient PM mix is equally harmful to exposed populations and as a consequence, there has been an enormous drive to identify which components and source are most harmful to health¹²⁶. The mechanisms through which PM elicits ill health are yet to be fully elucidated however current evidence supports an interactive chain of events involving inflammatory responses and oxidative stress¹²⁷. In the light of this, the effectiveness of portable HEPA air cleaners in removing PM_{2.5} and its chemical components (organic carbon, elemental carbon, sulfate, nitrate, ammonium, 21 selected metals) and reducing the capacity of particles to elicit damaging oxidative reactions through the generation of reactive oxygen species (ROS) in the indoor environment of 6 Beijing homes has also been assessed¹²⁸. Along with the above mentioned measurements, was an investigation into the relationship between air cleaner use and personal exposure. Whilst the HEPA filter air cleaners substantially lowered indoor PM_{2.5} and all its major components, an effect on reducing overall personal exposure was marginal. Since the participant whereabouts was not restricted to

the purified rooms, this was probably the result of activity patterns, bringing about short-time exposures to elevated PM_{2.5} concentrations both outdoors (e.g. traffic emissions) and indoors (e.g. cooking emissions) as well as a contribution from the uncharacterized indoor microenvironment. Results of the toxicity assay were indicative of reduced ROS activity in the indoor environment but this did not translate into a reduction in personal exposure to PM-induced ROS. The effects of combined ESP-HEPA filtration on cardiorespiratory disease risk indicators has also been examined by temporarily (during a 39-day intervention) removing either ESPs alone or both ESPs and HEPA filters from 3-part (coarse-ESP-HEPA) air-handling systems¹²⁹. HEPA filter removal increased PM_{2.5} concentrations but had no effect on a battery of cardiorespiratory biomarkers. Previous studies evaluating biomarker effects of filtration in healthy adults have shown greater associations after either short (up to 48 hours) or long (after a year) versus after intermediate durations (weeks). Of note, this prompted discussion over the possible presence of a short-term biomarker response, an intermediate-term return to baseline and then a long-term shift in biomarker levels following changes in pollutant exposure lasting days, weeks or a year, respectively. Removal of ESPs decreased O₃ concentrations and this was associated with reductions plasma-soluble P-selectin (marker of thrombosis) and systolic blood pressure, indicating that the concomitant low-level increases in indoor O₃ and O₃-derived products by this air cleaning technology may impact CV health.

511 **Table 3. Summary of studies investigating health effects of air filtration in homes of Asian megacities**
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Study	Study design, purifier type, filtration site, intervention duration	Exposure focus, health outcomes, location, study population	Indoor pollutant reduction & health outcome	Author conclusion
Chen et al 2015	Double-blind, crossover randomized to true/sham filtration Portable electret filter College dormitory 2 x 48 h; 14 d washout Participants in dormitory for entirety of intervention	PM _{2.5} Inflammation (CRP, fibrinogen, P-selectin, MCP-1, IL-1 β , TNF- α , IL-6, MPO); blood coagulation (sCD40L, PAI-1, t-PA, D-dimer); vasoconstriction (ET-1, ACE); BP; lung function; lung inflammation (FeNO) Shanghai, China 35 healthy, non-smoking college students; mean 23 years	PM _{2.5} : 57% (41.3 $\mu\text{g}/\text{m}^3$ with filtration & 96.2 $\mu\text{g}/\text{m}^3$ without filtration) $\downarrow$ MCP-1 (17.5%), IL-1 β (68.1%), MPO (32.8%), $\downarrow$ sCD40L (64.9%); $\downarrow$ Systolic BP (2.7%), $\downarrow$ diastolic BP (4.8%); $\downarrow$ FeNO (17%), $\leftrightarrow$ CRP, fibrinogen, P-selectin, TNF- α , IL-6, PAI-1, t-PA, D-dimer, vasoconstriction, lung function	Study demonstrated clear cardiopulmonary benefits of indoor air purification among young, healthy adults in a Chinese city with severe ambient particulate air pollution.
Li et al 2017	Double-blind, crossover randomized to true/sham filtration Portable electret filter College dormitory 2 x 9 d; 12 d washout Participants in dormitory much time as possible	PM _{2.5} BP, hormones (CRH, ACTH), insulin resistance, oxidative stress (8-OHdG, MDA, SOD, 8-iso-PGF2 α) & inflammation (sCD40L, CRP, IL-1 β , IL-6, TNF- α , ICAM-1) Shanghai, China 55 healthy, non-smoking college students; mean 20 years	PM _{2.5} : personal exposure: 54% (24.3 $\mu\text{g}/\text{m}^3$ during filtration & 53.1 $\mu\text{g}/\text{m}^3$ during control periods) PM _{2.5} : 82% 8.6 $\mu\text{g}/\text{m}^3$ with filtration & 46.8 $\mu\text{g}/\text{m}^3$ without filtration) $\downarrow$ diastolic & systolic BP; $\downarrow$ CRH & ACTH $\downarrow$ insulin resistance; $\downarrow$ 8-OHdG, MDA, SOD, 8-iso-PGF2 α , $\downarrow$ sCD40L, CRP, IL-1 β $\leftrightarrow$ TNF- α , ICAM-1	Study demonstrated short-term reductions in blood pressure and biomarkers of oxidative stress and inflammation following indoor air purification
Chuang et al 2017	Double-blind, crossover randomized to true/sham filtration AC electret filter Living/dining room, master bedroom & guest bedroom 2 x 1 year; no washout	PM _{2.5} , VOCs BP, inflammation (hs-CRP, fibrinogen), oxidative stress (8-OHdG) Taipai, Taiwan 200 healthy, non-smoking adults; mean age 43 years	PM _{2.5} : 43% (12.5 $\mu\text{g}/\text{m}^3$ with filtration & 22.0 $\mu\text{g}/\text{m}^3$ without filtration) VOCs: 67% (0.41 ppm with filtration & 1.25 ppm without filtration). $\downarrow$ SBP (6.7%), $\downarrow$ DBP (6.2%), $\downarrow$ 8-OHdG (53%), $\leftrightarrow$ fibrinogen, hs-CRP	Long-term indoor air filtration is associated with cardiovascular health of adults
Day et al 2017	Single pass central AHU with coarse filter (F8; MERV 12)-ESP-HEPA filtration split into: • Group A: HEPA & ESP removed from AHU • Group B: ESP removed from AHU	PM _{2.5} , O ₃ Respiratory oxidative stress (EBC MDA) Respiratory inflammation (FeNO, EBC pH, nitrate and nitrite) Lung function (FEV1, FVC, FEV1/FVC) Systemic inflammation and oxidative stress (CRP, 8-	Group A: Removal of HEPA & ESP: $\uparrow$ PM _{2.5} by 38 $\mu\text{g}/\text{m}^3$ $\leftrightarrow$ biomarkers Group B: removal of ESP: $\downarrow$ O ₃ exposure by 2.2 ppb $\downarrow$ sCD62P (16.1%) and $\downarrow$ SBP (3%)	Results suggest limited physiological responses to PM reductions associated with HEPA filtration, and that ESP use may increase cardiovascular health risk through increasing blood pressure & thrombosis markers

	Office & living quarters 39 days	OHdG, MDA), Vascular tone (SBP, DBP, PP) Arterial stiffness (PWV) Myocardial oxygen supply relative to demand (SEVR) Platelet activation (sCD62P) Endothelial dysfunction (vWF) Changsha City, China 89 adults working and residing on a working campus; mean age 32 years • Group A: n= 36 • Group B: n= 53		
Shao et al 2017	Double-blind, crossover randomized to true/sham filtration Portable HEPA Living room and bedroom 2x 14 d periods; no washout Participants indoors for 95% of the intervention	PM _{2.5} , BC, water soluble organics, NO ₃ ⁻ , SO ₄ ²⁻ , Zn ²⁺ , Pb ²⁺ , K ⁺ Lung function, inflammation (EBC, fibrinogen, CRP, IL-6, IL-8), HRV, BP Beijing, China 35 non-smoking adults • with COPD n=20, mean age 67 years • without COPD n = 15, mean age 65.9 years	PM _{2.5} : 60% (24 µg/m ³ with filtration & 60 µg/m ³ without); BC: 53% (1.81 µg/m ³ with filtration & 3.87 µg/m ³ without filtration); water soluble organics, NO ₃ ⁻ , SO ₄ ²⁻ , Zn ²⁺ , Pb ²⁺ , K ⁺ : 42-63% ↓IL-8 (58.59% in the total group & 70.04% in COPD subset); ↔ EBC, fibrinogen, CRP, IL-6, lung function, BP, HRV	Indoor air filtration produced clear improvement on indoor air quality, but no demonstrable changes in the cardio-respiratory outcomes in the seniors living with real-world air pollution exposures.
Cui et al 2018	Double-blind, crossover randomized to true/sham filtration Portable HEPA College dormitory 2x 13 h; 14 d washout	PM _{2.5} , UFP Lung function (FEV1, FVC), respiratory inflammation (FeNO), CV function (BP, augmentation index, subendocardial viability rate, heart rate pulse wave velocity); systemic inflammation (IL-6), coagulation (VWF, sCD62P) & oxidative stress (MDA & TBA) Shanghai, China 70 healthy, non-smoking college students; mean 22 years	PM _{2.5} : 72% (10.0 µg/m ³ with filtration & 33.2 µg/m ³ without filtration); UFP: 59% ↓ Airway impedance (7.1%); ↓ airway resistance (7.4%); ↓ small airway resistance (20.3%); ↓ resonant frequency (4.8%); ↓ VWF (26.9%) ↔ FEV1 & FVC, FeNO, CV function, IL-6, sCD62P, MDA,	A single overnight residential air filtration, capable of substantially reducing indoor particle concentrations, can lead to improved airway mechanics and reduced thrombosis risk.
Zhan et al 2018	6 homes air purifier operated with filter and without filter Portable HEPA filter Bedroom	PM _{2.5} , organic carbon, elemental carbon, sulfate, nitrate, ammonium, 21 selected metals, PM _{2.5} ROS Personal exposure to PM _{2.5} , PM _{2.5} components and ROS Beijing, China	<i>Indoor</i> PM _{2.5} : 83% (8.47 µg/m ³ with filtration & 49.0 µg/m ³ without); 70-95% PM _{2.5} components; PM _{2.5} ROS: clear decrease <i>Personal exposure</i> Marginal reductions in PM _{2.5} (mean: 67.8	Air cleaner can reduce indoor PM _{2.5} , all of its major components concentration but was not effective in reducing average 48-hour personal exposure to PM _{2.5} .

	48 h	6 participants	and 51.1 µg/m ³ during filtration and control periods respectively) & PM _{2.5} components; PM _{2.5} ROS: little change	
Barn et al 2018	Randomized to no or 1-2 air purifiers Portable HEPA filter Living room for apartments < 40m ² Living room & bedroom for apartments ≥ 40m ² 5 mo No imposed time-activity patterns	PM _{2.5} & tobacco smoke Blood cadmium Ulaanbaatar, Mongolia 512 Pregnant women (≤18 wks) aged ≥18 years • Intervention group n = 259 • Control group n= 253	PM _{2.5} : 29% (17.3 µg/m ³ with filtration & 24.5 µg/m ³ without filtration) PM _{2.5} 40% when first applied & 15% after 5 months use ↓Blood cadmium (14%)	Portable HEPA filter air cleaners can lower indoor PM _{2.5} concentrations and SHS exposures in highly polluted settings.

↔; no statistically significant change; ↓ or ↑ statistically different change

8-iso-PGF₂α: 8-iso-Prostaglandin F₂α; 8-OHdG: 8-hydroxy-2-deoxyguanosine; AC: air conditioning; ACE: angiotensin-converting enzyme; ACTH: adrenocorticotrophic hormone; BP: blood pressure; COPD: chronic obstructive pulmonary disease; CRH: corticotropin-releasing hormone; CRP: C-reactive protein; DBP: diastolic blood pressure; EBC: exhaled breath condensate; ESP: electrostatic precipitator; ET-1: endothelin-1; FeNO: fractional exhaled nitric oxide; FEV₁: forced expiratory volume in 1 second; FVC: forced vital capacity; HEPA: high efficiency particle arresting; HRV: heart rate variability; hs-CRP: high sensitivity C-reactive protein; ICAM-1: intracellular adhesion molecule-1; IL-1β: interleukin-1β; IL-6: interleukin-6; IL-8: interleukin-8; MERV: minimum efficiency reporting value; MDA: malondialdehyde; MPO: myeloperoxidase; O₃: ozone; PAI-1: plasminogen activator inhibitor-1; PM_{2.5}: particulate matter < 2.5 µm in diameter; PP: pulse pressure; PWV: pulse wave velocity; sCD40L: soluble CD40 ligand; SBP: systolic blood pressure; SEVR: subendocardial viability ratio; SOD: superoxide dismutase; TNF-α: tumor necrosis factor alpha; t-PA: tissue plasminogen activator; UFP: ultrafine particle; VOC: volatile organic carbon; vWF: von Willebrand factor; WBC: white blood cell count

5.4 Homes afflicted by exceptionally high household air pollution

Nearly 3 million people worldwide are exposed to a complex mixture of inorganic particles and irritant gases as a consequence of burning biomass fuels (wood, charcoal, crop residues and animal dung) on inefficient stoves in poorly ventilated homes, for cooking, lighting, and heating¹³⁰. Although the greatest proportions of exposed populations are in low-income countries of sub-Saharan Africa, India, China and Central America, a significant number of households in high-income countries still rely on solid fuel for heating homes. The magnitude of exposure, when one takes into account exposure intensity, time spent indoors, and the number of individuals exposed, results in a far greater contribution of household air pollution (HAP) to global PM exposure than any other source¹³¹. Whilst mean 24-h PM₁₀ levels between 200 and 2,000 µg/m³ are quite common, peak exposures of > 30,000 µg/m³ during periods of cooking have been reported¹³². Such emissions are a major contributor to respiratory infections, impaired lung growth, COPD, lung cancer, cataracts and low birth weight¹³³⁻¹³⁵. Limited evidence also supports associations with CV disease¹³⁶. Initiatives to aggressively reduce HAP exposure focus on a package of interventions that include fuel switching, improving cook stove efficiency, venting emissions and changes in behavior/home layout^{137,138}. Some, but not all, studies suggest that certain initiatives may be associated with reduced respiratory symptoms and lung function decline in women and severe pneumonia in children¹³⁹⁻¹⁴¹. Other trials investigating improved stoves have demonstrated significant improvements in blood pressure^{142,143}, ST-segment depression¹⁴⁴ and inflammatory biomarkers¹⁴⁵. The impact of improved ventilation strategies on HAP have also been investigated^{146,147}. Barnes et al¹⁴⁶ used a quasi-experimental design to evaluate a community counseling intervention in rural villages in the North West Province of South Africa on concentrations of PM₁₀ and CO measured on children younger than five. Whilst

counseling (to encourage burning outdoors when possible, opening at least two sources of ventilation during peak emission times and reducing the amounts of time that children spend in the indoor burning rooms while fires are burning) improved average PM_{10} and CO concentrations at the personal and micro-environment, post-intervention levels were generally still far above WHO guidelines. Weaver et al¹⁴⁷ tested behavioural and structural ventilation interventions on indoor $PM_{2.5}$ in Dhaka, Bangladesh in 59 good ventilation (window or door in ≥ 3 walls) and 29 poor ventilation (no window, one door) homes. The presence and opening of door(s)/window(s) were inversely associated with the number of hours $PM_{2.5}$ concentrations exceeded 100 and 250 $\mu g/m^3$. However owing to several cited barriers to increasing ventilation (outdoor odours/noise, theft risk, mosquito entry, perceptions of wasting electricity) and areas of high ambient $PM_{2.5}$ concentrations, indoor concentrations were deemed likely to remain above recommended levels. There are as yet no published studies on the use of PAC in homes of developing countries. Of relevance however, McNamara et al⁹⁶ compared the efficacy of high versus lower efficiency fiberglass filters in reducing indoor $PM_{2.5}$, coarse PM and endotoxin associated coarse PM concentrations in homes in Montana, Alaska and Idaho that use a wood stove for primary heating. Whilst the high efficiency filter showed a 66% reduction in indoor $PM_{2.5}$ concentrations relative to the lower efficiency model, both interventions significantly reduced coarse PM (63.3% and 40.6% reduction for high and lower efficiency filters respectively) and airborne endotoxin (91.8% and 80.4% reductions respectively), both of which are known respiratory irritants. Whilst these results support the use of high efficiency air filtration units for removing fine particles, the lower efficiency and hence lower cost filter alternatives can be effective for reducing coarse PM and airborne endotoxin in homes burning biomass fuel.

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575 **6.0 Indoor air quality in schools**

576 Schools are a vital element in our societies where children spend up to 5 to 8 hours a day
577 between the ages of 5 to 18¹⁴⁸. It is essential therefore that they provide the best possible
578 infrastructure, not only in terms of teaching but also with respect to climatic conditions
579 within the learning environment. Unfortunately it is well documented that the IAQ of
580 schools is invariably unacceptable and since many schools are centrally located within a
581 community, they are often situated close to major roads and frequent hours coinciding
582 with high traffic intensities. As a consequence, ambient air in the direct vicinity of school
583 buildings is often a considerable source of particularly toxic air pollution^{149,150}. Within
584 the classroom exists a multitude of furnishings, educational equipment/materials and
585 personal items, accommodating large numbers of people engaged in wide-ranging
586 activities. These unique characteristics give rise to a wealth of emissions from a multitude
587 of sources^{151,152}. Furthermore, whilst regular classroom and hallway cleaning is
588 important to maintain hygienic environments, intense cleaning procedures can themselves
589 increase exposure to indoor pollutants¹⁵³. Apart from the presence of airborne emissions
590 of indoor and outdoor origin, ventilation rates in many schools have been reduced to save
591 energy. At the same time, owing to inadequate funding, ventilation systems are often
592 inadequately operated and maintained. Children are also a population group that is
593 particularly vulnerable to potential health hazards related air pollution exposure owing to
594 immature and developing organ systems, increased ventilation of the lungs^{154,155} and a
595 compromised ability to deal with toxic compounds¹⁵⁶. In the classroom it is understood
596 that poor IAQ could have a negative impact on children's learning. It is therefore of
597 critical importance to minimize the concentration of air pollution in classrooms,
598 especially at schools located in close proximity to roadways, to ensure healthy

environments that maximize comfort and enable children to thrive physically and mentally.

5.1 Interventions to improve health and learning outcomes in schools through improved air quality

Several studies have reported associations between inadequate classroom ventilation and children's health and learning outcomes. In a review, Sundell et al¹⁵⁷ concluded that low ventilation rates in schools are associated with increased absenteeism and more respiratory symptoms in children. Since then Mendell et al¹⁵⁸ found that higher classroom ventilation rates were consistently and significantly associated with decreased illness-related absence. Assuming the associations were causal, a cost benefit analysis concluded that keeping ventilation rates below recommended levels in classrooms saves energy and money but has much larger costs from increased health problems and illness among students. Several studies provide strong evidence for making causal associations between school ventilation rates and test performance by children¹⁵⁹⁻¹⁶³. Using crossover experimental designs, Wargocki and Wyon^{159,160} showed that increasing the outdoor air delivery rate to Danish classrooms from 5.2 to 9.6 l/s or 3.0 to 8.5 l/s per person significantly improved test speed (but not error rate) performance in approximately 50% of tests. The average CO₂ level (taken as an indicator of human bio-effluents) was reduced from 1300 ppm to 900 ppm and as such the observed effects were assumed to be a consequence of improved classroom air quality. A similar experimental design employed by Bakó-Biró et al¹⁶¹ in English schools reported significantly improved speed and accuracy in cognitive performance tests upon increasing ventilation rate from 1.0 to 8.0 l/s per person. Effects of suboptimal classroom ventilation on school learning or achievement over time have also been suggested by 2 prospective studies focusing on long-term academic performance^{164,165}.

Data on the effectiveness of classroom based air cleaner interventions is very limited (Table 4). Su et al¹⁶⁶ evaluated the performance of upper room ultraviolet germicidal irradiation (UVGI) to reduce bioaerosol concentrations and student absenteeism. Culturable samples – only a fraction of course of all airborne organisms - collected within 10 minutes of students evacuating the UVGI rooms exhibited significantly lower fine (1-8 μm) but not coarse ($>8\mu\text{m}$) airborne bacteria (but not fungi). This did not translate into reduced overall student absenteeism rates and non-attendance due specifically airborne infectious diseases was not recorded. It should be noted that doors were frequently opened during the measurements, allowing potential infiltration effects from the corridor and beyond. Rosen and Richardson¹⁶⁷ placed electrostatic cleaning systems into two Swedish day care centres (n=63 and n=30 children) during year 2 of a 3-year study and reported reductions in the number of very fine particles of outdoor origin and fine particles produced indoors of 78% and 45% respectively. Absenteeism over the 3-year period due to illness was significantly reduced by 55% in the larger of the two institutions to levels equivalent to those documented in family-based care. Considerable reductions in the concentration of airborne particles were reported in classrooms equipped with electrostatic air cleaners installed mechanically ventilated systems and this effect was greater in rooms with lower outdoor air supply rates¹⁶⁸. This was not however accompanied by improved performance of a wide range of tasks by children aged 10 to 12 years, children's perception of the classroom environment, symptom intensity or on air quality as perceived by a sensory panel. A pilot randomized controlled trial has also assessed the feasibility of HEPA air cleaners to reduce particulate pollutants in classrooms of asthmatic children in inner-city elementary schools¹⁶⁹. Sustained (over one year) reductions in classroom $\text{PM}_{2.5}$ and BC levels were accompanied by a modest improvement in peak flow, but not in forced expiratory volume in 1 second and asthma

649 symptoms. This rather limited effect on asthma morbidity may be related to the fact that
650 children spend more time outdoors during the warmer months, reducing the efficacy of
651 improving IAQ.

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Table 4. Summary of studies investigating effects of classroom based air cleaner interventions on health and performance

Study	Study design, purifier type, filtration site, intervention duration	Exposure focus, outcome measures, location, study population	Indoor pollutant reduction & health/performance outcome	Author conclusion
Su et al 2016	UVGI group: n=2 classrooms with 4 upper room UVGI units installed on 4 walls Control group: n=6 classrooms, no units 9 months	Bioaerosol Student absenteeism Midwest USA 18-27 students per classroom; third & fourth grade	Reduced fine (1-8 µm) airborne bacteria only when microorganisms were > 160 CFU/m ³ otherwise no effect No effect on coarse (>8 µm) airborne bacteria, airborne fungi ↔ absenteeism rates	Upper room UVGI can reduce culturable bioaerosols in a crowded environment like classrooms
Rosen & Richardson 1999	Electrostatic air cleaners; 2 day care centres Installed close to each ceiling-mounted forced air inlet in rooms used by children Year 2 of a 3-year study	Very fine particles (PM _{0.3-3.0}); fine particles (PM ₃₋₇) Non-attendance rates due to illness Uddevalla, Sweden Day centre A: n=63 children; day centre B: n=30 children; aged 1-6 years	PM _{0.3-3.0} : 78%; PM ₃₋₇ : 43% ↓ 55% illness absenteeism over 3 years in day care centre A	The electrostatic air cleaning technology is cost-efficient and might be a way forward to improve IAQ.
Wargocki et al 2008	Blind crossover; 2 or 3 electrostatic cleaners operating or disabled within 5 pairs of mechanically ventilated classrooms across 5 schools Wall mounted; one week	Airborne particles Schoolwork performance, perceived environment, symptom intensity Denmark N=190 children; aged 10-12 years	↓PNC ↔ Schoolwork performance, perceived environment, symptom intensity	Although electrostatic air cleaners efficiently reduced the concentration of airborne particles in classrooms, this reduction did not show any of the expected short-term benefits for symptom intensity, environmental perceptions, or the performance of schoolwork for pupils aged 10-12 years
Jhun et al 2017	18 classrooms randomized to 4 air purifiers with (n=9 classrooms) or without (n=9 classrooms) filters HEPA; classroom floor 1 year	PM _{2.5} , BC PEF, FEV ₁ , asthma symptoms North eastern USA 25 asthmatic children (control n=13; intervention n=12); aged 6-10 years	PM _{2.5} : 49% (6.2 µg/m ³ to 2.4 µg/m ³) at first follow-up & 42% (6.2 µg/m ³ to 2.6 µg/m ³) at second follow-up BC: 58% (0.41 µg/m ³ to 0.13 µg/m ³) at first follow-up & 55% (0.41 µg/m ³ to 0.15 µg/m ³) at second follow-up ↔ PEF, FEV ₁ , asthma symptoms	A classroom-based air cleaner intervention led to significant reductions in PM _{2.5} and BC. Future large-scale studies should comprehensively evaluate the effect of school-based environmental interventions on pediatric asthma morbidity.

↔; no statistically significant change; ↓ or ↑ statistically different change

CFU: colony forming units; BC: black carbon, FEV₁: forced expiratory volume in 1 second; HEPA: high efficiency particle arresting; PEF: peak expiratory flow; PM_{2.5}: particulate matter < 2.5 µm in diameter; UVGI: ultraviolet germicidal irradiation

6.0 Air quality in offices

Many urban workers spend approximately 8 hours a day in offices, engaged with a number of people in various activities and often housed within buildings with sealed exterior shells equipped with highly automated HVAC systems. Studies evaluating the air quality in offices have identified electronic equipment, including computers, multifunctional office machines, air conditioners, and particularly photocopiers and printers, as being important sources of PM_{2.5}, PM₁₀, O₃ and VOCs¹⁷⁰⁻¹⁷². Poorly ventilated offices also tend to suffer from increased CO₂ as the working day progresses. Good air quality within the office environment is not only be beneficial to personal health (it has been said that around half of the illness affecting the workforce is related to conditions in the work environment), but also has a positive effect on the productivity of the staff.

6.1 Interventions to improve IAQ, health and productivity in offices

There is a very large literature base on the effects of office ventilation on productivity and health, which has been widely addressed in several reviews^{157,173-175}. A series of well-controlled experimental exposure studies in Denmark, Sweden and the UK have demonstrated that removing common indoor sources of air pollution (floor-coverings, personal computers, used supply air filters) has a significant and positive influence on the productivity of office workers¹⁷⁶⁻¹⁷⁸. The short-term (up to 5 hours) effects were repeatedly demonstrated even at pollutant levels having no measurable effects on the occupants' perception of air quality. These experimental findings were then validated in field intervention studies conducted in call centers in northern Europe¹⁷⁹ and the Tropics^{180,181} where significant positive effects of increased ventilation on productivity (be as high as 6–9%) were recorded. Of note, that the positive findings in the Danish field study were only recorded in the presence of new particulate filters and no filters were

employed in the studies conducted in the Tropics, suggest that used particulate filters in the HVAC system can represent a significant source of pollution. Milton¹⁸² demonstrated that among 3720 employees (and particularly among 600 office workers) of a large US manufacturer, doubling ventilation rates (from 12 to 24 l/s/person) reduced short-term sick leave by 35%. Increased ventilation rates (up to 25 l/s/person) in offices are also associated with reduced SBS symptoms in that drops from 10 to 5 l/s-person increases symptom prevalence by approximately 23% and increases from 10 to 25 l/s-person decreases prevalence by approximately 29%^{157,173}. Published studies investigating the efficacy of air cleaning interventions to improve both IAQ of offices and the health of employees is limited to installation of free-standing electrostatic air cleaners as an effective means of breathing zone particle filtration. This approach appears to significantly reduce dust concentration but has no effect on office worker reported symptoms¹⁹⁴⁻¹⁹⁶.

Modeling efforts focused on filtration systems have found that the overall benefits of use in office buildings are several times larger than the associated running costs¹⁸⁵. Montgomery et al¹⁸⁶ developed theoretical models of the financial costs and benefits of HVAC air filtration systems in an office in cities around the world representing wide variations in outdoor air quality, electricity prices. Analyses showed that, although the operation cost of filtration systems varied by a factor of 3 between cities, the monetized health benefits of filter installations outweighed the operation costs by up to a factor of 10, and in the majority of scenarios, the net benefits were greatest for the highest efficiency filters. More recent studies have evaluated alternative, energy saving ventilation strategies such as those with dynamic control sequences in modeling the interplay between energy use, profitable IAQ impacts and negative IAQ health impacts due to indoor particle and ozone exposure¹⁸⁷. Modeling has also suggested that

implementing a high efficiency filter can mitigate negative effects of ventilation whilst higher ventilation rates can increase the efficacy of filtration¹⁸⁸. The effects of ventilation rate and air filtration efficiency on the chronic health risks associated with indoor VOCs and PM_{2.5} concentrations from occupant exposures in offices, schools, grocery, and other retail stores have also been explored using simulation models¹⁸⁹. Using disability adjusted life years to account for both cancer and non-cancer effects, results indicate that increasing ventilation rates alone is ineffective at reducing chronic disease burdens in these commercial buildings and that alternative strategies such as pollutant source control and the use of particle filtration, should receive greater priority.

7.0 Air quality in cars

Automobiles have become a necessity in modern life to the extent that a significant percentage of the population spends a proportion of time in passenger cars on a daily basis. The microenvironment of vehicle interiors is unique with respect to its relatively small volume and diverse mix of potentially high concentrations of internally generated air pollution¹⁹⁸, as well UFP emissions from mobile sources (mainly on-road vehicles) that infiltrate the cabin from outside¹⁹⁹. Pollutants of in-cabin origin include tobacco smoke, biological aerosols and emissions from the wide variety of internal materials (especially in newly produced vehicles) including hard and soft plastics, adhesives, paints and lubricants. Ambient emissions will be particularly high when driving and idling on over congested routes and canyon-like street configurations that hinder dispersive actions and trap pollutants at vehicle level²⁰⁰. A significant and disproportionate share of total daily personal exposure to PM can occur within a vehicle cabin, even during short (~30 minute) journeys^{201,202}, and systematic reviews conclude that commuters using motorized transport have a higher level of air pollution exposure compared to cyclists and pedestrians^{203,204}. Exposure to UFPs in transport microenvironments varies considerably

depending on a number of factors²⁰⁵. For instance in-vehicle UFP concentrations result from influx and removal rates and these in turn will be influenced by the rate of air turnover, physical characteristics of the vehicle, driving conditions, in-cabin filter efficiency and particle size²⁰⁶⁻²⁰⁸. Considerable evidence exists from observational and controlled studies linking traffic-related pollution and adverse health effects²⁰⁹. Moreover, experimental studies suggest that a biological response to components or a mix of traffic related pollutants can occur following very short-term exposures^{210,211}. In-vehicle panel studies provide additional evidence that traffic PM exposures at commonly experienced concentrations among car commuters can be associated with a cardiorespiratory response²¹²⁻²¹⁶.

7.1 Health benefits of in-cabin air quality interventions (Table 5)

In a randomized, controlled, cross-over study, Laumbach et al²¹⁷ reported decreased oxidative stress in the respiratory tract but no effect on HRV in healthy young participants who rode for 1.5 hours in passenger vehicles during rush-hour traffic wearing air purifying respirators blinded to HEPA filtration. The study was small and the young student population is unlikely to reflect more susceptible populations. The use of cabin air particle filters with active charcoal in an experimental human exhaust study demonstrated significantly reduced symptoms in healthy subjects but no effects on nasal airway lavage, acoustic rhinometry and lung function²¹⁸. Subsequent work by the same group evaluating the efficacy of more developed cabin air filters reported decreased exhaust-induced subjective symptoms but no significant changes in lung function or inflammatory markers²¹⁹. The feasibility of mitigating cardiovascular risks associated with the inhalation of traffic related pollutants by filtering particulate matter from the vehicle passenger cabins has also been investigated^{220,221}. During 2-hour exposures to

Southern Californian freeway air, a high-efficiency filtration system within a modified passenger van reduced particle count by 95% but did not remove gases²²⁰. Whilst most of the vascular and cardiac health endpoints remained unchanged, filtration did result in average decreases in atrial ectopic beat incidence, N-terminal pro B-type natriuretic peptide and vascular endothelial growth factor, suggesting a possible protective effect on atrial arrhythmia. Another study exploring the impact of in-car AC system on air quality improvement and CV health observed decreased HRV indices associated with increased levels of in-car PM_{2.5} when the AC was turned off²²¹. Turning on the system, using either outside or recirculated inside air, lowered in-car PM_{2.5} levels and improved HRV indices. Apart from traffic-related pollutants, another in-cabin health risk stems from exposure, within a confined and often shared space, of airborne infectious agents²²², allergens²²³ and endotoxins²²⁴. Use of AC systems in the cabin has been shown to effectively reduce by more than 80% of the total number of microorganisms, including bacterial and fungal spores and bioaerosol²²⁵⁻²²⁷. However, those bacteria and fungi filtered from the air stream by AC filters can proliferate and furthermore, the air stream passing through the vehicle filtration system can aerosolize filter-borne bacteria and fungi reintroducing them back into the vehicle cabin. Indeed, Li et al²²⁸ collected samples of dust from AC and engine filters from 30 cars in 4 four locations of China and studied them for bacteria, fungi, and endotoxins. Dust from their AC filters contained relatively high levels of bacteria (~26,150 CFU/mg), fungi (~1,287 CFU/mg), and endotoxins (~5,527 endotoxin units/mg) including more than 400 different types of bacterial species that included opportunistic pathogens and an abundance of 18 types of allergenic fungal species. The observation of fluorescent peaks around 2.5 µm within the first 5 minutes of AC use was attributed to the aerosolization of filter-borne microbes. To address the question as to whether commercial in-car microbial air decontamination devices can mitigate this risk,

784 Sattar et al²²⁹ tested 3 HEPA filter devices that could be plugged into the car's power
785 supply. Each device was tested against Staphylococcus aureus at their highest fan speeds
786 in a 3.25 m³ modified passenger cabin of a 4-door sedan accommodated within a
787 biosafety level 3 containment facility. The 3 devices took 1.5, 2.3 and 9.7 hours to meet
788 an arbitrarily set performance criterion constituting the number of hours taken for a 3-
789 log₁₀ reduction in the level of airborne challenge bacterium.

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791 **Table 5. Summary of studies investigating health effects of in-car air cleaning interventions**

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Study	Study design, purifier type, intervention duration	Exposure focus, health outcomes, location, study population	Indoor pollutant reduction & health outcome	Author conclusion
Laumbach et al 2014	Single blinded randomized, cross-over: air purifying respirator with or without HEPA filtration 2x 1.5-hr rides in a passenger vehicle in morning rush-hour traffic	No exposure measurement HRV, oxidative stress (EBC nitrite, sum of nitrite and nitrate, MDA, 8-isoprostane) New Jersey, USA 21 healthy adults; mean age 22.4 years	- ↓ 19% EBC nitrite, ↓48% EBC sum of nitrite & nitrate ↔ malondialdehyde 8-isoprostane, HRV	Increases in markers of oxidative stress in EBC may represent early biological responses to widespread exposures to traffic related air pollution particles that affect passengers in vehicles on heavily trafficked roadways.
Rudell et al 1999	Six one hour chamber exposures to 300 µg/m ³ DDE: 1: air, 2: unfiltered DDE, 3-6: DDE filtered with four different cabin air filters* *particle filters +/- active charcoal filters	DEP Subjective symptoms, NAL, acoustic rhinometry, , lung function Umeå, Sweden 32 healthy adults; age 21-53 years	Particle filters: ↓DEP ↔ symptom intensity, NAL, rhinometry, lung function Combined particle & activated charcoal filters: ↓DEP ↓symptoms & discomfort ↔ NAL, rhinometry, lung function	The use of active charcoal filters and a particle filter clearly reduced the intensity of symptoms induced by diesel exhaust. Complementary studies on vehicle cabin air filters may result in further diminishing the biomedical effects of diesel exhaust in subjects exposed in traffic & workplaces.
Muala et al 2014	Randomized double-blind controlled crossover to 4 one hour chamber exposures to DE: 1: air; 2: unfiltered DE; 3: DE filtered through particle filter; 4: DE filtered through particle filter with active charcoal	PM ₁₀ , NO ₂ , hydrocarbons Subjective symptoms, lung function (FEV ₁ , FVC), inflammation (IL-6, TNFα, P-selectin, sICAM-1, CD40L) Umeå, Sweden 30 healthy adults; age 21-53 years	Particle filter ↓46% PM ₁₀ Particle filter plus active charcoal component ↓78% PM ₁₀ ; ↓75% NO ₂ ; ↓50% hydrocarbons ↓symptoms & discomfort ↔ lung function, inflammation	Data demonstrate the effectiveness of cabin filters to protect subjects travelling in vehicles from diesel exhaust emissions.
Hinds et al 2010	Two 2-hour exposures to freeway air* in a 9-passenger van modified with a high-efficiency filtration system delivering (1) filtered or (2) unfiltered air to an exposure chamber inside the van. *two freeways: one with mostly gasoline vehicles; one with a high proportion of heavy-duty diesel trucks	UFP, PM _{2.5} , PM ₁₀ , carbon monoxide, carbon dioxide, BC, PB PAH, oxides of nitrogen ECG, BP, lung function, inflammation (fibrinogen, IL-6, CRP, MPO, MCP-1); vascular response/injury (sE-selectin, VEGF, sVCAM, sICAM, MMP9, MPO, t-PAI-1), myocardial response to hemodynamic changes (NT-proBNP). Southern California, USA 19 adults; mean age 71 years	PNC: 95%; PM _{2.5} : 81%; PM ₁₀ : 75% BC & PB PAH: 95% Gases: no change ↓20% atrial ectopic beat incidence ↓30% blood NT pro-BNP & VEGF ↔ BP, lung function, inflammatory & vascular biomarkers	Study documents a cardiac and vascular response associated with freeway travel that provides new insight into the association of inhalation of traffic related pollutants to arrhythmia...a risk that could be mitigated by filtering particulate matter from the vehicle passenger cabins.
Chuang et al 2013	2 h commute by a car with AC during the morning rush hour AC operation modes:	PM _{2.5} HRV indices (SDNN, r-MSSD)	PM _{2.5} in off-mode (35.5 µg/m ³), OA-mode (13.2 µg/m ³), & IA-mode (16.3 µg/m ³),	In-car PM _{2.5} is associated with autonomic alteration. Utilization of the car's AC system can improve air quality and modify the

	Use of outside air (OA-mode) Circulating inside air (IA-mode) Off (Off-mode)	Taipei, Taiwan 60 healthy adults aged 20-50 years	Off-mode: 2.7% & 4.1% decreases in SDNN & r-MSSD per IQR increase in in-car PM _{2.5} OA and IA modes: slight decreases in SDNN (OA mode: 0.1%; IA mode: 1.3%) and r-MSSD (OA mode: 1.1%; IA mode: 1.8%) per IQR increase in in-car PM _{2.5}	effects of in-car PM _{2.5} on HRV indices among human subjects during the commute.
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↔; no statistically significant change; ↓ or ↑ statistically different change

BC: black carbon; CD40L: cluster of differentiation 40 ligand; CRP: C-reactive protein; EBC: exhaled breadth condensate; ECG: electrocardiogram; DDE: diluted diesel exhaust; DEP: diesel exhaust particles; FEV₁: forced expiry volume in 1 second; FVC: forced vital capacity; HEPA: high efficiency particle arresting; HRV: heart rate variability; IL-6: interleukin-6; MDA: malondialdehyde; MMP9: matrix-metalloproteinase-9; MPO: myeloperoxidase NAL: nasal airway lavage; NT pro-BNP: N-terminal pro B-type natriuretic peptide; PB PAH: particle bound polycyclic aromatic hydrocarbons; PM_{2.5}: particulate matter < 2.5 µm in diameter; PM₁₀: particulate matter < 10 µm in diameter; r-MSSD: square root of the mean of the sum of the squares of differences between adjacent NN intervals; SDNN: standard deviation of NN intervals; sICAM-1: soluble intercellular adhesion molecule-1; sVCAM: soluble vascular cell adhesion molecule; TNFα: tumor necrosis factor-alpha; UFP: ultrafine particle; VEGF: vascular endothelial growth factor

8.0 Discussion

Increasing urbanization, technological development and specialized occupational activities have culminated in an 'indoor generation', where most human activities take place within an enclosed space, characterized by a chemically diverse and complex air quality. Source control is, and will always be, the universally preferred approach to reduce contaminants within an indoor setting. This however is becoming increasingly insufficient, technically unfeasible or economically unviable. The second strategy of ensuring sufficient ventilation using air of appropriate quality is also being challenged – by both invariably poor outdoor air quality and our quest for a low carbon economy. Whilst the former directly adds to the burden of indoor air pollution, both factors attract mitigation measures that are leading to efforts to seal off indoor spaces. Depending upon the actions implemented, these measures have the potential of improving or degrading IAQ and as a consequence, health. For instance, dynamic and predictive developments such as demand-controlled and hybrid ventilation, in association with harnessing renewable resources, promise to be effective and efficient strategies. Nevertheless, any repercussions that result in inadequate ventilation will, as research summarized in this review continues to confirm, increase exposure to endogenous indoor air pollutants, heighten health risks (asthma, airway obstruction and SBS symptoms) and curtail concentration, learning and productivity. Further challenges to 'indoor living' relate to the incomplete understanding of the causal associations between indoor air pollutants (aside from CO, formaldehyde, radon and ETS) and health outcomes and unlike ambient air, the relative absence of IAQ measurements, controls/guidance and indices.

Despite the emergence of a wide array of air cleaning technologies, investigations into the effectiveness of personal units in the domestic setting is generally limited to media filtration, largely owing to the lack of investigations on other types of cleaning devices.

Studies have reported that air cleaners equipped with either HEPA filters or electrostatic plates are effective at reducing indoor PM_{2.5} concentrations by approximately 30-80% with the majority of this variability attributed to study design (use of one or more units), duration of the intervention, internal air flow and user compliance. With respect to health effects, some of the null associations observed in studies conducted in areas of unremarkable ambient air quality and in wood-smoke communities could in part be explained by small sample sizes, large variations in filtration efficiency, baseline differences in health outcomes and use of medication. In addition, the relatively low baseline pollution concentrations ($\sim 6.5\text{--}8\text{ }\mu\text{g}/\text{m}^3$) and small ($\sim 3\text{--}4\text{ }\mu\text{g}/\text{m}^3$) absolute reductions in indoor PM_{2.5} levels following filtration may have limited the ability to detect any relationship between the interventions and health outcomes. The latter however does not resonate with evidence suggesting no threshold exists below which PM_{2.5} no longer poses a health risk to the population and thus, the compelling argument for implementing strategies to reduce particulate pollution at both ends of the severity spectrum. Nevertheless, it is interesting that the more notable observations of improved health outcomes stem from studies (generally featuring larger sample sizes and more frequent washout periods) conducted in homes situated in Asian megacities with high baseline indoor air pollution concentrations ($\sim 22\text{--}96\text{ }\mu\text{g}/\text{m}^3$) that underwent substantial absolute reductions ($\sim 23\text{--}55\text{ }\mu\text{g}/\text{m}^3$ in 5 studies conducted in Beijing or Shanghai; $9.5\text{ }\mu\text{g}/\text{m}^3$ in one conducted in Taipei) following filtration. Fairly consistent health benefits constituted reductions in BP as well as markers of inflammation, oxidative stress and pro-coagulation pathways following periods ranging from a single overnight filtration to a yearlong intervention¹¹⁷⁻¹²⁰. Of note, was the one study focusing on an older group of residents, some of whom were COPD patients, that reported no demonstrable changes in a suite of cardio-respiratory outcome parameters¹²¹, suggesting short term intervention can be of

limited health benefit with exposure to extreme high outdoor air pollution levels. In that indoor air filtration produces clear reductions in indoor pollution concentrations, longer term interventions should be investigated particularly in vulnerable populations (individuals with chronic CV or respiratory disease, children, fetuses, and the elderly) that spend most of their time indoors and as such, could benefit from the clean indoor environment that air purifiers provide. Findings that an air cleaner reduces $PM_{2.5}$ concentrations within a home but not personal exposure to $PM_{2.5}$ ¹²⁸ suggests that study participant activities whilst outdoors without respiratory protection will outweigh the protective effects provided by air filtration within a bedroom and/or living room. Future studies should employ real-time sensors to collect data from all such (indoor and outdoor) activities to quantitatively assess complete exposure profiles as well as housing information such as room area, ventilation rate and an infiltration factor. Furthermore, despite the 54-83% reductions in indoor particulate concentrations achieved by the filtration devices within the urban Chinese homes, average $PM_{2.5}$ remained high (10 – 24 $\mu g/m^3$) probably owing to high outdoor-to-indoor penetration in such highly polluted environments. To this end, calls have been made for large randomized clinical studies among at-risk populations with hard CV endpoints (e.g. prevention of myocardial infarction) to test whether indoor air purifiers with HEPA filters plus outdoor personal-protection (e.g. N95 respirator) result in more substantial reductions in exposure and actual clinical benefits²³⁰. Such initiatives may provide a mechanism to confirm, or otherwise, the optimistic modelled projected health benefits and costs associated with particle filtration. In schools, numerous investigations have reported the positive effects of increased ventilation and as such, improved IAQ on respiratory symptoms, absenteeism, test performance and long-term academic performance in school children. The proven effectiveness of air filtration systems that are built into school HVAC systems^{231,232} as well

as stand-alone air filtration systems in classrooms relying on natural ventilation²³³ in reducing indoor pollutants of outdoor origin suggests they represent a critical mitigation measure at schools located near heavily trafficked roads, industry and other important sources of air toxics. Future research should focus on identifying the optimal technologies for removing specific indoor air pollutants (e.g. VOCs versus PM), quantifying short- and long-term health and learning impacts of installing such devices and evaluating the cost benefits resulting from improved IAQ and from a reduction in student exposure to outdoor-infiltrated particles and organic pollutants.

Offices represent another indoor space dedicated to working in which there is a large evidence base indicating that removing common indoor sources of air pollution and increasing ventilation is associated with increased productivity, reduced short-term sick leave, SBS symptoms, inflammation, respiratory infections, asthma and allergy. However whilst such data have attained some consensus within the indoor air research community, a survey by Hamilton et al²³⁴ found that such benefits are not established in the perceptions of US building stakeholders (tenants, owners, operators, and designers/consultants). The minority of respondents thought a ventilation-filtration upgrade would positively impact productivity, absenteeism, or health whilst the majority overestimated costs. Moreover, green building professionals did not represent a group more likely to recognize IAQ benefits, and were less likely to be willing to pay for ventilation and filtration upgrades. These views suggest that to encourage a greater understanding of, and investment in, IAQ-related upgrades in the workplace, requires greater stakeholder education and outreach strategies and possibly, the inclusion of additional building technology to sense and report risks related to IAQ.

Any benefit air cleaning technologies have on human health ultimately relies upon their performance and in the main, this is based upon short-term laboratory tests using tobacco

smoke, aerosolized dust, pollen and potassium chloride particles. Looking forward, to better characterize long-term performance in the real world, necessitates testing against hazardous ultrafine particles that dominate particulate concentrations in outdoor air, over long durations in well-characterized indoor environments to examine primary (beneficial) and secondary (detrimental) impacts^{235,236}. Such tests should consider cleaning impacts on multiple contaminants, easily identify common comparative benchmarks such as CADR, single-pass removal efficiency and energy consumption and serve as a clear educational tool regarding optimal usage and maintenance (eg filter changes). As other types of cleaning technologies progress to commercialization, we can look forward to well-designed intervention studies to aid in the selection of particular air cleaners for specific applications. For example confirmation of the potential reliability and durability of PCO technologies that boast low energy consumption credentials is dependent upon developments that can demonstrate (a) high adsorption performance of various VOCs, (b) low/no generation of by-products and catalyst deactivation and (c) an ability of trapping photons from UV to sunlight spectrum⁴¹. Studies are also focusing on the feasibility of overcoming technology shortcomings by designing hybrid devices from various synergistic combinations of air cleaning techniques²³⁷⁻²³⁹.

In summary, large-scale international/national interventions as well as personal prevention approaches have the potential to improve the quality of indoor air – an environment where the majority of society spends most of their lives. Between the extremes of this spectrum, the private and the public sector must also address the challenge through the design, construction and maintenance of housing, schools, the workplace and vehicles. Whilst there remains an ongoing role for the three basic strategies (source control, ventilation, air cleaning) to attain this goal, as exposure to indoor environments increases, further emphasis will be placed upon air cleaning technologies. We can undoubtedly look forward

to further research and development of such technologies to drive this field forward from a scientific to a health policy standpoint and in doing ensure that indoor living has a positive impact on health and promotes learning and productivity at work.

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940 **List of abbreviations**

941		
942	AC	Air conditioning
943	BC	Black carbon
944	BP	Blood pressure
945	CADR	Clean air delivery rate
946	CO	Carbon monoxide
947	CO ₂	Carbon dioxide
948	COPD	Chronic obstructive pulmonary disease
949	CRP	C-reactive protein
950	CV	Cardiovascular
951	EPA	Environmental Protection Agency
952	ESP	Electrostatic precipitator
953	ETS	Environmental tobacco smoke
954	HEPA	High efficiency particle arresting
955	HVAC	Heating ventilation and air conditioning
956	IL-6	Interleukin-6
957	IAQ	Indoor air quality
958	MERV	Minimum efficiency reporting value
959	MVF	Microvascular function
960	NO ₂	Nitrogen dioxide
961	NO _x	Oxides of nitrogen
962	O ₃	Ozone
963	PAC	Personal air cleaner
964	PAH	Polycyclic aromatic hydrocarbon
965	PCO	Photocatalytic oxidation
966	PM	Particulate matter
967	PM _{2.5}	PM less than 2.5 µm in diameter
968	PM ₁₀	PM less than 10 µm in diameter
969	SBS	Sick building syndrome
970	SHS	Second hand smoke
971	UFP	Ultrafine particle
972	UVGI	Ultraviolet germicidal irradiation
973	VOC	Volatile organic carbon
974	WHO	World Health Organization

References

1. Firkit J. The cause of the symptoms found in the Meuse Valley during the fog of December, 1930. *Bulletin of the Royal Academy of Medicine (Belgium)* 1931;11:683-741.
2. Ciocco A, Thompson DJ. A follow-up of Donora ten years after: methodology and findings. *American journal of public health and the nation's health.* 1961;51:155-164.
3. Logan WP. Mortality in the London fog incident, 1952. *Lancet.* 1953;1(6755):336-338.
4. Dockery DW, Pope CA, 3rd, Xu X, et al. An association between air pollution and mortality in six U.S. cities. *N Engl J Med.* 1993;329(24):1753-1759.
5. WHO. Review of evidence on health aspects of air pollution—REVIHAAP project, technical report. 2013; http://www.euro.who.int/_data/assets/pdf_file/0004/193108/REVIHAAP-Final-technical-report-final-version.pdf?ua=1. Accessed June 5, 2018.
6. Pedersen M, Garne E, Hansen-Nord N, et al. Exposure to air pollution and noise from road traffic and risk of congenital anomalies in the Danish National Birth Cohort. *Environ Res.* 2017;159:39-45.
7. Orioli R, Cremona G, Ciancarella L, Solimini AG. Association between PM10, PM2.5, NO2, O3 and self-reported diabetes in Italy: A cross-sectional, ecological study. *PLoS One.* 2018;13(1):e0191112.
8. Sunyer J, Suades-Gonzalez E, Garcia-Esteban R, et al. Traffic-related Air Pollution and Attention in Primary School Children: Short-term Association. *Epidemiology.* 2017;28(2):181-189.

9. Oudin A, Forsberg B, Adolfsson AN, et al. Traffic-Related Air Pollution and Dementia Incidence in Northern Sweden: A Longitudinal Study. *Environ Health Perspect.* 2016;124(3):306-312.
10. Clancy L, Goodman P, Sinclair H, Dockery DW. Effect of air-pollution control on death rates in Dublin, Ireland: an intervention study. *Lancet.* 2002;360(9341):1210-1214.
11. Pope CA, 3rd, Schwartz J, Ransom MR. Daily mortality and PM10 pollution in Utah Valley. *Archives of environmental health.* 1992;47(3):211-217.
12. Hedley AJ, Wong CM, Thach TQ, Ma S, Lam TH, Anderson HR. Cardiorespiratory and all-cause mortality after restrictions on sulphur content of fuel in Hong Kong: an intervention study. *Lancet.* 2002;360(9346):1646-1652.
13. Pope CA, 3rd, Ezzati M, Dockery DW. Fine-particulate air pollution and life expectancy in the United States. *N Engl J Med.* 2009;360(4):376-386.
14. Rich DQ, Zareba W, Beckett W, et al. Are ambient ultrafine, accumulation mode, and fine particles associated with adverse cardiac responses in patients undergoing cardiac rehabilitation? *Environ Health Perspect.* 2012;120(8):1162-1169.
15. Klepeis NE, Nelson WC, Ott WR, et al. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *Journal of exposure analysis and environmental epidemiology.* 2001;11(3):231-252.
16. WHO. Public health, environmental and social determinants of health (PHE). 2014; http://www.who.int/phe/health_topics/outdoorair/databases
Accessed May 31, 2018.

17. Rajagopalan S, Brook RD. Indoor-Outdoor Air Pollution Continuum and CVD Burden. An Opportunity for Improving Global Health. *Glob Heart*. 2012;7(3):207-213.
18. Li Y, Leung GM, Tang JW, et al. Role of ventilation in airborne transmission of infectious agents in the built environment - a multidisciplinary systematic review. *Indoor Air*. 2007;17(1):2-18.
19. Lan L, Wargocki P, Wyon DP, Lian Z. Effects of thermal discomfort in an office on perceived air quality, SBS symptoms, physiological responses, and human performance. *Indoor Air*. 2011;21(5):376-390.
20. IOM. *Indoor Allergens: Assessing and Controlling Adverse Health Effects*. Washington, DC: The National Academies Press; 1993.
21. Weschler CJ. Changes in indoor pollutants since the 1950s. *Atmospheric Environment*. 2009;43(1):153-169.
22. Panagiotaras D. Comprehensive Experience for Indoor Air Quality Assessment: A Review on the Determination of Volatile Organic Compounds (VOCs). *Journal of Physical Chemistry & Biophysics*. 2014;4(5).
23. Weschler CJ. Ozone in indoor environments: concentration and chemistry. *Indoor Air*. 2000;10(4):269-288.
24. Weschler CJ, Nazaroff WW. SVOC exposure indoors: fresh look at dermal pathways. *Indoor Air*. 2012;22(5):356-377.
25. Wong JPS, Carslaw N, Zhao R, Zhou S, Abbatt JPD. Observations and impacts of bleach washing on indoor chlorine chemistry. *Indoor Air*. 2017;27(6):1082-1090.

26. Wisthaler A, Weschler CJ. Reactions of ozone with human skin lipids: sources of carbonyls, dicarbonyls, and hydroxycarbonyls in indoor air. *Proc Natl Acad Sci U S A*. 2010;107(15):6568-6575.
27. Zhou S, Forbes MW, Katrib Y, Abbatt JPD. Rapid Oxidation of Skin Oil by Ozone. *Environmental Science & Technology Letters*. 2016;3(4):170-174.
28. WHO. Dampness and mould. WHO Guidelines for Indoor Air Quality. 2009; <http://www.euro.who.int/document/E92645.pdf>. Accessed May 31, 2018.
29. WHO. Guidelines for Indoor Air Quality: Selected pollutants. 2010; http://www.euro.who.int/_data/assets/pdf_file/0009/128169/e94535.pdf Accessed May 31, 2018.
30. EPA. Energy savings plus health: indoor air quality guidelines for multifamily building upgrades. 2016; https://www.epa.gov/sites/production/files/2016-02/documents/esh_multifamily_building_upgrades_508c_02_09_2016.pdf. Accessed May 18, 2018.
31. EPA. Indoor Air Quality Tools for Schools Coordinator's Guide. A Guide to Implementing an IAQ Program. 2009; https://www.epa.gov/sites/production/files/2014-11/documents/coordinators_guide.pdf. Accessed May 2, 2018.
32. NICE. Indoor air quality at home. 2018; <https://www.nice.org.uk/guidance/indevelopment/gid-ng10022>. Accessed May 18, 2018.

33. Asikainen A, Carrer P, Kephalopoulos S, Fernandes ED, Wargocki P, Hanninen O. Reducing burden of disease from residential indoor air exposures in Europe (HEALTHVENT project). *Environmental Health*. 2016;15.
34. Wargocki P. The Effects of Ventilation in Homes on Health. *International Journal of Ventilation*. 2013;12(2):101-118.
35. Ole Fanger P. *Sensory Characterization of Air Quality and Pollution Sources*. Dordrecht: Springer; 1992.
36. Asikainen A, Hänninen O, Brelih N, et al. The Proportion of Residences in European Countries with Ventilation Rates below the Regulation Based Limit Value. *International Journal of Ventilation*. 2013;12(2):129-134.
37. Dimitroulopoulou C. Ventilation in European dwellings: A review. *Building and Environment*. 2012;47:109-125.
38. Zhang YP, Mo JH, Li YG, et al. Can commonly-used fan-driven air cleaning technologies improve indoor air quality? A literature review. *Atmospheric Environment*. 2011;45(26):4329-4343.
39. Bahri M, Haghighat F. Plasma-Based Indoor Air Cleaning Technologies: The State of the Art-Review. *Clean-Soil Air Water*. 2014;42(12):1667-1680.
40. Luengas A, Barona A, Hort C, Gallastegui G, Platel V, Elias A. A review of indoor air treatment technologies. *Reviews in Environmental Science and Bio-Technology*. 2015;14(3):499-522.
41. Zhong LX, Haghighat F. Photocatalytic air cleaners and materials technologies - Abilities and limitations. *Building and Environment*. 2015;91:191-203.
42. Siegel JA. Primary and secondary consequences of indoor air cleaners. *Indoor Air*. 2016;26(1):88-96.

43. Zhao P, Siegel JA, Corsi RL. Ozone removal by HVAC filters. *Atmospheric Environment*. 2007;41(15):3151-3160.
44. EPA. Residential Air Cleaners (Second Edition): A Summary of Available Information. 2009; <https://www.epa.gov/indoor-air-quality-iaq/residential-air-cleaners-second-edition-summary-available-information>. Accessed May 31, 2018.
45. Bliss S. *Best practices guide to residential construction: materials, finishes, and details*. London: Wiley; 2005.
46. Yu BF, Hu ZB, Liu M, Yang HL, Kong QX, Liu YH. Review of research on air-conditioning systems and indoor air quality control for human health. *Int J Refrig*. 2009;32:3-20.
47. Guieysse B, Hort C, Platel V, Munoz R, Ondarts M, Revah S. Biological treatment of indoor air for VOC removal: potential and challenges. *Biotechnol Adv*. 2008;26(5):398-410.
48. Waring MS, Siegel JA. The effect of an ion generator on indoor air quality in a residential room. *Indoor Air*. 2011;21(4):267-276.
49. Chen W, J.S. Z, Zhang ZZ. Performance of Air Cleaners for removing volatile organic compounds in indoor air. *ASHRAE Transactions*. 2005;111(1):1101-1114.
50. Jo W-K, Yang C-H. Granular-activated carbon adsorption followed by annular-type photocatalytic system for control of indoor aromatic compounds. *Separation and Purification Technology*. 2009;66(3):438-442.
51. Huang ZH, Kang F, Liang KM, Hao J. Breakthrough of methylethylketone and benzene vapors in activated carbon fiber beds. *J Hazard Mater*. 2003;98(1-3):107-115.

52. Kim K-J, Ahn H-G. The effect of pore structure of zeolite on the adsorption of VOCs and their desorption properties by microwave heating. *Microporous and Mesoporous Materials*. 2012;152:78-83.
53. Pei L, Zhou J, Zhang L. Preparation and properties of Ag-coated activated carbon nanocomposites for indoor air quality control. *Building and Environment*. 2013;63:108-113.
54. Hubbard HF, Coleman BK, Sarwar G, Corsi RL. Effects of an ozone-generating air purifier on indoor secondary particles in three residential dwellings. *Indoor Air*. 2005;15(6):432-444.
55. Waring MS, Siegel JA, Corsi RL. Ultrafine particle removal and generation by portable air cleaners. *Atmospheric Environment*. 2008;42(20):5003-5014.
56. EPA. Ozone Generators that are Sold as Air Cleaners: An Assessment of Effectiveness and Health Consequences 2014; https://www.epa.gov/sites/production/files/2014-08/documents/ozone_generator.pdf. Accessed May 18, 2018.
57. Hyttinen M, Rautio A, Pasanen P, et al. Airborne Infection Isolation Rooms – A Review of Experimental Studies. *Indoor and Built Environment*. 2011;20(6):584-594.
58. Mo JH, Zhang YP, Xu QJ, Lamson JJ, Zhao RY. Photocatalytic purification of volatile organic compounds in indoor air: A literature review. *Atmospheric Environment*. 2009;43(14):2229-2246.
59. Wang SB, Ang HM, Tade MO. Volatile organic compounds in indoor environment and photocatalytic oxidation: State of the art. *Environment International*. 2007;33(5):694-705.

60. Huang Y, Ho SSH, Lu YF, et al. Removal of Indoor Volatile Organic Compounds via Photocatalytic Oxidation: A Short Review and Prospect. *Molecules*. 2016;21(1).
61. Shiraishi F, Ishimatsu T. Toluene removal from indoor air using a miniaturized photocatalytic air purifier including a preceding adsorption/desorption unit. *Chemical Engineering Science*. 2009;64(10):2466-2472.
62. Hay SO, Obee T, Luo Z, et al. The viability of photocatalysis for air purification. *Molecules*. 2015;20(1):1319-1356.
63. Ourrad H, Thevenet F, Gaudion V, Riffault V. Limonene photocatalytic oxidation at ppb levels: Assessment of gas phase reaction intermediates and secondary organic aerosol heterogeneous formation. *Applied Catalysis B: Environmental*. 2015;168-169:183-194.
64. Fan X, Zhu TL, Wang MY, Li XM. Removal of low-concentration BTX in air using a combined plasma catalysis system. *Chemosphere*. 2009;75(10):1301-1306.
65. Liang Y, Wu Y, Sun K, et al. Rapid inactivation of biological species in the air using atmospheric pressure nonthermal plasma. *Environ Sci Technol*. 2012;46(6):3360-3368.
66. Bo Z, Yan JH, Li XD, Chi Y, Cen KF, Chéron BG. Effects of Oxygen and Water Vapor on Volatile Organic Compounds Decomposition Using Gliding Arc Gas Discharge. *Plasma Chemistry and Plasma Processing*. 2007;27(5):546-558.

67. Wan Y, Fan X, Zhu T. Removal of low-concentration formaldehyde in air by DC corona discharge plasma. *Chemical Engineering Journal*. 2011;171(1):314-319.
68. Vandenbroucke AM, Morent R, De Geyter N, Leys C. Non-thermal plasmas for non-catalytic and catalytic VOC abatement. *J Hazard Mater*. 2011;195:30-54.
69. Mista W, Kacprzyk R. Decomposition of toluene using non-thermal plasma reactor at room temperature. *Catalysis Today*. 2008;137(2-4):345-349.
70. Hoebe WFLM, Beckers FJCM, Pemen AJM, van Heesch EJM, Kling WL. Oxidative degradation of toluene and limonene in air by pulsed corona technology. *Journal of Physics D: Applied Physics*. 2012;45(5):055202.
71. Foarde KK. Development of a Method for Measuring Single-Pass Bioaerosol Removal Efficiencies of a Room Air Cleaner. *Aerosol Science and Technology*. 1999;30(2):223-234.
72. Hanley JT, Ensor DS, Smith DD, Sparks LE. Fractional aerosol filtration efficiency of in-duct ventilation air cleaners. *Indoor Air*. 1994;4:169-178.
73. Raynor PC, Chae SJ. The long-term performance of electrically charged filters in a ventilation system. *Journal of occupational and environmental hygiene*. 2004;1(7):463-471.
74. Davidson JH, McKinney PJ. Chemical Vapor Deposition in the Corona Discharge of Electrostatic Air Cleaners. *Aerosol Science and Technology*. 1998;29(2):102-110.
75. First MW, Banahan KF, Dumyah TS. Performance of Ultraviolet Germicidal Irradiation Lamps and Luminaires in Long-Term Service. 2007;3:181-188.

76. Metts TA, Batterman SA. Effect of VOC loading on the ozone removal efficiency of activated carbon filters. *Chemosphere*. 2006;62(1):34-44.
77. Ward M, Siegel J. Modeling filter bypass: impact on filter efficiency. *ASHRAE Transactions*. 2005;111:1091-1100.
78. IOM. Clearing the Air: Asthma and Indoor Air Exposures. 2000.
79. Reisman RE. Do air cleaners make a difference in treating allergic disease in homes? *Annals of allergy, asthma & immunology : official publication of the American College of Allergy, Asthma, & Immunology*. 2001;87(6 Suppl 3):41-43.
80. Wood RA. Air filtration devices in the control of indoor allergens. *Current allergy and asthma reports*. 2002;2(5):397-400.
81. Sublett JL, Seltzer J, Burkhead R, et al. Air filters and air cleaners: rostrum by the American Academy of Allergy, Asthma & Immunology Indoor Allergen Committee. *J Allergy Clin Immunol*. 2010;125(1):32-38.
82. Sublett JL. Effectiveness of air filters and air cleaners in allergic respiratory diseases: a review of the recent literature. *Current allergy and asthma reports*. 2011;11(5):395-402.
83. McDonald E, Cook D, Newman T, Griffith L, Cox G, Guyatt G. Effect of Air Filtration Systems on Asthma. *Chest*. 2002;122(5):1535-1542.
84. Fisk WJ. Health benefits of particle filtration. *Indoor Air*. 2013;23(5):357-368.
85. Karotki DG, Spilak M, Frederiksen M, et al. An indoor air filtration study in homes of elderly: cardiovascular and respiratory effects of exposure to particulate matter. *Environ Health*. 2013;12:116.
86. Padro-Martinez LT, Owusu E, Reisner E, et al. A Randomized Cross-over Air Filtration Intervention Trial for Reducing Cardiovascular Health Risks in

- Residents of Public Housing near a Highway. *Int J Environ Res Public Health*. 2015;12(7):7814-7838.
87. Brugge D, Simon MC, Hudda N, et al. Lessons from in-home air filtration intervention trials to reduce urban ultrafine particle number concentrations. *Building and Environment*. 2017;126:266-275.
 88. Park HK, Cheng KC, Tetteh AO, Hildemann LM, Nadeau KC. Effectiveness of air purifier on health outcomes and indoor particles in homes of children with allergic diseases in Fresno, California: A pilot study. *J Asthma*. 2017;54(4):341-346.
 89. Rice JL, Brigham E, Dineen R, et al. The feasibility of an air purifier and secondhand smoke education intervention in homes of inner city pregnant women and infants living with a smoker. *Environ Res*. 2018;160:524-530.
 90. Lanphear BP, Hornung RW, Khoury J, Yolton K, Lierl M, Kalkbrenner A. Effects of HEPA air cleaners on unscheduled asthma visits and asthma symptoms for children exposed to secondhand tobacco smoke. *Pediatrics*. 2011;127(1):93-101.
 91. Butz AM, Matsui EC, Breyse P, et al. A randomized trial of air cleaners and a health coach to improve indoor air quality for inner-city children with asthma and secondhand smoke exposure. *Archives of pediatrics & adolescent medicine*. 2011;165(8):741-748.
 92. Zhao D, Azimi P, Stephens B. Evaluating the Long-Term Health and Economic Impacts of Central Residential Air Filtration for Reducing Premature Mortality Associated with Indoor Fine Particulate Matter (PM_{2.5}) of Outdoor Origin. *Int J Environ Res Public Health*. 2015;12(7):8448-8479.

93. Zuraimi MS, Tan ZC. Impact of residential building regulations on reducing indoor exposures to outdoor PM_{2.5} in Toronto. *Building and Environment*. 2015;89:336-344.
94. Fisk WJ, Chan WR. Effectiveness and cost of reducing particle-related mortality with particle filtration. *Indoor Air*. 2017;27(5):909-920.
95. Aldred JR, Darling E, Morrison G, Siegel J, Corsi RL. Benefit-cost analysis of commercially available activated carbon filters for indoor ozone removal in single-family homes. *Indoor Air*. 2016;26(3):501-512.
96. McNamara ML, Thornburg J, Semmens EO, Ward TJ, Noonan CW. Reducing indoor air pollutants with air filtration units in wood stove homes. *Sci Total Environ*. 2017;592:488-494.
97. Henderson DE, Milford JB, Miller SL. Prescribed burns and wildfires in Colorado: impacts of mitigation measures on indoor air particulate matter. *J Air Waste Manag Assoc*. 2005;55(10):1516-1526.
98. Barn P, Larson T, Noullett M, Kennedy S, Copes R, Brauer M. Infiltration of forest fire and residential wood smoke: an evaluation of air cleaner effectiveness. *J Expo Sci Environ Epidemiol*. 2008;18(5):503-511.
99. Wheeler AJ, Gibson MD, MacNeill M, et al. Impacts of air cleaners on indoor air quality in residences impacted by wood smoke. *Environ Sci Technol*. 2014;48(20):12157-12163.
100. Chen AL, Cao QL, Zhou J, Yang B, Chang VWC, Nazaroff WW. Indoor and outdoor particles in an air-conditioned building during and after the 2013 haze in Singapore. *Building and Environment*. 2016;99:73-81.

101. Ward TJ, Semmens EO, Weiler E, Harrar S, Noonan CW. Efficacy of interventions targeting household air pollution from residential wood stoves. *J Expo Sci Environ Epidemiol*. 2017;27(1):64-71.
102. Allen RW, Carlsten C, Karlen B, et al. An air filter intervention study of endothelial function among healthy adults in a woodsmoke-impacted community. *Am J Respir Crit Care Med*. 2011;183(9):1222-1230.
103. Kajbafzadeh M, Brauer M, Karlen B, Carlsten C, van Eeden S, Allen RW. The impacts of traffic-related and woodsmoke particulate matter on measures of cardiovascular health: a HEPA filter intervention study. *Occup Environ Med*. 2015;72(6):394-400.
104. Noonan CW, Semmens EO, Smith P, et al. Randomized Trial of Interventions to Improve Childhood Asthma in Homes with Wood-burning Stoves. *Environmental Health Perspectives*. 2017.
105. Liu JC, Pereira G, Uhl SA, Bravo MA, Bell ML. A systematic review of the physical health impacts from non-occupational exposure to wildfire smoke. *Environ Res*. 2015;136:120-132.
106. Koenig JQ, Larson TV, Hanley QS, et al. Pulmonary function changes in children associated with fine particulate matter. *Environ Res*. 1993;63(1):26-38.
107. Larson TV, Koenig JQ. Wood smoke: emissions and noncancer respiratory effects. *Annu Rev Public Health*. 1994;15:133-156.
108. Fisk WJ, Chan WR. Health benefits and costs of filtration interventions that reduce indoor exposure to PM_{2.5} during wildfires. *Indoor Air*. 2017;27(1):191-204.

109. Lelieveld J, Evans JS, Fnais M, Giannadaki D, Pozzer A. The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature*. 2015;525(7569):367-371.
110. Cohen AJ, Brauer M, Burnett R, et al. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. *The Lancet*. 2017;389(10082):1907-1918.
111. Chao CY, Wong KK, Chen EC. Size Distribution of Indoor Particulate Matter in 60 Homes in Hong Kong. *Indoor Built Environment*. 2002;11:18-26.
112. He C. Contribution from indoor sources to particle number and mass concentrations in residential houses. *Atmospheric Environment*. 2004;38(21):3405-3415.
113. Fan D, Cao S, Zhang Y, et al. Preliminary study on indoor PM_{2.5} pollution levels of residents in Lanzhou during heating period. *Journal of Environmental Health*. 2014(3):232-234.
114. Wang Y, Cui L, Zhou L, et al. Investigation of indoor PM_{2.5} and PM_{1.0} in some houses in Nanjing. *J Environ Health*. 2013;10:900.
115. Kelly FJ, Zhu T. Transport solutions for cleaner air. *Science*. 2016;352:934-936.
116. Apte JS, Marshall JD, Cohen AJ, Brauer M. Addressing Global Mortality from Ambient PM_{2.5}. *Environ Sci Technol*. 2015;49(13):8057-8066.
117. Chen R, Zhao A, Chen H, et al. Cardiopulmonary benefits of reducing indoor particles of outdoor origin: a randomized, double-blind crossover trial of air purifiers. *J Am Coll Cardiol*. 2015;65(21):2279-2287.

118. Li H, Cai J, Chen R, et al. Particulate Matter Exposure and Stress Hormone Levels: A Randomized, Double-Blind, Crossover Trial of Air Purification. *Circulation*. 2017;136(7):618-627.
119. Cui X, Li F, Xiang J, et al. Cardiopulmonary effects of overnight indoor air filtration in healthy non-smoking adults: A double-blind randomized crossover study. *Environ Int*. 2018;114:27-36.
120. Chuang HC, Ho KF, Lin LY, et al. Long-term indoor air conditioner filtration and cardiovascular health: A randomized crossover intervention study. *Environ Int*. 2017;106:91-96.
121. Shao D, Du Y, Liu S, et al. Cardiorespiratory responses of air filtration: A randomized crossover intervention trial in seniors living in Beijing: Beijing Indoor Air Purifier Study, BIAPSY. *Sci Total Environ*. 2017;603-604:541-549.
122. Barn P, Gombojav E, Ochir C, et al. The effect of portable HEPA filter air cleaners on indoor PM_{2.5} concentrations and second hand tobacco smoke exposure among pregnant women in Ulaanbaatar, Mongolia: The UGAAR randomized controlled trial. *Science of the Total Environment*. 2018;615:1379-1389.
123. Salpietro CD, Gangemi S, Minciullo PL, et al. Cadmium concentration in maternal and cord blood and infant birth weight: a study on healthy non-smoking women. *Journal of perinatal medicine*. 2002;30(5):395-399.
124. Johnston JE, Valentiner E, Maxson P, Miranda ML, Fry RC. Maternal cadmium levels during pregnancy associated with lower birth weight in infants in a North Carolina cohort. *PLoS One*. 2014;9(10):e109661.

125. Wang H, Liu L, Hu YF, et al. Maternal serum cadmium level during pregnancy and its association with small for gestational age infants: a population-based birth cohort study. *Sci Rep*. 2016;6:22631.
126. Kelly FJ, Fussell JC. Size, source and chemical composition as determinants of toxicity attributable to ambient particulate matter. *Atmospheric Environment*. 2012;60:504-526.
127. Kelly FJ, Fussell JC. Role of oxidative stress in cardiovascular disease outcomes following exposure to ambient air pollution. *Free Radic Biol Med*. 2017;110:345-367.
128. Zhan Y, Johnson K, Norris C, et al. The influence of air cleaners on indoor particulate matter components and oxidative potential in residential households in Beijing. *Sci Total Environ*. 2018;626:507-518.
129. Day DB, Xiang J, Mo J, et al. Combined Use of an Electrostatic Precipitator and a HEPA Filter in Building Ventilation Systems: Effects on Cardiorespiratory Health Indicators in Healthy Adults. *Indoor Air*. 2017.
130. Sood A. Indoor fuel exposure and the lung in both developing and developed countries: an update. *Clinics in chest medicine*. 2012;33(4):649-665.
131. Smith K, R. . Fuel combustion air pollution. Exposure and health: the situation in developing countries. *Annu Rev Energy Environ*. 1993;18:529-566.
132. Balakrishnan K, Ghosh S, Ganguli B, et al. State and national household concentrations of PM_{2.5} from solid cookfuel use: results from measurements and modeling in India for estimation of the global burden of disease. *Environ Health*. 2013;12(1):77.

133. Kim KH, Jahan SA, Kabir E. A review of diseases associated with household air pollution due to the use of biomass fuels. *J Hazard Mater.* 2011;192(2):425-431.
134. Perez-Padilla R, Schilman A, Riojas-Rodriguez H. Respiratory health effects of indoor air pollution. *The international journal of tuberculosis and lung disease : the official journal of the International Union against Tuberculosis and Lung Disease.* 2010;14(9):1079-1086.
135. Lin HH, Suk CW, Lo HL, Huang RY, Enarson DA, Chiang CY. Indoor air pollution from solid fuel and tuberculosis: a systematic review and meta-analysis. *The international journal of tuberculosis and lung disease : the official journal of the International Union against Tuberculosis and Lung Disease.* 2014;18(5):613-621.
136. Haikerwal A, Akram M, Del Monaco A, et al. Impact of Fine Particulate Matter (PM_{2.5}) Exposure During Wildfires on Cardiovascular Health Outcomes. *J Am Heart Assoc.* 2015;4(7).
137. Baumgartner J, Smith KR, Chockalingam A. Reducing CVD Through Improvements in Household Energy: Implications for Policy-Relevant Research. *Glob Heart.* 2012;7(3):243-247.
138. Ezzati M, Baumgartner JC. Household energy and health: where next for research and practice? *Lancet.* 2017;389(10065):130-132.
139. Kalu N, Lufesi N, Havens D, Mortimer K. Implementation of World Health Organization Integrated Management of Childhood Illnesses (IMCI) Guidelines for the Assessment of Pneumonia in the Under 5s in Rural Malawi. *PLoS One.* 2016;11(5):e0155830.

140. Smith KR, McCracken JP, Weber MW, et al. Effect of reduction in household air pollution on childhood pneumonia in Guatemala (RESPIRE): a randomised controlled trial. *Lancet*. 2011;378(9804):1717-1726.
141. Mortimer K, Ndamala CB, Naunje AW, et al. A cleaner burning biomass-fuelled cookstove intervention to prevent pneumonia in children under 5 years old in rural Malawi (the Cooking and Pneumonia Study): a cluster randomised controlled trial. *Lancet*. 2017;389(10065):167-175.
142. Alexander D, Northcross A, Wilson N, et al. Randomized Controlled Ethanol Cookstove Intervention and Blood Pressure in Pregnant Nigerian Women. *Am J Respir Crit Care Med*. 2017;195(12):1629-1639.
143. McCracken JP, Smith KR, Diaz A, Mittleman MA, Schwartz J. Chimney stove intervention to reduce long-term wood smoke exposure lowers blood pressure among Guatemalan women. *Environ Health Perspect*. 2007;115(7):996-1001.
144. McCracken J, Smith KR, Stone P, Diaz A, Arana B, Schwartz J. Intervention to Lower Household Wood Smoke Exposure in Guatemala Reduces ST-Segment Depression on Electrocardiograms. *Environmental Health Perspectives*. 2011;119(11):1562-1568.
145. Olopade CO, Frank E, Bartlett E, et al. Effect of a clean stove intervention on inflammatory biomarkers in pregnant women in Ibadan, Nigeria: A randomized controlled study. *Environ Int*. 2017;98:181-190.
146. Barnes B, Mathee A, Thomas E. The impact of health behaviour change intervention on indoor air pollution indicators in the rural North West Province, South Africa. *Journal of Energy in Southern Africa*. 2011;22(3):35-44.

147. Weaver AM, Parveen S, Goswami D, et al. Pilot intervention study of household ventilation and fine particulate matter concentrations in a low-income Urban Area, Dhaka, Bangladesh. *American Journal of Tropical Medicine and Hygiene*. 2017;97(2):615-623.
148. OECD. How long do students spend in the classroom? 2012; [http://www.oecd.org/education/EAG2014-Indicator_D1_\(eng\).pdf](http://www.oecd.org/education/EAG2014-Indicator_D1_(eng).pdf) Accessed May 8, 2018.
149. Mazaheri M, Clifford S, Jayaratne R, et al. School children's personal exposure to ultrafine particles in the urban environment. *Environ Sci Technol*. 2014;48(1):113-120.
150. Reche C, Viana M, Rivas I, et al. Outdoor and indoor UFP in primary schools across Barcelona. *Sci Total Environ*. 2014;493:943-953.
151. Hodgson AT, Shendell DG, Fisk WJ, Apte MG. Comparison of predicted and derived measures of volatile organic compounds inside four new relocatable classrooms. *Indoor Air*. 2004;14 Suppl 8:135-144.
152. Mishra N, Bartsch J, Ayoko GA, Salthammer T, Morawska L. Volatile Organic Compounds: Characteristics, distribution and sources in urban schools. *Atmospheric Environment*. 2015;106:485-491.
153. Singer BC, Coleman BK, Destailats H, et al. Indoor secondary pollutants from cleaning product and air freshener use in the presence of ozone. *Atmospheric Environment*. 2006;40(35):6696-6710.
154. Landrigan PJ, Kimmel CA, Correa A, Eskenazi B. Children's health and the environment: public health issues and challenges for risk assessment. *Environ Health Perspect*. 2004;112(2):257-265.

155. McConnell R, Berhane K, Gilliland F, et al. Asthma in exercising children exposed to ozone: a cohort study. *Lancet*. 2002;359(9304):386-391.
156. Faustman EM, Silbernagel SM, Fenske RA, Burbacher TM, Ponce RA. Mechanisms underlying Children's susceptibility to environmental toxicants. *Environ Health Perspect*. 2000;108 Suppl 1:13-21.
157. Sundell J, Levin H, Nazaroff WW, et al. Ventilation rates and health: multidisciplinary review of the scientific literature. *Indoor Air*. 2011;21(3):191-204.
158. Mendell MJ, Eliseeva EA, Davies MM, et al. Association of classroom ventilation with reduced illness absence: a prospective study in California elementary schools. *Indoor Air*. 2013;23(6):515-528.
159. Wargocki P, Wyon D. The Effects of Moderately Raised Classroom Temperatures and Classroom Ventilation Rate on the Performance of Schoolwork by Children (RP-1257). *HVAC&R Research*. 2007;13(2):193-220.
160. Wargocki P, Wyon DP. The effects of outdoor air supply rate and supply air filter condition in classrooms on the performance of schoolwork by children (RP-1257). *Hvac&R Research*. 2007;13(2):165-191.
161. Bakó-Biró Z, Clements-Croome DJ, Kochhar N, Awbi HB, Williams MJ. Ventilation rates in schools and pupils' performance. *Building and Environment*. 2012;48:215-223.
162. Petersen S, Jensen KL, Pedersen AL, Rasmussen HS. The effect of increased classroom ventilation rate indicated by reduced CO₂ concentration on the performance of schoolwork by children. *Indoor Air*. 2016;26(3):366-379.

163. Twardella D, Matzen W, Lahrz T, et al. Effect of classroom air quality on students' concentration: results of a cluster-randomized cross-over experimental study. *Indoor Air*. 2012;22(5):378-387.
164. Haverinen-Shaughnessy U, Moschandreas DJ, Shaughnessy RJ. Association between substandard classroom ventilation rates and students' academic achievement. *Indoor Air*. 2011;21(2):121-131.
165. Mendell MJ, Eliseeva EA, Davies MM, Lobscheid A. Do classroom ventilation rates in California elementary schools influence standardized test scores? Results from a prospective study. *Indoor Air*. 2016;26(4):546-557.
166. Su CX, Lau J, Gibbs SG. Student absenteeism and the comparisons of two sampling procedures for culturable bioaerosol measurement in classrooms with and without upper room ultraviolet germicidal irradiation devices. *Indoor and Built Environment*. 2016;25(3):551-562.
167. Rosen CG, Richardson G. Would removing indoor air particulates in children's environments reduce rate of absenteeism } A hypothesis. *The Science of the Total Environment*. 1999;234:87-93.
168. Wargocki P, Wyon DP, Lynge-Jensen K, Bornehag CG. The effects of electrostatic particle filtration and supply-air filter condition in classrooms on the performance of schoolwork by children (RP-1257). *Hvac&R Research*. 2008;14(3):327-344.
169. Jhun I, Gaffin JM, Coull BA, et al. School Environmental Intervention to Reduce Particulate Pollutant Exposures for Children with Asthma. *The journal of allergy and clinical immunology In practice*. 2017;5(1):154-159.e153.

170. Wensing M, Schripp T, Uhde E, Salthammer T. Ultra-fine particles release from hardcopy devices: sources, real-room measurements and efficiency of filter accessories. *Sci Total Environ.* 2008;407(1):418-427.
171. He C, Morawska L, Taplin L. Particle emission characteristics of office printers. *Environ Sci Technol.* 2007;41:6039-6045.
172. Koivisto AJ, Hussein T, Niemelä R, Tuomi T, Hämeri K. Impact of particle emissions of new laser printers on modeled office room. *Atmospheric Environment.* 2010;44(17):2140-2146.
173. Fisk WJ, Mirer AG, Mendell MJ. Quantitative relationship of sick building syndrome symptoms with ventilation rates. *Indoor Air.* 2009;19(2):159-165.
174. Seppanen O, Fisk WJ, Lei QH. Ventilation and performance in office work. *Indoor Air.* 2006;16(1):28-36.
175. Seppanen OA, Fisk WJ. Summary of human responses to ventilation. *Indoor Air, Supplement.* 2004;14(SUPPL. 7):102-118.
176. Wargocki P. Perceived Air Quality, Sick Building Syndrome (SBS) Symptoms and Productivity in an Office with Two Different Pollution Loads. *Indoor Air.* 1999;9.
177. Wargocki P, Wyon DP, Sundell J, Clausen G, Fanger PO. The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms and productivity. *Indoor air.* 2000;10(4):222-236.
178. Wargocki P. Subjective perceptions, symptom intensity and performance: a comparison of two independent studies, both changing similarly the pollution load in an office. *Indoor Air.* 2002.

179. Wargocki P, Wyon DP, Fanger PO. The performance and subjective responses of call-center operators with new and used supply air filters at two outdoor air supply rates. *Indoor Air*. 2004;14 Suppl 8:7-16.
180. Tham KW, Willem HC. Temperature and ventilation effects on performance and neurobehavioral-related symptoms of tropically acclimatized call center operators near thermal neutrality. *ASHRAE Transactions*. 2005;3:663-672.
181. Tham KW, Willem HC, Sekhar SC, Wyon DP, Wargocki P, Fanger PO. *Temperature and ventilation effects on the work performance of office workers (study of a call center in the tropics)*. Vol 3. Singapore: Stallion Press; 2003.
182. Milton DK. Risk of Sick Leave Associated with Outdoor Air Supply Rate, Humidification, and Occupant Complaints. *Indoor Air*. 2000;10:212-.
183. Fisk WJ, Black D, Brunner G. Changing ventilation rates in U.S. offices: Implications for health, work performance, energy, and associated economics. *Building and Environment*. 2012;47:368-372.
184. Fisk WJ, Black D, Brunner G. Benefits and costs of improved IEQ in U.S. offices. *Indoor Air*. 2011;21(5):357-367.
185. Beko G, Clausen G, Weschler CJ. Is the use of particle air filtration justified? Costs and benefits of filtration with regard to health effects, building cleaning and occupant productivity. *Building and Environment*. 2008;43(10):1647-1657.
186. Montgomery JF, Reynolds CCO, Rogak SN, Green SI. Financial implications of modifications to building filtration systems. *Building and Environment*. 2015;85:17-28.
187. Ben-David T, Rackes A, Waring MS. Alternative ventilation strategies in US offices: Saving energy while enhancing work performance, reducing

- absenteeism, and considering outdoor pollutant exposure tradeoffs. *Building and Environment*. 2017;116:140-157.
188. Ben-David T, Waring MS. Interplay of ventilation and filtration: Differential analysis of cost function combining energy use and indoor exposure to PM_{2.5} and ozone. *Building and Environment*. 2018;128:320-335.
 189. Chan WR, Parthasarathy S, Fisk WJ, McKone TE. Estimated effect of ventilation and filtration on chronic health risks in U.S. offices, schools, and retail stores. *Indoor Air*. 2016;26(2):331-343.
 190. Mendell MJ, Smith AH. Consistent pattern of elevated symptoms in air-conditioned office buildings: a reanalysis of epidemiologic studies. *American journal of public health*. 1990;80(10):1193-1199.
 191. Woodard ED, Friedlander B, Leshner RJ, Font W, Kinsey R, Hearne FT. Outbreak of hypersensitivity pneumonitis in an industrial setting. *Jama*. 1988;259(13):1965-1969.
 192. Bernstein RS, Sorenson WG, Garabrant D, Reaux C, Treitman RD. Exposures to respirable, airborne *Penicillium* from a contaminated ventilation system: clinical, environmental and epidemiological aspects. *American Industrial Hygiene Association journal*. 1983;44(3):161-169.
 193. Menzies D, Popa J, Hanley JA, Rand T, Milton DK. Effect of ultraviolet germicidal lights installed in office ventilation systems on workers' health and wellbeing: double-blind multiple crossover trial. *Lancet*. 2003;362(9398):1785-1791.
 194. Croxford. A Study of Local Electrostatic Filtration and Main Pre-Filtration on Airborne and Surface Dust Levels in Air-Conditioned Office Premises. *Indoor Air*. 2000.

195. Wyon DP, Tham KW, Croxford B, Young A, Oreszczyn T. The effects on health and self-estimated productivity of two experimental interventions which reduced airborne dust levels in office premises. *Proceedings of Healthy Buildings*. 2000;1:641-646.
196. Skulberg KR, Skyberg K, Kruse K, et al. The effects of intervention with local electrostatic air cleaners on airborne dust and the health of office employees. *Indoor Air*. 2005;15(3):152-159.
197. Ma H, Shen H, Shui T, Li Q, Zhou L. Experimental study on ultrafine particle removal performance of portable air cleaners with different filters in an office room. *International Journal of Environmental Research and Public Health*. 2016;13 (1) (no pagination)(102).
198. Yoshida T. Estimation of absorption of aromatic hydrocarbons diffusing from interior materials in automobile cabins by inhalation toxicokinetic analysis in rats. *J Appl Toxicol*. 2010;30(6):525-535.
199. Muller D, Klingelhofer D, Uibel S, Groneberg DA. Car indoor air pollution - analysis of potential sources. *J Occup Med Toxicol*. 2011;6(1):33.
200. McNabola A, Broderick BM, Gill LW. Relative exposure to fine particulate matter and VOCs between transport microenvironments in Dublin: Personal exposure and uptake. *Atmospheric Environment*. 2008;42(26):6496-6512.
201. Boogaard H, Borgman F, Kamminga J, Hoek G. Exposure to ultrafine and fine particles and noise during cycling and driving in 11 Dutch cities. *Atmospheric Environment*. 2009;43(27):4234-4242.
202. Fruin S, Westerdahl D, Sax T, Sioutas C, Fine PM. Measurements and predictors of on-road ultrafine particle concentrations and associated pollutants in Los Angeles. *Atmospheric Environment*. 2008;42(2):207-219.

203. Cepeda M, Schoufour J, Freak-Poli R, et al. Levels of ambient air pollution according to mode of transport: a systematic review. *The Lancet Public health*. 2017;2(1):e23-e34.
204. Karanasiou A, Viana M, Querol X, Moreno T, de Leeuw F. Assessment of personal exposure to particulate air pollution during commuting in European cities--recommendations and policy implications. *Sci Total Environ*. 2014;490:785-797.
205. Knibbs LD, Cole-Hunter T, Morawska L. A review of commuter exposure to ultrafine particles and its health effects. *Atmospheric Environment*. 2011;45(16):2611-2622.
206. Gong L, Xu B, Zhu Y. Ultrafine Particles Deposition Inside Passenger Vehicles. *Aerosol Science and Technology*. 2009;43(6):544-553.
207. Xu B, Zhu Y. Quantitative Analysis of the Parameters Affecting In-Cabin to On-Roadway (I/O) Ultrafine Particle Concentration Ratios. *Aerosol Science and Technology*. 2009;43(5):400-410.
208. Xu B, Liu S, Liu J, Zhu Y. Effects of Vehicle Cabin Filter Efficiency on Ultrafine Particle Concentration Ratios Measured In-Cabin and On-Roadway. *Aerosol Science and Technology*. 2011;45(2):234-243.
209. HEI. Special Report 17: Traffic-related air pollution: a critical review of the literature on emissions, exposure and health effects 2010; <https://www.healtheffects.org/publication/traffic-related-air-pollution-critical-review-literature-emissions-exposure-and-health>. Accessed May 31, 2018.

210. Ghio AJ, Hall A, Bassett MA, Cascio WE, Devlin RB. Exposure to concentrated ambient air particles alters hematologic indices in humans. *Inhal Toxicol.* 2003;15(14):1465-1478.
211. Peters A, von Klot S, Heier M, et al. Exposure to traffic and the onset of myocardial infarction. *N Engl J Med.* 2004;351(17):1721-1730.
212. Adar SD, Gold DR, Coull BA, Schwartz J, Stone PH, Suh H. Focused exposures to airborne traffic particles and heart rate variability in the elderly. *Epidemiology.* 2007;18(1):95-103.
213. Riediker M, Williams R, Devlin R, Griggs T, Bromberg P. Exposure to particulate matter, volatile organic compounds, and other air pollutants inside patrol cars. *Environ Sci Technol.* 2003;37(10):2084-2093.
214. Laumbach RJ, Kipen HM. Acute effects of motor vehicle traffic-related air pollution exposures on measures of oxidative stress in human airways. *Ann N Y Acad Sci.* 2010;1203:107-112.
215. Shields KN, Cavallari JM, Hunt MJ, et al. Traffic-related air pollution exposures and changes in heart rate variability in Mexico City: a panel study. *Environ Health.* 2013;12:7.
216. Sarnat JA, Golan R, Greenwald R, et al. Exposure to traffic pollution, acute inflammation and autonomic response in a panel of car commuters. *Environ Res.* 2014;133:66-76.
217. Laumbach RJ, Kipen HM, Ko S, et al. A controlled trial of acute effects of human exposure to traffic particles on pulmonary oxidative stress and heart rate variability. *Part Fibre Toxicol.* 2014;11:45.

218. Rudell B, Wass U, Horstedt P, et al. Efficiency of automotive cabin air filters to reduce acute health effects of diesel exhaust in human subjects. *Occup Environ Med.* 1999;56(4):222-231.
219. Muala A, Sehlstedt M, Bion A, et al. Assessment of the capacity of vehicle cabin air inlet filters to reduce diesel exhaust-induced symptoms in human volunteers. *Environ Health.* 2014;13(1):16.
220. Hinds WC. Cardiovascular Health Effects of Fine and Ultrafine Particles during Freeway Travel. *Report Prepared for the California Air Resources Board and the California Environmental Protection Agency.* 2010.
221. Chuang HC, Lin LY, Hsu YW, Ma CM, Chuang KJ. In-car particles and cardiovascular health: an air conditioning-based intervention study. *Sci Total Environ.* 2013;452-453:309-313.
222. Lee J, Jo W. Exposure to airborne fungi and bacteria while commuting in passenger cars and public buses. *Atmospheric Environment.* 2005;39(38):7342-7350.
223. Kumar P, Lopez M, Fan W, Cambre K, Elston RC. Mold contamination of automobile air conditioner systems. *Annals of allergy.* 1990;64(2 Pt 1):174-177.
224. Sattar SA, Tetro J, Springthorpe VS. Impact of changing societal trends on the spread of infections in American and Canadian homes. *American journal of infection control.* 1999;27(6):S4-21.
225. Vonberg RP, Gastmeier P, Kenneweg B, Holdack-Janssen H, Sohr D, Chaberny IF. The microbiological quality of air improves when using air conditioning systems in cars. *BMC infectious diseases.* 2010;10:146.

226. Jo WK, Lee JH. Airborne fungal and bacterial levels associated with the use of automobile air conditioners or heaters, room air conditioners, and humidifiers. *Archives of environmental & occupational health*. 2008;63(3):101-107.
227. Wang YF, Tsai CH, Huang YT, et al. Size distribution of airborne fungi in vehicles under various driving conditions. *Archives of environmental & occupational health*. 2013;68(2):95-100.
228. Li J, Li M, Shen F, Zou Z, Yao M, Wu CY. Characterization of biological aerosol exposure risks from automobile air conditioning system. *Environ Sci Technol*. 2013;47(18):10660-10666.
229. Sattar SA, Zargar B, Wright KE, Rubino JR, Ijaz MK. Airborne Pathogens inside Automobiles for Domestic Use: Assessing In-Car Air Decontamination Devices Using *Staphylococcus aureus* as the Challenge Bacterium. *Applied and environmental microbiology*. 2017;83(10).
230. Brook RD, Rajagopalan S. "Stressed" About Air Pollution: Time for Personal Action. *Circulation*. 2017;136(7):628-631.
231. McCarthy MC, Ludwig JF, Brown SG, Vaughn DL, Roberts PT. Filtration effectiveness of HVAC systems at near-roadway schools. *Indoor Air*. 2013;23(3):196-207.
232. MacNeill M, Dobbin N, St-Jean M, et al. Can changing the timing of outdoor air intake reduce indoor concentrations of traffic-related pollutants in schools? *Indoor Air*. 2016;26(5):687-701.
233. Polidori A, Fine PM, White V, Kwon PS. Pilot study of high-performance air filtration for classroom applications. *Indoor Air*. 2013;23(3):185-195.

234. Hamilton M, Rackes A, Gurian PL, Waring MS. Perceptions in the U.S. building industry of the benefits and costs of improving indoor air quality. *Indoor Air*. 2016;26(2):318-330.
235. Peck RL, Grinshpun SA, Yermakov M, Rao MB, Kim J, Reponen T. Efficiency of portable HEPA air purifiers against traffic related combustion particles. *Building and Environment*. 2016;98:21-29.
236. P, Saari S, Kuuluvainen H, Kalliohaka T, Taipale A, Ronkko T. Performance of ventilation filtration technologies on characteristic traffic related aerosol down to nanocluster size. *Aerosol Science and Technology*. 2017;51(12):1398-1408.
237. Sim KM, Park HS, Bae GN, Jung JH. Antimicrobial nanoparticle-coated electrostatic air filter with high filtration efficiency and low pressure drop. *Sci Total Environ*. 2015;533:266-274.
238. Pierpaoli M, Giosue C, Ruello ML, Fava G. Appraisal of a hybrid air cleaning process. *Environmental science and pollution research international*. 2017;24(14):12638-12645.
239. Besov AS, Vorontsov AV, Parmon VN. Fast adsorptive and photocatalytic purification of air from acetone and dimethyl methylphosphonate by TiO₂ aerosol. *Applied Catalysis B: Environmental*. 2009;89(3-4):602-612.

Highlights

- HEPA filter or electret air purifiers reduce indoor PM_{2.5} concentrations by 30-80%.
- More consistent health improvements stem from studies in Asian megacity homes.
- Studies should now evaluate longer interventions in vulnerable people with real-time sensors.
- Modelling work reports significant health/performance/economic benefits of air filtration.