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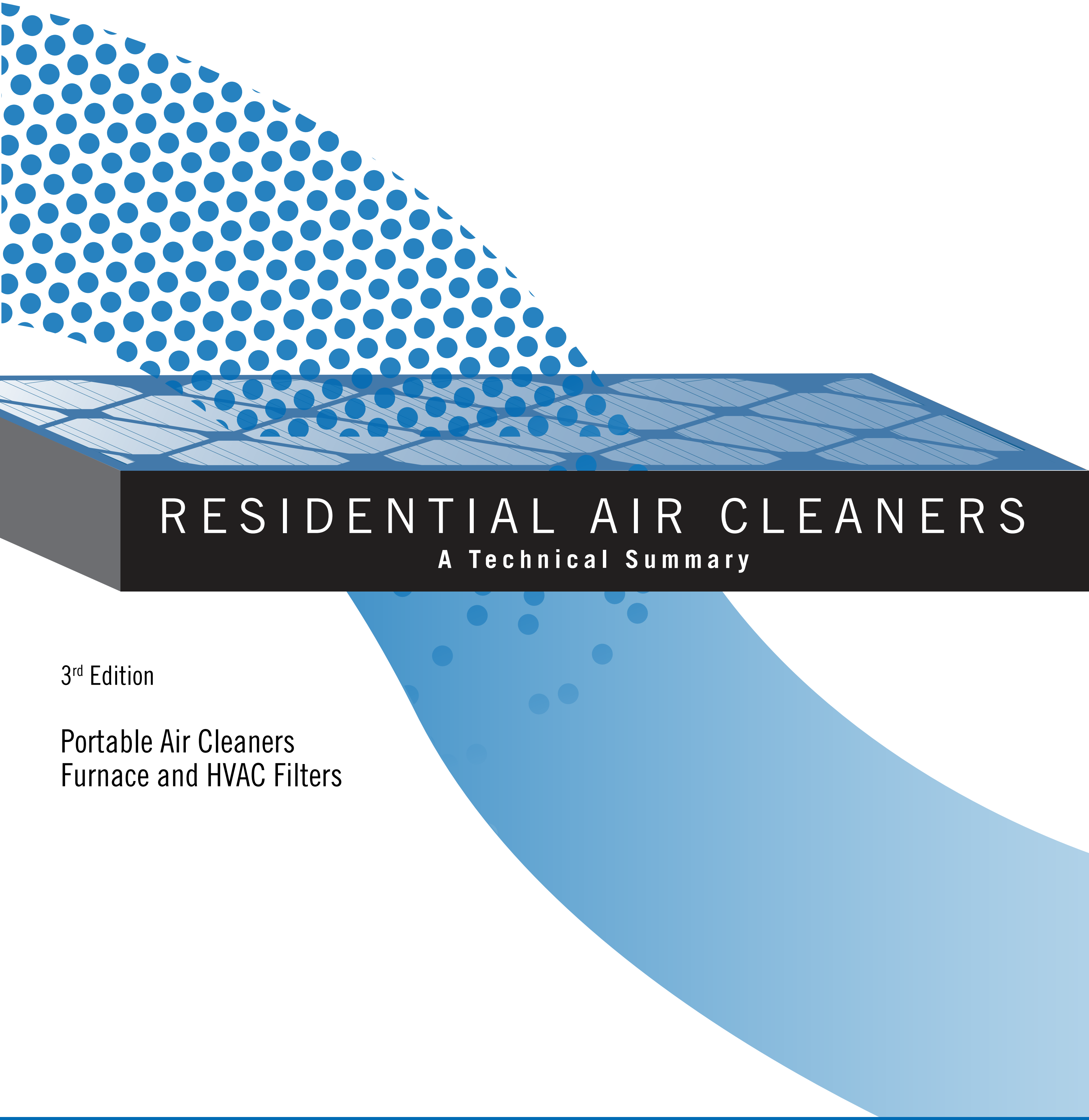

# RESIDENTIAL AIR CLEANERS

## A Technical Summary

3rd Edition

Portable Air Cleaners
Furnace and HVAC Filters

Indoor Air Quality (IAQ)

# FOREWORD

This document was developed by the U.S. Environmental Protection Agency (EPA), Office of Radiation and Indoor Air, Indoor Environments Division. It focuses on air cleaners for residential use; it does not address air cleaners used in large or commercial structures such as office buildings, schools, large apartment buildings, or public buildings. It should be particularly useful to residential housing design professionals, public health officials, and indoor air quality professionals. It may serve as a reference for anyone who designs, builds, operates, inspects, maintains, or otherwise works with buildings, heating, ventilating and air conditioning (HVAC) equipment, and/or portable air cleaners/sanitizers. This includes home services professionals, builders, remodelers, contractors, and architects.

In addition to providing general information about the types of pollutants affected by air cleaners, this document discusses the types of air-cleaning devices and technologies available, metrics that can be used to compare air-cleaning devices, the effectiveness of air-cleaning devices in removing indoor air pollutants, and information from intervention studies on the effects that air cleaners can have on health and on health markers.

A briefer companion publication, designed for the general public, **Guide to Air Cleaners in the Home**, is also available on the EPA website at www.epa.gov/indoor-air-quality-iaq/guide-air-cleaners-home.

# ACKNOWLEDGMENTS

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**EPA Establishment Number:** Federal pesticide law requires manufacturers of ozone generators to list an EPA establishment number on the product's packaging. This number merely identifies the facility that manufactured the product. Its presence does not imply that EPA endorses the product, nor does it imply that EPA has found the product to be safe or effective.

**Ozone generators that are sold as air cleaners** intentionally produce the gas ozone. No federal government agency has approved these devices for use in occupied spaces. For more information regarding ozone generators that are sold as air cleaners, see www.epa.gov/indoor-air-quality-iaq/ozone-generators-are-sold-air-cleaners.

**ENERGY STAR® labels:** Some portable air cleaners sold in the consumer market are ENERGY STAR® qualified. Please note the following disclaimer on their packaging: "This product earned the ENERGY STAR® by meeting strict energy efficiency guidelines set by the US EPA. EPA does not endorse any manufacturer claims of healthier indoor air from the use of this product."

**Disclaimer:** EPA neither certifies nor recommends particular brands of air filters or home air-cleaning devices including portable air cleaners or purifiers.

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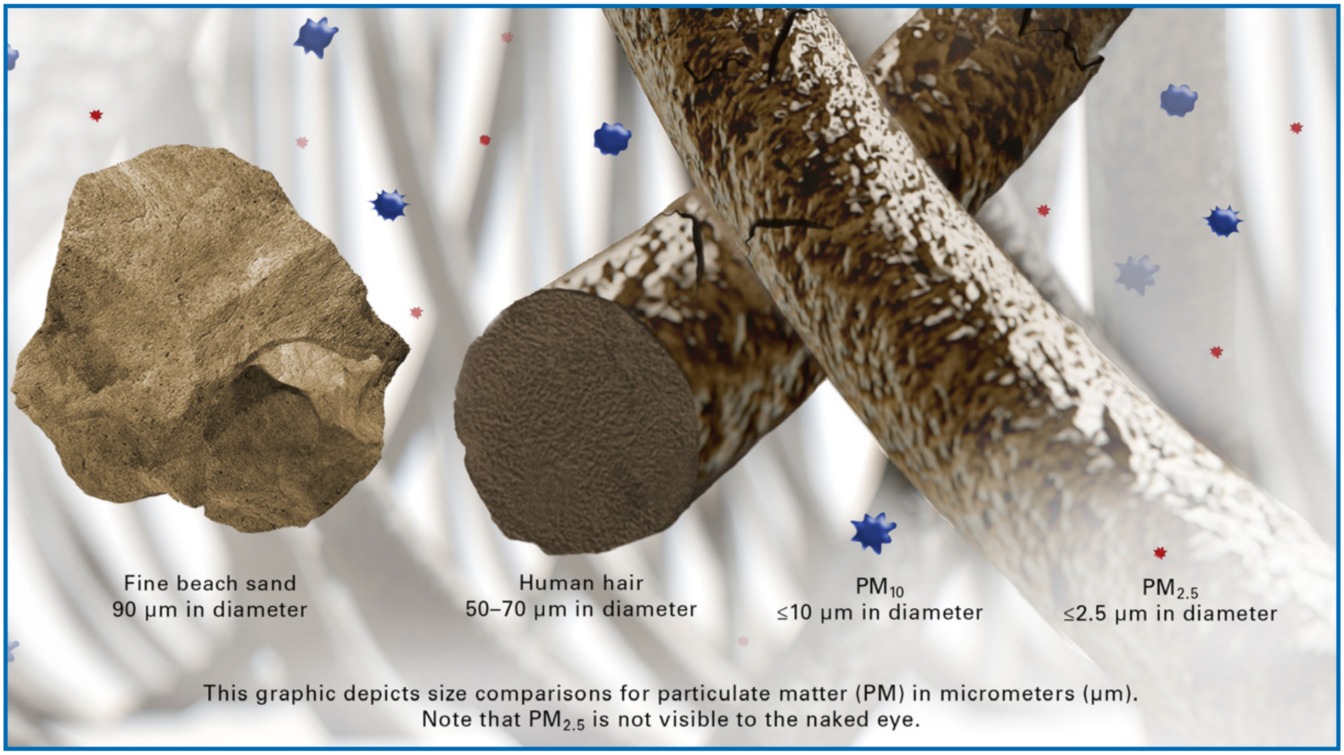

Figure 1. The image above depicts the size of fine ($PM_{2.5}$) and coarse ($PM_{10}$) particulate matter compared to a grain of sand and human hair.

## SUMMARY

Common indoor air pollutants include a wide variety of particulate matter (PM) and gaseous contaminants.

Airborne PM ranges in size from a few nanometers (nm) to tens of micrometers (μm) and is composed of both biological and non-biological matter. Indoor particles are commonly categorized into coarse particles ($PM_{10}$) at 10 μm to 2.5 μm diameter, fine particles ($PM_{2.5}$) at 2.5 μm or smaller, and ultrafine particles at 1 μm ($PM_1$) or smaller. Types of indoor particles, ranked generally from largest to smallest in size, include pollen, fibers, fungal spores and fragments, dust, pet dander, allergens, bacteria, vehicle exhaust infiltrated from outdoors, viruses, and emissions from smoking, cooking, and other combustion sources. Fine particles ($PM_{2.5}$) in outdoor air are known to cause adverse human health effects. Research on intervention studies summarized in this document confirms that fine particles are also a health concern for indoor exposures. To illustrate their relative sizes, Figure 1 depicts fine and coarse PM compared with human hair and sand.

Indoor biological particles include microorganisms, bacterial and fungal spores, and fragments of those spores. These particles can enter homes through multiple routes. Bacteria enter homes from outdoors and are emitted by human and pet occupants. Fungal spores primarily enter homes from outdoors and can grow on indoor surfaces when moisture is present. Fungal spores can grow inside heating, ventilating, and air-conditioning (HVAC) systems in the presence of condensation on cooling coils, drain pans, and internal thermal insulation or on the surfaces of the air-handling unit and ductwork.

Gaseous contaminants found indoors include organic and inorganic compounds. Organic compounds include a large number of volatile organic compounds (VOCs) emitted from building materials, architectural coatings, and consumer products; semivolatile organic compounds such as pesticides and fire retardants; and aldehydes such as formaldehyde from building materials and other sources. Inorganic compounds include carbon monoxide and nitrogen oxides emitted from combustion sources, ozone that infiltrates from outdoors, and radon that infiltrates from the soil. Note that EPA does not recommend air cleaning to reduce the health risks associated with radon and radon progeny.

The most economical and effective way to address indoor air pollution is usually to reduce or eliminate avoidable sources of pollutants and then to exhaust to the outdoors the unavoidable particles, gases, and excessive water vapor that come from normal indoor activities such as cooking, cleaning, and showering.

Beyond minimizing sources and exhausting indoor pollutants to outdoors, it is often possible to dilute pollutant concentrations by ventilating a home with cleaner outdoor air. However, opportunities for dilution using outdoor air are frequently limited by weather conditions or by contaminants in the outdoor air.

When source reduction and dilution are insufficient, air-cleaning devices can be useful. These fall into two general categories: **portable air cleaners** and **HVAC or furnace filters and other duct-mounted air cleaners** installed in a home's central HVAC system.

Portable air cleaners are stand-alone units that must be plugged in and turned on to operate. Portable air cleaners are also commonly called air purifiers or air sanitizers.

Furnace filters and other duct-mounted air cleaners are installed either at the base of the air-handling unit or upstream in return grilles. They will filter the air whenever the HVAC system fan is operating. They will not filter the air when the HVAC fan is not on, even if the air-cleaning device itself is on or activated.

Many portable and in-duct air cleaners combine more than one air-cleaning technology to accomplish their goals.

Two types of air-cleaning technologies are commonly used in duct-mounted and portable air cleaners to remove particles from the air: **fibrous media air filters** and **electronic air cleaners** (including **electrostatic precipitators [ESPs]** and **ionizers**). Fibrous media air filters remove particles by capturing them on fibrous filter materials. ESPs and ionizers remove particles by an active electrostatic charging process that requires electricity to charge particles that become attracted to and adhere to oppositely charged plates or other indoor surfaces. Another type of electronic air-cleaner technology, **ultraviolet germicidal irradiation (UVGI)**, is designed to reduce the number of viable airborne microorganisms by killing or deactivating them.

A number of air-cleaning technologies are designed to either remove gaseous air pollutants or convert them to (ideally) harmless byproducts using a combination of physical and chemical processes. Gas-phase air-cleaning technologies include **adsorbent media air filters** such as **activated carbon, chemisorbent media air filters, photocatalytic oxidation (PCO)**, **plasma**, and **intentional ozone generators sold as air cleaners**. Compared to the control of PM, gas-phase pollutant control is much more complex. Only adsorbent and chemisorbent media air filters have been shown to be effective gas-phase air cleaners for some gaseous pollutants without producing potentially harmful byproducts, although not all gaseous air pollutants are removed equally. Adsorbent media air filters have a finite capacity for adsorption and therefore must contain sufficient sorbent media for the application and must be replaced regularly.

To use portable air cleaners, furnace filters, or other duct-mounted air cleaners to good effect, it is crucial to understand the difference between two parameters that influence the performance of air-cleaning devices: **efficiency** and **effectiveness**. The efficiency of an air-cleaning device is a fractional measure of its ability to reduce the concentration of pollutants in the air that passes once through the device. The fractional efficiency of a device is measured in a laboratory, where all relevant variables are controlled. The effectiveness of an air-cleaning device or system is a measure of its ability to remove pollutants from the spaces it serves in real-world situations.

The most helpful parameter for understanding the effectiveness of portable air cleaners is the **clean air delivery rate (CADR)**, which is a measure of a portable air cleaner's delivery of relatively clean air, expressed in cubic feet per minute (cfm). The CADR is a product of the fractional removal efficiency for a particular pollutant and the airflow rate through the air cleaner. A higher CADR relative to the size of the room will increase the effectiveness of a portable air cleaner. A CADR can theoretically be generated for either gases or particles; however, current test standards only rate CADRs for the removal of particles.

The most helpful parameter for understanding the efficiency of furnace filters and other in-duct air cleaners is the fractional removal efficiency for the pollutant(s) it is designed to remove. The most widely used fibrous media air filter test method for duct-mounted particle filters in the United States is ASHRAE Standard 52.2, which evaluates the removal efficiency for particles 0.3 to 10 μm in diameter. Results are reported as a **Minimum Efficiency Reporting Value (MERV)** ranging from MERV 1 to MERV 16 based on the average removal efficiency across three particle size ranges: 0.3–1 μm, 1–3 μm, and 3–10 μm. Other commercially common proprietary test metrics for in-duct air filters include the **Microparticle Performance Rating (MPR)** and **Filter Performance Rating (FPR)**; these are proprietary rating systems. In general, the higher the filter rating, the higher a filter's removal efficiency for at least one particle size range. Although standards for testing the removal efficiency of gas-phase in-duct air cleaners also exist, they are not yet widely used and reported.

## Research Overview

A comprehensive review of current research (as of early 2018) indicates the following:

### *Air Cleaners and Indoor Air Quality*

- **Intervention studies of air cleaners operating in homes have consistently found statistically significant reductions in indoor exposures to indoor $PM_{2.5}$, $PM_{10}$, and/or particle number counts with the use of portable air cleaners, whereas levels of allergens in dust were only sometimes affected. Studies of air cleaners in homes that address gas-phase pollutants are extremely limited, and consistent reductions have not been demonstrated.**

Most studies have reported reductions in PM exposures with the use of high-efficiency particulate air (HEPA) or other high-efficiency portable air cleaners on the order of approximately 50 percent or higher. Only a few studies investigated the use of central in-duct particle filtration, and reductions in PM exposures were not as consistent, in part because of typically low system runtimes. Only a few studies have investigated the effects of gas-phase air cleaners in homes.

### *Air Cleaners and Health*

- **Most air cleaner intervention studies have found statistically significant associations between the introduction and use of portable air cleaners in homes and at least one measure or marker of improved health outcome, although the improvements were typically modest.**

Specific health outcomes or markers of health outcomes that have been correlated with portable air cleaner use in homes include allergy and asthma symptoms and several markers of cardiovascular effects that are commonly associated with exposure to PM of both indoor and outdoor origin. However, most of the health improvements were relatively small in magnitude and, when multiple outcomes were measured, typically only a fraction of health outcomes or biomarkers of health outcomes were improved. To date, no studies were found that systematically investigated whether using sorbent media gas-phase filtration, PCO, plasma, or ionizer air cleaners in homes or other buildings has a positive effect on the health of occupants.

### *Air Cleaners Must be Operated to be Effective*

The amount of time that an air cleaner operates influences its ability to reduce pollutant concentrations and associated health risks. If they are not operating, they will not be effective. This limits the effectiveness of both categories of air cleaners.

Typically, air cleaning is limited to less than 25 percent of the 8,760 hours in a year. In the case of portable air cleaners, some intervention studies show that after an initial period of use and enthusiasm, the device is often not maintained properly, operated less frequently, turned off completely, or placed into storage, often because of occupant annoyance related to noise or other factors.

### *Portable Air Cleaners and Noise*

- **Operating noise can influence whether occupants use portable air cleaners. Portable air cleaner performance ratings are determined at maximum airflow and therefore typically maximum noise levels. Quantified noise levels are seldom shown on consumer product packaging.**

Objectionable noise levels can reduce usage and discourage the placement of air cleaners in sleeping spaces where people spend a large percentage of their time. Since noise is seldom quantified or reported in a standardized manner on consumer packaging, it can be challenging to compare devices on the basis of noise rating. The CADR label on product packaging is typically the highest CADR achievable, which generally occurs at the highest airflow setting. At lower airflow settings an air cleaner may have lower noise production, but it will also be less effective at pollutant removal.

### *Furnace Filters and Fine Particulate Matter*

- **Furnace filters with a MERV 13 and above rating require at least 50 percent removal efficiency for 0.3–1 µm particles.**

Particle filters that are tested following ASHRAE Standard 52.2 test method—the most widely used filter test standard in the United States—are not required to report their fractional removal efficiency for the small particles that contribute most to indoor $PM_{2.5}$ concentrations unless they achieve a MERV 11 or above. MERV 11 filters must achieve at least 20 percent removal efficiency for 0.3–1 µm particles, while only MERV 13 and above require at least 50 percent removal efficiency for 0.3–1 µm particles. Because high concentrations of fine particles are associated with health risks—especially in sensitive populations such as children, the elderly, and those with existing respiratory health problems like asthma and allergies—**EPA recommends that consumers who are concerned about small particles choose furnace filters with at least a MERV 13 rating or as high a MERV rating as the system fan and filter track can accommodate.** However, selection of any increased efficiency media furnace filter—including MERV 13 to 16 or HEPA—must also take into account the compatibility of the filter with the existing ducted HVAC system to ensure that airflow will not be impeded by the added resistance of the filter. **To accommodate a higher efficiency furnace filter in an existing home, a trained professional may need to modify the system.**

### *Furnace Filters and HVAC System Operation*

- **The effectiveness of furnace filters and other duct-mounted air cleaners is limited by the operating hours of fan in the HVAC system in which they are installed and whether they are properly maintained.**

In some locations, such as where air-conditioning is not needed or where air-conditioning is provided by window air conditioners, central HVAC systems may not operate at all or not for many months of the year. Low system runtimes can greatly limit the effectiveness of a furnace filter or other in-duct air cleaner simply by not passing air through it long enough to yield substantial reductions in indoor pollutant concentrations. Because of these limitations in system operation, experimental data and theoretical predictions indicate that for particle removal, medium-high efficiency furnace filters, such as some MERV 12 filters and most MERV 13 filters, are likely to be almost as effective as HEPA filters in reducing the concentrations of most sizes of indoor particles, including those linked to health effects. However, field studies have not yet confirmed that central HVAC system fans operate long enough for high-efficiency furnace filters and other duct-mounted air cleaners to reduce concentrations of indoor particles and gases sufficiently to demonstrably improve health outcomes. Additionally, no filter or air cleaner, regardless of its rating, will be effective if it is not properly maintained. Manufacturers provide guidance on how often filters must be replaced, cleaned, or otherwise serviced to ensure that they perform as intended.

### *Byproduct Emissions From Some Air Cleaner Technologies*

Some air cleaning technologies may emit potentially harmful byproducts during operation. For example, PCO air cleaners have been shown to generate formaldehyde, acetaldehyde, nitrogen dioxide, and carbon monoxide. Plasma air cleaners have been shown to form particles, ozone, carbon monoxide, and formaldehyde as byproducts. Additionally, many electronic air cleaner devices—including portable and duct-mounted ESPs, ionizers or ion generators, uncoated UVGI lamps, and other products that advertise the use of “plasma,” “ions,” and other similar terms—can generate high amounts of ozone. Ozone is a well-documented lung irritant. Intentional ozone generators should not be used in occupied spaces.

**No federal agency has approved the use in occupied spaces of air cleaners that intentionally emit ozone.** Ozone and ozone-generating devices are also discussed in more detail in EPA’s “Ozone Generators that are Sold as Air Cleaners,” which can be found at www.epa.gov/indoor-air-quality-iaq/ozone-generators-are-sold-air-cleaners.

The California Air Resources Board mandates device testing for ozone production following UL Standard 867, but currently no national regulation or voluntary program exists that requires independent measurement and certification that the production of ozone from these devices does not reach hazardous levels. Apart from California Air Resources Board requirements, no U.S. standard, regulation, or industry consensus program requires measurement and disclosure of ozone production by air cleaners.

## Selecting and Using Portable and In-Duct Air Cleaners

Research suggests that when selecting and using air-cleaning devices, consumers can make more informed decisions by keeping in mind these practical factors:

- **Types of air cleaners with documented improvements in indoor air quality and health effects:** Field-testing and simulation studies show that high-efficiency furnace filters (e.g., MERV 13 and above), duct-mounted air cleaners, and portable air cleaners with high CADRs can substantially reduce levels of airborne particles and, in some cases, gaseous pollutants in a home. High-efficiency fibrous media filters (including HEPA-rated filters for portable air cleaners, and MERV 13 and above furnace filters for central HVAC systems) and sorbent media filters with adequate amounts of media are generally most effective and have the fewest limitations or adverse consequences. Furthermore, studies have shown that portable air cleaners with CADRs that are adequate for the size of the space can reduce some adverse health effects and related biomarkers associated with PM exposure in sensitive populations such as children, people with asthma and allergies, and the elderly, as well as in healthy individuals.
- **Noise from portable air cleaners:** Noise is an important issue with many portable air cleaners, particularly when operating at higher airflow rates, because users often turn them off to avoid the noise. Noise can be an important factor when selecting an air cleaner.
- **Sizing portable air cleaners:** Portable air cleaners should have a CADR that is large enough for the size of the room in which it is operated. For example, an air cleaner that has a CADR of 250 for dust particles can reduce dust particle levels to the same concentration as would be achieved by adding 250 cfm of clean air to the space in question. Units tested according to procedures established by the Association of Home Appliance Manufacturers (AHAM) carry an AHAM-Verified® label that suggests the appropriate maximum room size for the device. The size rating is intended to provide an 80 percent reduction in particle levels (at equilibrium conditions) as compared to levels without the air cleaner operating. Portable air cleaners often achieve a high CADR by using a HEPA filter, although other technologies can also achieve a high CADR.
- **Placement of portable air cleaners:** Place portable air cleaners where the most vulnerable occupants spend most of their time. Infants, elders, and asthmatics are more vulnerable than healthy adults. A bedroom can be a good place to locate and operate an air cleaner. Also, place any portable air cleaners so that their clean air reaches the breathing zone of occupants as directly as possible, without obstruction from furnishings or addition of fine particles by common sources such as printers. Otherwise, “short-circuiting” could occur, in which the output flow does not reach the intended area. Additionally, manufacturer instructions may indicate that the air cleaner be placed a certain distance from any objects that might obstruct airflow.
- **Consider the sequence of air-cleaning technologies in an air cleaner:** Many air cleaners combine two or more air-cleaning technologies to accomplish multiple goals. The order in which individual technologies are combined with respect to the direction of airflow can be very important for determining its effectiveness. For example, an activated carbon filter installed upstream of an air-cleaner technology that generates gaseous byproducts would be less effective

in limiting indoor concentrations of those byproducts than an activated carbon filter installed downstream.

- **Installation of furnace filters and duct-mounted air cleaners:** Furnace filters and duct-mounted air cleaners must have easy access for regular filter replacement, inspection, and any required maintenance. Some furnace filters and duct-mounted air cleaners may also require HVAC system modifications for their installation, such as a wider filter track or additional electrical power. **Any system modification and installation should be done by a trained professional.**
- **Monitoring and control:** Some air cleaners have monitoring and control features, such as the ability to schedule operation, control by a smartphone, or monitor filter status. To the extent that these features result in more operating hours when the spaces are actually occupied, and more frequent cleaning or replacement of filter media, they should be able to improve the air-cleaning effectiveness of the device.
- **Pollutant sensors and indicators:** Some consumer-grade air cleaners now include pollutant sensors or indicators of some indoor pollutant concentrations, but to date no studies were found that have investigated their performance over time. Although they may not be as accurate as more expensive professional grade sensors, they may provide useful indicators of relative pollutant concentrations. These indicators could provide occupants with immediate visual feedback that their current activities are either increasing or reducing pollutant concentrations. These indicators could also be used to automatically control the operation of the device in response to real-time pollutant concentrations.
- **Removal of moldy odors:** Some air cleaners can remove moldy odors and airborne mold or bacterial spores and their fragments. However, air cleaners will not prevent mold growth, nor will they rid the house of mold. To permanently remove the source of moldy odors, it is necessary to remove mold growth and eliminate the sources of moisture that allow it to grow.
- **Removal of chemical odors:** Air cleaners that are designed only to remove particles cannot control gaseous pollutants, including those that contribute to chemical odors. For example, air cleaners designed only to remove particles will not remove all of the odorous compounds or the carcinogenic gas-phase pollutants from tobacco smoke.
- **Costs:** Cost may also be a consideration in using air cleaners. Major costs include the initial purchase price, maintenance (such as cleaning or replacing filters and parts), and operation (such as electricity costs). The cost of professional installation of an upgraded media filter or an electronic air filter in the HVAC system must also be considered. The most effective air cleaners, those with high airflow rates and efficient pollutant capture systems, are generally the most expensive. Maintenance and operating costs vary depending on the device, and these costs should be considered when choosing a particular unit. Operating cost is important because air cleaning is an ongoing process, and units require filter replacement or cleaning and other maintenance to remain effective. Although central HVAC systems can distribute filtered air to more places throughout the house, they commonly cost approximately twice as much to operate as a typical portable HEPA air cleaner operating for the same amount of time.

## INTRODUCTION

The best way to address residential indoor air pollution usually is to control or eliminate the source of the pollutants and to ventilate the home with clean outdoor air. But source control is sometimes impractical as a remedial measure, and ventilation may be limited by weather conditions or the levels of contaminants in the outdoor air.

If the usual methods of managing indoor air pollutants are insufficient, air-cleaning devices may be useful. Air filters and other air-cleaning devices are designed to remove pollutants from indoor air. They can be installed in the ductwork of most home HVAC systems to clean the air in the entire house, or the same technology can be used in portable air cleaners that clean the air in single rooms or specific areas. Most air-cleaning devices are designed to remove particles or gases, but some destroy, degrade, or transform contaminants that pass through them.

This publication focuses on air cleaners for residential use; it does not address air cleaners used in large or commercial structures such as office buildings, schools, large apartment buildings, or public buildings. It should be particularly useful to residential housing design professionals, public health officials, and indoor air quality professionals. In addition to providing general information about the types of pollutants affected by air cleaners, this document discusses:

- The types of air-cleaning devices and technologies available
- Metrics that can be used to compare air-cleaning devices
- The effectiveness of air-cleaning devices in removing indoor air pollutants
- Information from intervention studies on the impact that air cleaners can have on health and on health markers
- Additional factors to consider when deciding whether to use an air-cleaning device and, if so, which type

## INDOOR AIR POLLUTANTS

Two main categories of indoor air pollutants can affect the quality of air in a home: PM and gaseous pollutants.

**PM** can be composed of microscopic solids, liquid droplets, or a mixture of solids and liquid droplets suspended in air. Also known as particle pollution, PM can be made up of a number of components, including acids such as nitric and sulfuric acids, organic chemicals, metals, soil or dust particles, and biological contaminants. Among the particles that can be found in a home are:

- Dust, as solid PM
- Fumes and smoke, which are mixtures of solid and liquid particles
- Particles of outdoor origin, which are complex mixtures of solid and liquid particles
- Biological contaminants, including viruses, bacteria, pollen, fungal spores and fragments, dust mite and cockroach body parts and droppings, and animal dander

Particles exist in a wide range of sizes. Small particles can be ultrafine, fine, or coarse. Of primary concern from a health standpoint are fine particles that have a diameter of 2.5 μm or less (i.e., $PM_{2.5}$). These fine particles can be inhaled, and they penetrate deep into the lungs where they may cause acute or chronic health effects. Ultrafine particles, smaller than 0.1 μm (100 nm) in diameter, penetrate far into the alveolar region of the lungs and can translocate to the brain via the olfactory nerve. Coarse particles, between 2.5 and 10 μm in diameter (i.e., $PM_{2.5\text{-}10}$), usually do not penetrate as far into the lungs; they tend to settle in the upper respiratory tract where they can irritate the eyes, nose, and throat. Large particles are greater than 10 µm in diameter, or roughly one-sixth the width of a human hair. They can be trapped in the nose and throat and expelled by coughing, sneezing, or swallowing.

Fine particles are directly emitted into indoor air from a variety of sources including tobacco smoke, chimneys and flues that are improperly installed or maintained, unvented combustion appliances such as gas stoves and kerosene or gas space heaters, woodstoves, fireplaces, electric stoves, printers, incense, candles, and ozone reactions with emissions from indoor sources of organic compounds. Fine particles also include outdoor particles that infiltrate indoors (such as traffic emissions or wildfire smoke), viruses, and some bacteria.

Among the smaller biological particles found in a home are some bacteria, mold and bacterial fragments and spores, some plant allergens, a significant fraction of cat and dog dander, and a small portion of dust mite body parts and droppings. Larger particles include dust, pollen, some fungal fragments and spores, a smaller fraction of cat and dog dander, a significant fraction of dust mite body parts and cockroach body parts and droppings, and human skin flakes.

Biological particles such as bacteria and fungal spores and fragments enter a house by various routes, including open windows, joints and cracks in walls, and on clothing and shoes, food, or pets. Fungi and some bacteria can be found in either the vegetative or the spore stage of their life cycle. Vegetative bacteria and fungi are in the growth and reproductive stage; they are not spores. Some bacteria form spores, an inactive stage characterized by a thick protective coating, to survive harsh environmental conditions. Most fungi produce tiny spores to reproduce. Fungal spores will enter the growth and reproductive stage of their life cycle in locations where sufficient moisture and nutrients are available, such as on basement walls, in refrigerators, on HVAC coils, on air filters, and in drip pans.

**Gaseous pollutants** include inorganic gases such as combustion gases (e.g., carbon monoxide and nitrogen dioxide), ozone, and organic chemicals that are not attached to particles. Hundreds of different gaseous pollutants have been detected in indoor air.

Sources of indoor combustion gases include combustion appliances such as gas stoves, tobacco smoke, and vehicles from which exhaust infiltrates from attached garages or the outdoors. Sources of ozone include infiltration from outdoors and intentional or unintentional generation by laser printers and some devices sold as air cleaners.

Sources of airborne gaseous organic compounds include tobacco smoke; building materials and furnishings; and products such as paints, adhesives, dyes, solvents, caulks, cleaners, deodorizers, cleaning chemicals, waxes, hobby and craft materials, and pesticides. Organic compounds may also come from cooking; human, plant, and animal metabolic processes; and outdoor sources.

Radon is a colorless, odorless, radioactive gas that can be found in indoor air. It comes from radium in natural sources such as rock, soil, ground water, natural gas, and mineral building materials (e.g., granite countertops). As uranium breaks down, it releases radon, which in turn produces short-lived radioactive particles called “progeny,” some of which attach to dust particles. Radon progeny may deposit in the lungs and irradiate respiratory tissues. Radon typically moves through the ground and into a home through cracks and holes in the foundation. Radon may also be present in well water and can be released into the air when that water is used for showering and other household activities. In a small number of homes, building materials also can give off a significant amount of radon. EPA does not recommend air cleaning to reduce the health risks associated with radon and radon progeny.

## THREE STRATEGIES TO REDUCE INDOOR AIR POLLUTANTS

Three basic strategies to reduce pollutant concentrations in indoor air are source control, ventilation, and air cleaning.

**Source control** eliminates individual sources of pollutants or reduces their emission. It is usually the most effective strategy for reducing pollutants. Many sources of pollutants in the home can be avoided or removed (U.S. EPA 1995). For example, solid wood or alternative materials can be used in place of pressed wood products that are likely to be significant sources of formaldehyde. Smokers can smoke outdoors. Combustion appliances can be adjusted to decrease their emissions. Any areas contaminated by microbial growth should not only be cleaned and dried, but the underlying moisture problem should also be addressed.

**Ventilation** with outdoor air is also a strategy for diluting indoor air pollutant concentrations, provided that the outdoor air is relatively clean and dry or that it can be made so through mechanical means such as filtering. Outdoor air enters buildings in three ways. Small amounts of air are constantly entering by infiltration through the building enclosure. Larger amounts enter when windows and doors are left open for extended periods and can also be brought in by continuous supply or exhaust fans.

Most existing residential forced air heating systems and air-conditioning systems in the United States do not intentionally bring outdoor air into the house. However, residential HVAC design practice is changing. Current consensus standards and some residential buildings codes have recently changed to encourage or require deliberate and continuous outdoor air ventilation. To date, however, no national regulatory requirement or standard exists that requires removal of fine particles or gases from outdoor air used for continuous ventilation.

Local exhausting of air from the kitchen when cooking and from bathrooms when showering provides occupants an effective way to achieve reductions in the otherwise unavoidable high concentrations of water vapor, particles, and gases that result from daily household activity. Note, however, that the act of exhausting air from the bathrooms or kitchen pulls outdoor air into that home. So to gain the greatest benefit from exhaust, it is important any replacement ventilation air be clean and dry.

**Air cleaning** has proven useful when used along with source control and ventilation, although it is not a substitute for either method. Air cleaning alone cannot ensure adequate indoor air quality where significant sources are present, when exhaust and outdoor air ventilation are insufficient, or when the operating hours of an air-cleaning device are not sufficient to reduce indoor pollutant concentrations. The remainder of this document focuses on air cleaning.
For more information, see also the *ASHRAE Position Document on Filtration and Air Cleaning* (ASHRAE 2015a).

## TYPES OF AIR CLEANERS

There are two basic categories of air cleaners: portable air cleaners, and HVAC/furnace filters and other duct-mounted air cleaners. Stand-alone portable air cleaners are generally designed to filter or clean the air in a single room or area. Furnace filters and other duct-mounted air cleaners are installed in a home's central HVAC system and can provide filtered or cleaned air to many parts of a home, but only when the HVAC system fan is operating.

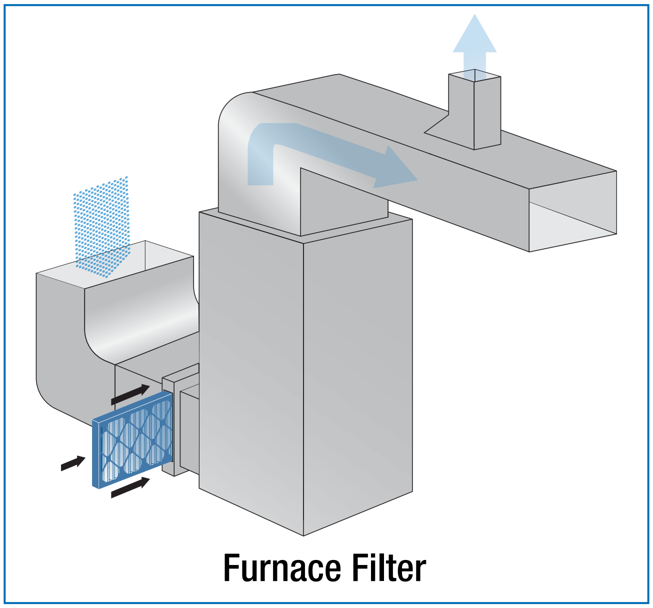

Figure 2. This graphic depicts the installation of an air filter in a typical furnace.

Figure 3. This image shows an example of a typical portable air cleaner installation.

**Furnace filters and other duct-mounted air-cleaning devices** are typically installed in the return ducts of HVAC systems, as shown in Figure 2. They are installed either at the base of the air-handling unit or upstream in return grilles. The typical low-efficiency furnace air filter is a simple air cleaner that captures particles in the airstream to protect fan motors, heat exchangers, and ducts from soiling. Such filters are not designed to improve indoor air quality, but the HVAC system can be upgraded by using more efficient air filters to remove additional particles. Other air-cleaning devices such as ESPs, UVGI air cleaners, and a number of gas-phase filters are sometimes used in the ductwork of home HVAC systems. These air-cleaning technologies are described in more detail in subsequent sections.

**Portable air cleaners** are available as small tabletop units and larger console units. They are used to clean the air in a single room, as shown in Figure 3, but not in an entire house. The units can be moved to wherever continuous and localized air cleaning is needed. Larger console units may be useful in houses that are not equipped with forced air heating and/or air-conditioning systems. Portable air cleaners are also commonly called air purifiers or air sanitizers.

The basic components of a portable air cleaner include a filter or other air cleaning technology and a fan that propels air through that filter/air cleaner. Portable air cleaners may also have a panel filter with bonded fine granules of activated carbon, an activated carbon filter encased in a frame, or other sorbent mixtures to remove gases and odorous compounds. Beyond simple filtration and sorption of odorous compounds using carbon, some portable air cleaners add further technologies to increase pollutant removal, inactivation, or conversion. Technologies can include electrostatic precipitation, ion generation, or ultraviolet (UV) lamps in combination with catalysts for photocatalytic conversion of gaseous contaminants. Some units marketed as having the quietest operation may have no fan; however, units that do not have a fan typically are much less effective than units that have a fan.

## UNDERSTANDING EFFICIENCY VERSUS EFFECTIVENESS

To use portable air cleaners, furnace filters, or other duct-mounted air cleaners to good effect, it is crucial to understand the difference between two parameters that influence the performance of air-cleaning devices: **efficiency** and **effectiveness**.

**Efficiency:** The efficiency of an air-cleaning device is a fractional measure of its ability to reduce the concentration of pollutants in the air that passes once through the device. The efficiency of a device is measured in a laboratory, where all relevant variables are controlled. Efficiency ratings allow comparison between different devices when they are tested under the same conditions (e.g., the same flow rate, air speed, pollutant concentrations).

**Effectiveness:** The effectiveness of an air-cleaning device or system is a measure of its ability to remove pollutants from the spaces in which it is operated.

The effectiveness of the device or system is a function of its use in real-world situations. While this can be simulated under controlled conditions in a laboratory test space, the in-use effectiveness of any device depends on many factors including its location, installation, airflow rate, and operating hours. In fact, these factors may have stronger influences on its effectiveness than does its laboratory-tested efficiency. As an example, while a given device can have a high laboratory-measured and certified efficiency, its effectiveness (i.e., its effect on pollutant concentrations in the occupied space that it serves) will be zero if no air passes through that device because it is turned off, or if very little air passes through the device because its airflow rate is too low or if its operation is intermittent, or if its filter media is so clogged that little or no air can pass through it.

In addition, the air cleaner removal rate must also be competitive with other removal processes that occur within the space to be effective (Batterman et al. 2005; Shaughnessy and Sextro 2006). Other removal mechanisms within the space include surface deposition (for particles) or adsorption (for gases), indoor air reactions (typically for gases), and ventilation (outdoor air exchange). For example, an air cleaner operating in a space with multiple open windows may be less effective than when operating in a space with closed windows because ventilation through the open windows is likely to be a more dominant removal mechanism (assuming outdoor air is cleaner than indoor air).

## TYPES OF AIR-CLEANING TECHNOLOGIES

Within each category of air cleaner, one or more **air-cleaning technologies** may be used to accomplish its goals, and some air-cleaning technologies have clear advantages over others. The available technologies vary in the type of pollutant that they can remove or reduce (e.g., different PM sizes, different kinds of gases, airborne microbes), their mechanism of action (e.g., pollutant collection, conversion, inactivation, destruction), and the potential side effects of their use (e.g., primary energy use requirements, secondary impacts on equipment performance, direct emissions of pollutants, secondary pollutant formation) (ASHRAE 2008; NAFA 2007). Table 1 summarizes the most commonly used air-cleaning technologies available in products currently on the market and the pollutants they are designed to control. Each technology is explained in more detail in the following sections. The list does not include other potential air-cleaning strategies such as material coatings that are designed to passively remove gaseous pollutants or biofiltration strategies such as ornamental potted plants or active bio-walls.

**Table 1. Summary of Air-Cleaning Technologies**

| Air-cleaning technology | Targeted indoor air pollutant(s) | Mechanism(s) of action | Advantages | Disadvantages | Test standards (and rating metrics) |
|---|---|---|---|---|---|
| Fibrous filter media | Particles | Collection: Filter fibers capture particles<br>• Mechanical filtration media rely on mechanical forces alone<br>• Electrostatically-charged (i.e., "electret") media use mechanical fibers with an electrostatic charge applied to collect oppositely charged particles, enhancing removal efficiency | • If rated efficiency is high, they can have excellent removal capabilities for many particle sizes<br>• Mechanical media filters see improved efficiency with loading | • Regular replacement is required<br>• Used particle filters can be a source of sensory pollution/odors<br>• High pressure drops on some fibrous media filters can negatively impact HVAC systems<br>• Electret media filters see reduced efficiency with loading<br>• Confusing number of test standards and rating metrics | Filters:<br>• ANSI/ASHRAE Standard 52.2 (MERV)<br>• ISO 16890 (ePM)<br>• ISO 29463 (HEPA)<br>• Proprietary test standards (FPR, MPR)<br>Portable air cleaners:<br>• AHAM AC-1 (CADR) |
| Electrostatic precipitation (ESP) | Particles | Collection: Corona discharge wire charges incoming particles, which collect on oppositely charged plates | • Can have high removal efficiency for a wide range of particle sizes<br>• Low pressure drop and minimal impacts on HVAC systems<br>• Low maintenance requirements | • Sometimes ESPs have high ozone and nitrogen oxide generation rates<br>• Efficiency typically decreases with loading and plates require cleaning<br>• High electric power draw requirements | ANSI/UL Standard 867 for electrical safety and ozone emissions (similar to IEC 60335-2-65) (pass/fail; no rating metric) |
| Ionizers (i.e., ion generators) | Particles | Collection: Similar to ESP, ionizers use a high-voltage wire or carbon fiber brush to electrically charge air molecules, which produces negative ions that attach to airborne particles; the charged particles are then collected either on oppositely charged plates in the air cleaner or become attracted to other surfaces in the room and deposited elsewhere | • Typically low power draw requirements<br>• Quiet<br>• Low maintenance | • Generates ozone<br>• Typically low effectiveness because of very low airflow rates and clean air delivery rates (CADRs) | None specific to ionizers, although AHAM AC-1 can be used to measure CADR |
| Ultraviolet germicidal irradiation (UVGI) | Microbes | Destruction: UV light kills/inactivates airborne microbes | • Can be effective at high intensity with sufficient contact time<br>• Can be used to inactive microbes on cooling coils and other surfaces | • Uncoated lamps can generate ozone<br>• Potential for eye injury<br>• Effectiveness increases with lamp intensity, which is typically low in residential UVGI air cleaners<br>• High electrical power draw requirements<br>• Inactivates but does not remove microbes | Air irradiation:<br>• ANSI/ASHRAE Standard 185.1<br>Surface irradiation:<br>• ANSI/ASHRAE Standard 185.2 |
| Adsorbent media | Gases | Collection: Gases physically adsorb onto high-surface-area media (typically activated carbon) | • Potential for high removal efficiency for many gaseous pollutants in air cleaners with a sufficient amount of media for the application<br>• No byproduct formation | • Regular replacement is required because its adsorption capacity is exhausted and physical adsorption is a reversible process, meaning pollutants may not be permanently captured<br>• Effectiveness of many consumer-grade systems with small amounts of activated carbon is unknown<br>• High pressure drops on some sorbent media filters can negatively impact HVAC systems<br>• Different removal efficiency for different gases at different concentrations<br>• Standard test methods are not widely used | Media:<br>• ANSI/ASHRAE Standard 145.1 (no rating metric)<br>In-duct air cleaners:<br>• ANSI/ASHRAE Standard 145.2 (no rating metric)<br>No effectiveness standards |

## Table 1 (continued). Summary of Air-Cleaning Technologies

| Air-cleaning technology | Targeted indoor air pollutant(s) | Mechanism(s) of action | Advantages | Disadvantages | Test standards (and rating metrics) |
|---|---|---|---|---|---|
| Chemisorbent media | Gases | Collection: Gases chemically adsorb onto media coated or impregnated with reactive compounds | • Potential for high removal efficiency for many gaseous pollutants<br>• Chemisorption is an irreversible process, meaning pollutants are permanently captured | • Regular replacement is required because its chemisorption capacity is exhausted<br>• Effectiveness of many consumer-grade systems is unknown<br>• High pressure drops on some sorbent media filters can negatively impact HVAC systems<br>• Different removal efficiency for different gases at different concentrations | Media:<br>• ANSI/ASHRAE Standard 145.1 (no rating metric)<br>In-duct air cleaners:<br>• ANSI/ASHRAE Standard 145.2 (no rating metric)<br>No effectiveness standards |
| Catalytic oxidation | Gases | Conversion: Most utilize photocatalytic oxidation (PCO) in which a high-surface-area medium is coated with titanium dioxide as a catalyst; incoming gases adsorb onto the media and UV lamps irradiate and activate the titanium dioxide, which reacts with the adsorbed gases to chemically transform them | • Can degrade a wide array of gaseous pollutants (e.g., aldehydes, aromatics, alkanes, olefins, halogenated hydrocarbons)<br>• Can be combined with adsorbent media to improve effectiveness | • Can generate harmful byproduct such as formaldehyde, and acetaldehyde, and ozone<br>• No standard test methods<br>• Often relatively low removal efficiency for many indoor gases, but high variability in removal for different gases<br>• Lack of field studies to validate performance<br>• Catalyst often has a finite lifespan | None specific to PCO |
| Plasma | Gases | Conversion: Electric current is applied to create an electric arc; incoming gases are ionized and bonds are broken to chemically transform the gaseous pollutants | • Can have high removal efficiency<br>• Can be combined with other air-cleaning technologies (e.g., PCO) to improve performance and minimize byproduct formation | • Wide variety of plasma generation types yields confusion on how a product actually works<br>• Byproducts are formed from many plasma technologies, including particles, ozone, formaldehyde, carbon monoxide, chloroform, nitrogen oxides, and a large number of other organic gases<br>• Most studies have investigated gaseous removal while fewer have evaluated particle removal | None specific to plasma |
| Intentional ozone generation | Gases | Conversion: Intentional generation of ozone using corona discharge, UV, or other method to oxidize odorous compounds and other gases | • Reacts with many indoor gases<br>• Can be combined with other less-harmful technologies such as adsorbent media | • High ozone generation rates<br>• High amounts of byproduct formation<br>• Can cause degradation to indoor materials | None specific to ozone generators |

Note that "Gases" are inorganic gases (e.g., carbon monoxide, nitrogen dioxide, ozone) and organic gases (e.g., volatile organic compounds, aldehydes).

Passive material coatings (Darling et al. 2016) and active bio-walls (Soreanu et al. 2013; Waring 2016) have shown some promise, but they are not widely commercially available, and published research on their effectiveness remains limited. Potted plants have been shown to be ineffective and impractical for pollutant removal because there is no active airflow and the number of plants required to effectively clean air is not feasible in most environments (Cruz et al. 2014; Girman et al. 2009; Waring 2016).

## Air-Cleaning Technologies Used for Removing Particles

Two types of air-cleaning technologies are commonly used in duct-mounted and portable air cleaners to **remove particles** from the air: **fibrous media air filters and electronic air cleaners**. Air-cleaning devices designed only to remove particles are incapable of controlling gases and some odors. For example, they will not remove the odor and many of the carcinogenic gas-phase pollutants from tobacco smoke and the musty/moldy odor from microbial contamination. Particles of liquid tobacco smoke trapped by an air filter may give off odorous organic gases (Offermann et al. 1992).

**Particle size and mass affects the performance of both types of particulate air-cleaning technologies because particles must first be suspended in the air to be removed.** Whether installed in the ducts of HVAC systems or used in portable air cleaners, most air filters have a good efficiency rating for removing coarse particles. These particles include dust, pollen, some mold spores, animal dander, and particles that contain dust mite and cockroach body parts and droppings. **However, because these larger particles settle out of the air and onto surfaces rather rapidly, air filters are not likely to remove them effectively from the home** (Institute of Medicine 2000; Shaughnessy and Sextro 2006; Wood 2002). Therefore, since many indoor allergens are large particles, effective allergen control requires routine cleaning and dust control. For more on allergen control, visit www.epa.gov/asthma.

Although human activities such as walking, sweeping, and vacuuming can resuspend particles, most of the larger particles will resettle before they enter the HVAC system or portable air cleaner to be removed by a particle air filter. It should also be noted that a significant fraction of cat and dog allergens and a small portion of dust mite allergens associated with mite feces are carried on small particles. Consequently, they are more easily dispersed throughout a house, remain airborne longer, and are more likely to be removed by air cleaners (Custovic 1998; Luczynska 1988).

### *Fibrous Media Air Filters*

**Fibrous media air filters** remove particles by capturing them onto fibrous filter materials. Fibrous media filters vary widely in their ability to remove particles. Particle removal efficiency depends on a number of parameters including particle size, face velocity, filter thickness, filter porosity, filter fiber dimensions, dust loading conditions, and whether or not the media are modified by the manufacturer to initially have an electrostatic charge on the fibers (e.g., electret vs. non-electret media). In general, fibrous media filters without an electrostatic charge tend to increase in efficiency with dust loading over time, and fibrous media filters with an electrostatic charge initially tend to decrease in efficiency with dust loading as the charge is diminished over time. However, filters that become excessively loaded will tend to decrease the effectiveness of a furnace filter or portable air cleaner because of reduced airflow through the filter and/or increased bypass airflow around a clogged filter, so it is important to follow manufacturer recommendations for regular filter replacement.

### *Test Metrics for Fibrous Media Air Filters*

Manufacturers use a number of test standards to evaluate the particle removal efficiency of fibrous media air filters. Removal efficiency is typically characterized for different particle sizes (for furnace air filters) or for different particle sources and sizes (for portable air cleaners). The most widely used fibrous media air filter test method for duct-mounted particle filters in the United States is ASHRAE Standard 52.2, which is a national consensus standard that evaluates the removal efficiency for particles 0.3 to 10 µm in diameter. Results are reported as a **MERV** ranging from MERV 1 to MERV 16 based on the average removal efficiency across three particle size ranges, including 0.3–1 µm, 1–3 µm, and 3–10 µm. Other test metrics for in-duct air filters include the proprietary **MPR (Micro-particle Performance Rating) and FPR (Filter Performance Rating)**. None of these test standards measures the removal efficiency of particles smaller than 0.3 µm, although it is technically possible to measure below 0.3 µm, as frequently is done by research laboratories.

In general, the higher the MERV rating, the higher a filter's removal efficiency for at least one particle size range tested in the ASHRAE 52.2 test standard. However, only MERV 11 filters and above are explicitly tested for their ability to remove the smaller 0.3–1 µm particles that are of greatest health concern because they make up a significant fraction of $PM_{2.5}$ mass concentrations. MERV 11 filters must achieve at least 20 percent removal efficiency for 0.3 to 1 µm particles, while only MERV 13 and above require at least 50 percent removal efficiency for 0.3 to 1 µm particles. It should also be noted that a recent filter test standard published by the International Organization for Standardization *(ISO 16890- 1:2016: Air Filters for General Ventilation–Part 1: Technical Specifications, Requirements and Classification System Based Upon Particulate Matter Efficiency [ePM])* was developed to explicitly address particle removal on the basis of $PM_{10}$, $PM_{2.5}$, and $PM_1$ mass concentrations, but it is not yet widely used in the United States (ISO 2016; Stephens 2018; Tronville and Rivers 2016).

## High-Efficiency Particulate Air (HEPA) Filters

**In residential air cleaners, filters described as being HEPA filters are generally equivalent to MERV 16 and offer the highest available particle removal efficiency of fibrous media air filters for a wide range of particle sizes.**

Note that, in health care and industrial settings, the HEPA designation has more explicit and narrowly defined performance characteristics, and more rigorous test standards are applied to its use. While the HEPA-designated home air filters usually perform at high levels comparable to a MERV 16, there is no widely accepted definition of HEPA performance in consumer products. Thus, they are unlikely to be equivalent in performance to HEPA-designated filter systems used in health care buildings and industrial processes, but still have very high removal efficiency (i.e., usually 99% or higher) for the reported particle sizes tested.

### *Types of Fibrous Media Air Filters*

Flat or panel filters are relatively inexpensive filters generally consisting of coarse glass fibers, coated animal hair, vegetable fibers, synthetic fibers (such as polyester or nylon), synthetic foams, metallic wools, or expanded metals and foils. The filter media may be pre-treated by the manufacturer with a viscous substance, such as oil, that causes particles to stick to the fibers. **Flat or panel air filters typically have a MERV of 1 to 4** and thus have very low removal efficiency for most particle sizes, albeit with slightly higher efficiency for large particles (MacIntosh et al. 2008; Stephens and Siegel 2012, 2013). These filters are usually about 1-2 inches thick. They are commonly used in residential furnaces and air-conditioning systems, and they are also often used as pre-filters for higher efficiency filters. For the most part, such filters in in-duct applications are used only to protect the HVAC equipment from the buildup of unwanted materials on fan motors, heat exchangers, and other surfaces, rather than to protect occupants from exposure to airborne fine particles.

**Pleated, extended surface, and unpleated pad filters typically have a MERV of 5 to 13 or higher** and generally have higher particle removal efficiency for most particle sizes compared to panel filters. However, their removal efficiency for smaller particles varies substantially by MERV and can even vary within different makes and models of filters with the same MERV rating (U.S. EPA 2008). Pleating the filter medium increases surface area, reduces air velocity through the filter media, and allows the use of smaller fibers and increased packing density of the filter without a large drop in airflow rate. Additionally, these filters often have an extended lifespan because of their increased surface area. A wire frame in the form of a pocket or V-shaped cardboard separators may be used to maintain the pleat spacing. The media used in pleated filters can be fiber mats, bonded glass fibers, synthetic fibers, cellulose fibers, wool felt, and other cotton-polyester material blends.

The airflow resistance of these filters generally, but not necessarily, increases as the MERV increases for a given thickness. The reason that airflow resistance does not necessarily increase with MERV is that higher MERV-rated filters often use more filter media by increasing the pleating and the filter thickness. However, filters with electrostatically charged media can have higher MERV ratings without an increased airflow resistance. Three main types of electrostatically charged media are used: resin wool, a plastic film, or a fiber called electret (an electrostatically sprayed polymer). Their electrostatic charge attracts and captures particles. The fibers of electret filters are somewhat larger than the fibers of other flat filters, resulting in relatively low pressure drop and greater efficiency in filtering smaller particles.

**Higher efficiency filters with a MERV of 14 to 16** will typically have a higher average resistance to airflow than medium-efficiency filters of the same thickness, although most manufacturers now rely on extended depth filters and extensive pleating to achieve these high MERV ratings with low resistance to airflow.

**HEPA filters** are another type of pleated filter. They also have very deep pleats with a much larger surface area than conventional pleated filters. Consequently, they remove fine and ultrafine particles with higher efficiency than lower rated fibrous media air filters.

Figure 4 shows an example of several commercially available residential fibrous media air filter products for central in-duct applications, ranging from 1-inch fiberglass MERV 4 filters to 5-inch deep pleated MERV 16 filters.

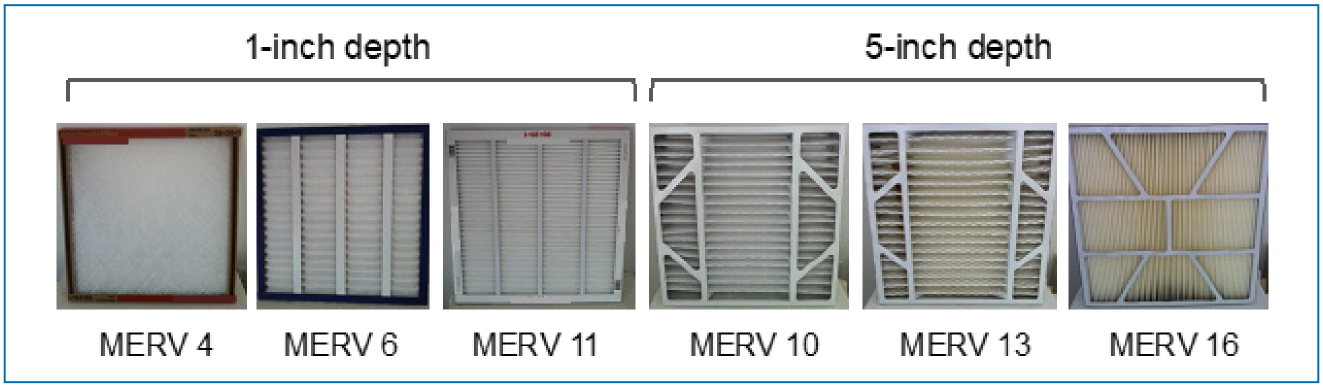

Figure 4. Example of several commercially available residential fibrous media air filter products for central in-duct applications.
Image credit: Brent Stephens.

## *Practical Considerations for Using Fibrous Media Air Filters*

The performance of fibrous media air filters in residences depends not only on the removal efficiency of the media, but also on factors such as the:

- Indoor particle size and size-specific mass concentrations
- Amount of dust loaded on the air filter
- Airflow rate, velocity, and resistance to airflow through the filter media
- Bypass airflow that flows around the air filter because of poor installation
- System or device runtime, which governs how much air passes through the filter

**Particle size greatly affects the removal efficiency of, and the likelihood of removal by, fibrous media air filters.** Most fibrous media air filters have a U-shaped removal efficiency curve that varies by particle size, in which the highest removal efficiency occurs for both the largest (e.g., > 3 μm) and the smallest (e.g., < 0.03 μm) particles (Figure 5). However, these same particle sizes also tend to have the highest deposition rates indoors, meaning that they deposit onto surfaces rapidly (U.S. EPA 2008). This means that deposition to surfaces and removal by filters compete with each other for particle removal and that even a very high-efficiency filter may not have as large of an effect on indoor particle concentrations as expected (Lee et al. 2015). Further, because filter removal is a strong function of particle size, the underlying size distribution of indoor particles inside the home can greatly influence the magnitude of reductions in PM mass concentrations (Azimi et al. 2014, Stephens, 2018).

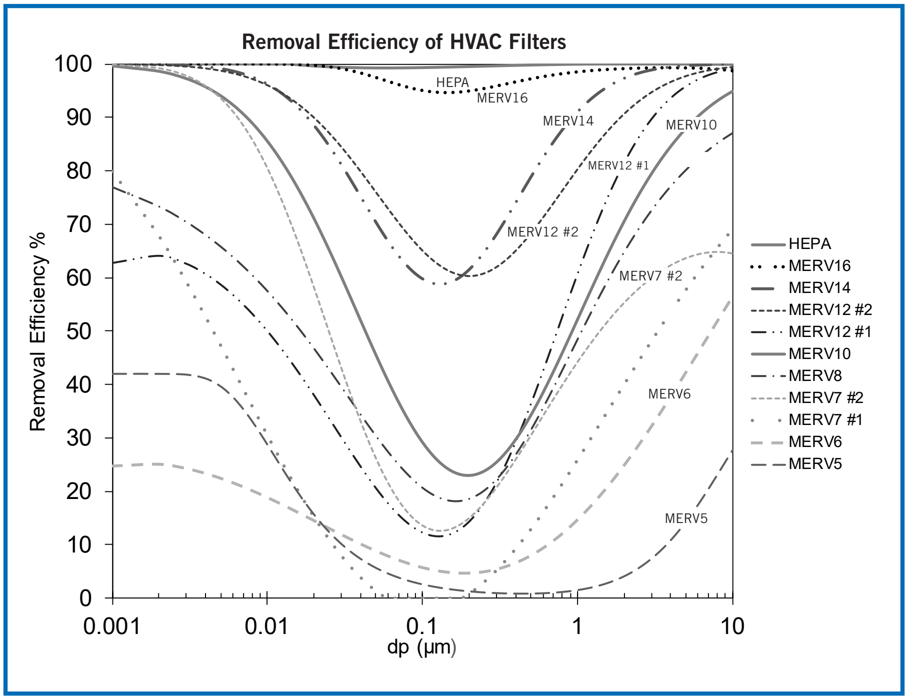

Figure 5. Typical size-resolved removal efficiency curves for new (clean) fibrous media air filters rated by the MERV metric as tested in reported in Azimi et al. (2014). Reprinted from *Atmospheric Environment*, Vol. 98, Parham Azimi, Dan Zhao, and Brent Stephens, Estimates of HVAC filtration efficiency for fine and ultrafine particles of outdoor origin, pages 337–346, copyright (2014), with permission from Elsevier.

**Dust loading will affect the removal efficiency of fibrous media air filters in different ways for different particle sizes.** Although it is difficult to make generalizations with available data because filter products vary so widely, filters that rely on mechanical means alone for removing particles typically have an improved efficiency for some particle size ranges (particularly coarse particles) as they become loaded with dust over time (Figure 6) (Hanley et al. 1994; Hanley and Owen 2003; Owen et al. 2003; U.S. EPA 2008). Conversely, the removal efficiency of electret filters sometimes decreases for some particle sizes (including fine and ultrafine particles) as the media becomes loaded with particles because the charge is diminished over time (Figure 7) (Hanley et al. 1994; Hanley and Owen 2003; Owen et al. 2003; U.S. EPA 2008). Further, both the initial and final operating resistance of a fully dust-loaded filter must also be accounted for in the design of a system and filter combination because it is the maximum resistance against which the fan operates. It is also worth noting that filter loading and pressure drop increases are a function of many factors, including filter type, removal efficiency over time, indoor particle concentrations, and system runtimes (Stephens et al. 2010; Waring and Siegel 2008).

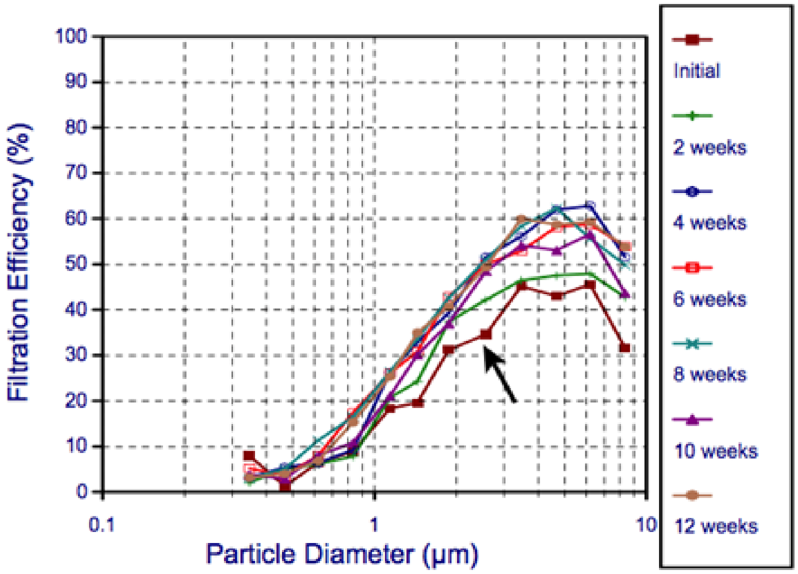

Figure 6. Example size-resolved removal efficiency curves for new (MERV 5 when clean) and loaded non-electret fibrous media air filters as tested in reported in Hanley and Owen (2003). ©ASHRAE from ASHRAE Research Project Final Report 1190-RP.

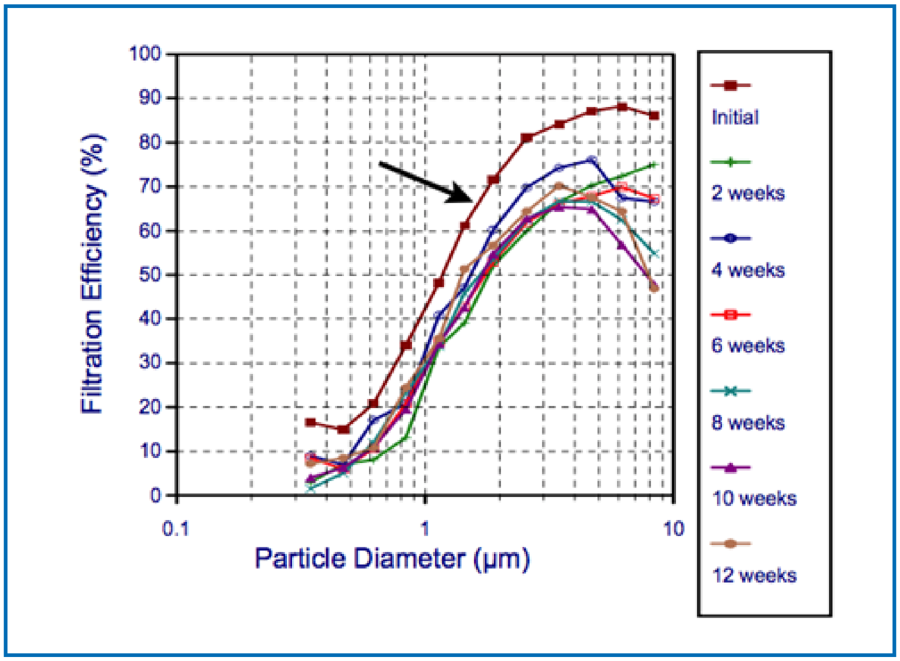

Figure 7. Example size-resolved removal efficiency curves for new (MERV 11 when clean) and loaded electret fibrous media air filters as tested in reported in Hanley and Owen (2003). ©ASHRAE from ASHRAE Research Project Final Report 1190-RP.

**Airflow rate, velocity, and resistance to airflow through the filter media will affect the performance of fibrous media air filters installed in any system that has a fan.** The pressure drop across fibrous media filters is typically greater than that in electronic air cleaners and will slowly increase over the filter's useful life as it becomes loaded over time (Stephens et al. 2010). Flat or panel filters are typically only 1–2 inches thick, have low airflow resistance, and are relatively inexpensive. Pleated or extended surface filters of the same thickness will typically have a higher pressure drop and a higher resistance to airflow. However, deeper pleated or extended surface filters, which may be as much as 4–12 inches thick, will increase the area of the filtration medium and limit the airflow resistance of the filter. **Selection of any increased efficiency media filter must also take into account the compatibility of the filter with the existing ducted HVAC system in place to ensure that airflow will not be impeded by the added resistance.** Modifications to the system may be required to install a retrofit to accommodate a higher efficiency filter media. Additionally, filters installed at the return grille rather than at the air-handling unit can also have a smaller effect on the overall airflow resistance because they can often be larger in both area and thickness.

**Bypass airflow that flows around an air filter because of poor installation will reduce air filter effectiveness.** The paths traveled by the air through a filter installed in a portable air cleaner or in a central HVAC system are important in determining effectiveness (e.g., see Figure 8). Homeowners should install furnace filters and duct-mounted air cleaners in HVAC systems such that leakage of air bypassing the filter is minimized; it is essential to follow the manufacturer's installation instructions. Duct-mounted air filter effectiveness can be substantially reduced because of air leakage flowing around a filter installed in a poorly matched or poorly constructed filter frame or gasket (VerShaw et al. 2009). Another form of bypass airflow also includes flow from unconditioned spaces through return duct leakage, which can circumvent the filter if it is installed at a return grille, rather than at the base of an air-handling unit.

Figure 8. Example of large amounts of bypass airflow around a filter in an air-handling unit because of improper installation combined with excessive loading that increased the pressure drop across the filter beyond what the filter was capable of supporting. Photo credit: Brent Stephens.

### *Electrostatic Precipitators (ESPs) and Ionizers*

ESPs and ionizers are electronic air cleaners that use a powered electrostatic process to charge particles, which then become attracted to oppositely charged plates or other indoor surfaces to remove airborne particles.

**ESPs** use a high-voltage wire to charge incoming particles, which are then collected onto oppositely charged plates inside the air cleaner. ESPs remove and collect small airborne particles and often have an initial single-pass removal efficiency of 60 percent or more for most particle sizes, increasing to as much as 95 percent depending on the airflow rate (the lower the airflow rate, the greater the removal efficiency) (Morawska et al. 2002). This efficiency will be highest for clean ESPs, but their efficiency decreases as the collecting plates become loaded with particles (Howard-Reed et al. 2003; Wallace et al. 2004). ESPs can also have different removal efficiencies for particles with different compositions, as the electrical properties of some particles will affect their ability to hold a charge.

**Ionizers**, or ion generators, use a high-voltage wire or carbon fiber brush to electrically charge air molecules, which produces negative ions that attach to airborne particles. Subsequently, the charged particles can attach to nearby surfaces such as walls or furniture (i.e., plate-out), or to one another, and settle faster. Ion generators are the simplest form of electronic air cleaner and are available as tabletop, portable, or ceiling-mounted units. However, because ionizers typically do not utilize fans to move air past the air cleaner, ionizers typically have very low CADRs for most particle sizes (Waring et al. 2008). Additionally, the charged particles that result from ionizer operation will deposit on and soil room surfaces such as walls and curtains (Melandari et al. 1983; Offermann et al. 1985). Because these deposited particles remain in the room or area, they may be resuspended from the surfaces when disturbed by human activities such as walking or vacuuming, especially those larger than approximately 2 μm (Ferro et al. 2004; Qian and Ferro 2008).

#### *Possible Negative Effects of Particle Charging*

Another factor to consider related to ion generators is the effect of particle charging on deposition in the respiratory tract. Experiments have shown that particle deposition in the respiratory tract increases as particles become charged, so using ion generators may not reduce the dose of particles to the lungs (Melandari et al. 1983; Offermann et al. 1985). The effect of charge on very fine particles results in their higher deposition rate in the lungs compared to that of uncharged particles. Additionally, ESPs and ionizers may make a crackling sound as they accumulate dust, which may be a nuisance to some occupants.

### Cautions Concerning Ozone Production by ESPs and Ionizers

Like fibrous media air filters, ESPs and ionizers can be installed in HVAC systems or used in portable units. Although ESPs and ionizers remove small particles (including ultrafine particles), they do not remove gases or odors (Poppendieck et al. 2014; Sultan et al. 2011; Waring et al. 2008). And because ESPs and ionizers use high voltage to generate ionized fields, they may produce ozone, either as a byproduct or by design (U.S. EPA 2014). Ozone is a lung irritant that poses risks to health.

Some portable air cleaners that use ESPs and ionizers produce ozone as a byproduct (Consumers Union 2005; Waring et al. 2008; Jakober and Phillips 2008). Some makes and models of ESPs and ionizers can increase indoor ozone concentrations that can even exceed public health standards (Morrison et al. 2014). The California Air Resources Board, under Title 17 *Regulation for Limiting Ozone Emissions from Indoor Air Cleaning Devices* (California Code of Regulations 2009), certifies air cleaners in regard to ozone production. The Title 17 Regulation relies on a test method for evaluating ozone emissions from air cleaners described in ANSI/UL Standard 867 (UL 2011), which is also similar to the method described in IEC 60335-2-65 (IEC 2015).

Also, even at concentrations below public health standards, ozone reacts with chemicals emitted by common indoor sources such as household cleaning products, air fresheners, deodorizers, certain paints, polishes, wood flooring, carpets, and linoleum. The chemical reactions produce harmful byproducts that may be associated with adverse health effects in some sensitive populations. Byproducts that may result from reactions with ozone include ultrafine particles, formaldehyde, other aldehydes, ketones, peroxides, organic acids (Shaughnessy and Sextro 2006; U.S. EPA 2014; Wechsler 2006). Ozone and ozone-generating devices are discussed in EPA's "Ozone Generators that are Sold as Air Cleaners," which can be found at www.epa.gov/indoor-air-quality-iaq/ozone-generators-are-sold-air-cleaners.

## Ultraviolet Germicidal Irradiation (UVGI) Air Cleaners

Another type of electronic air cleaner technology, UVGI, is designed to reduce the number of viable airborne microorganisms.

### UVGI Technology

**UVGI air cleaners** are designed to use UV lamps to kill or deactivate microorganisms such as viruses, bacteria, and fungal spores and fragments that are airborne or growing on surfaces (e.g., cooling coils, drain pans, ductwork, filters). Both UV-A (long wave: 315–400 nm) and UV-C (short wave: 100–280 nm) are used in UVGI air cleaners. Most UV lamps that are used to deactivate microorganisms in residential settings are low-pressure mercury vapor lamps that emit UV-C radiation primarily at a wavelength of 254 nm, which has been shown to have germicidal effects (VanOsdell and Foarde 2002). Given sufficient exposure time and lamp power, UV light can penetrate the outer structure of a microorganism's cell(s) and alter its DNA, preventing replication and causing cell death. But some bacterial and mold spores are resistant to UV radiation, and to achieve reliable deactivation of spores, the lighting power must be high and the exposure times must be long (i.e., on the order of minutes and hours rather than the few seconds typical of most UVGI air cleaners).

### Types of UVGI Cleaners and Their Effectiveness

There are two types of UVGI applications in residences: air cleaners designed for airstream disinfection to reduce the viability of microorganisms as they flow through the HVAC system or portable air cleaner, and surface cleaners designed for surface disinfection that are most commonly used to prevent the growth of microorganisms on cooling coils inside an HVAC system (Kowalski and Bahnfleth 2000; VanOsdell and Foarde 2002). UVGI lamps for airstream or surface disinfection usually are located in the air duct of an HVAC system downstream of the filter and upstream of the cooling coil or in a portable air cleaner downstream of the filter. Two test standards are available for objectively evaluating the effectiveness of UVGI systems and components. UVGI lamps for in-duct airstream irradiation are tested using ANSI/ASHRAE Standard 185.1 (ASHRAE 2015b), and UVGI lamps for in-duct surface irradiation are tested using ANSI/ASHRAE Standard 185.2 (ASHRAE 2014).

If properly designed, the UVGI cleaner in a typical **airstream disinfection** application has the potential to reduce the viability of vegetative bacteria and molds and to provide low to moderate reductions in viruses but little, if any, reduction in bacterial and mold spores (CDC 2003; Kowalski and Bahnfleth 2000; Levetin et al. 2001). Spores tend to be resistant to UV radiation, and killing them requires a very high dosage (Cundith et al. 2002; VanOsdell and Foarde 2002; Xu et al. 2002).

UVGI cleaners in a **surface disinfection** application are installed in air-handling units to prevent or limit the growth of vegetative bacteria and molds on moist surfaces in the HVAC system (Kowalski and Bahnfleth 1998, 2000; Levetin et al. 2001; Luongo and Miller 2016). One study reported a 99 percent reduction in microbial contaminants growing on exposed HVAC surfaces but a reduction in airborne bacteria of only 25 to 30 percent (Menzies et al. 2003). One reason that the surface disinfection application provides only a slightly noticeable reduction in airborne microbial concentrations may be that microorganisms in the airstream are exposed to the UV light for a shorter time. Conversely, microorganisms growing on exposed HVAC surfaces are given prolonged direct UVGI exposure. Another study found that UV-C lamps yielded reduced microbial growth in duct lining and drain pans from air-handling units but cautioned that moisture control, properly designed dehumidifying and cooling HVAC processes, drain pans designed to drain, and installing nonporous surfaces downstream of coils should collectively continue to be the primary approaches to controlling microbial growth in air-handing units (Levetin et al. 2001). Limiting microbial growth on cooling coils has other benefits, such as improving the heat transfer rate of the coil, which improves energy efficiency (Wang et al. 2016a, b).

Prolonged direct UVGI exposure can destroy vegetative microbial growth—but not most spores—on the surfaces of forced-ventilation units, filters, cooling coils, or drain pans. Killing molds and bacteria while they are still in the susceptible vegetative state reduces the formation of additional spores. UV radiation is ineffective in killing microorganisms if they proliferate inside the filter media, system crevices, porous thermal insulation, or sound-absorbing fibrous material liners (Kowalski and Bahnfleth 2000).

A number of studies report that the most important performance elements of a UVGI system are the type of UV lamp and ballast, relative humidity, temperature, air velocity, and duct reflectivity (Kowalski and Bahnfleth 1998; Philips Lighting 1985, 1992; Scheir and Fencl 1996; VanOsdell and Foarde 2002). The effectiveness of UVGI cleaners in killing microorganisms may also vary depending on the UV irradiation dose, system design and application, system operation characteristics, and the microorganism targeted for deactivation.

Some UVGI cleaners used in HVAC systems or portable air cleaners are advertised to reduce dust mite allergens, airborne microorganisms (e.g., viruses, bacteria, molds) and their spores, and gaseous pollutants from indoor air. However, it is likely that the effective destruction of airborne viruses and fungal and bacterial spores requires much higher UV exposures than a typical residential UVGI air-cleaning unit provides (Kowalski and Bahnfleth 2000; Scheir and Fencl 1996; VanOsdell and Foarde 2002). No research or studies were found that show UV disinfection is effective in reducing dust mite and mold allergenicity or that UV radiation has the potential to remove gaseous pollutants. Both dead or live fungal particles can cause allergic reactions in sensitive populations. Therefore, UVGI cleaners might not be effective in reducing allergy and asthma symptoms. If mold is growing indoors, it should be removed, and the conditions leading to its growth should be addressed (U.S. EPA 2001).

Regular maintenance of UVGI systems is crucial and usually consists of cleaning the lamps of dust and replacing old lamps. Manufacturers' recommendations regarding safety precautions, exposure criteria, maintenance, and monitoring associated with the use of UVGI systems should be followed.

#### *Disadvantages of UVGI Cleaners*

Similar to ESPs, UVGI cleaners can generate large amounts of ozone as a byproduct of their operation (Morrison et al. 2014). Uncoated UV-C lamps that emit UV light with a wavelength of 254 nm and below can generate ozone through photolysis of oxygen and further reaction (e.g., $3O_2 \rightarrow \text{photolysis} \rightarrow 2O_3$). Because of this issue, some manufacturers apply a special coating to UV lamps (e.g., doped fused quartz lamps) to inhibit ozone production. The California Air Resources Board *Title 17 Regulation for Limiting Ozone Emissions from Indoor Air Cleaning Devices*, which relies on the ANSI/UL Standard 867 test method for evaluating ozone emissions from air cleaners (California Code of Regulations 2009) certifies UVGI air cleaners in regard to ozone. Another test standard, IEC 60335-2-65, Edition 2.2 2015-01, documents similar procedures for measuring ozone production from air-cleaning devices.

There is no specific standard test method to rate and compare the effectiveness of UVGI cleaners installed in either residential HVAC systems or portable air cleaners. Typical UVGI air cleaners designed for use in homes do not deliver sufficient UV doses to effectively kill or deactivate most airborne microorganisms because the exposure period is too short and/ or the intensity is too low. Thus, **UVGI does not appear to be effective as a sole control device. When UVGI is used, it should be used in addition to—not as a replacement for—conventional particle filtration systems, because UVGI does not actually capture or remove particles** (CDC 2003). Dead or deactivated biological particles can still contain irritants, allergens, and/ or toxins. Using UVGI in addition to HEPA filters or other high-efficiency filters (e.g., MERV 13 and above) in HVAC systems or in portable units offers only minimal infection control benefits over those provided by the filters alone (CDC 2003; Kowalski and Bahnfleth 1998). However, UVGI can be effective for inhibiting biological growth on HVAC cooling coils and drain pans as a result of longer exposure times.

### Air-Cleaning Technologies Used for Removing Gases

A number of air-cleaning technologies are designed to either remove gases or convert them to (ideally) harmless byproducts using a combination of physical and chemical processes. Gas-phase air-cleaning technologies include sorbent media air filters, PCO, plasma, and intentional ozone generators sold as air cleaners. (Note that ozone generators sold as air cleaners should not be used in occupied spaces. For more information, visit www.epa.gov/indoor-air-quality-iaq/ozone-generators-are-sold-air-cleaners.) None of these technologies are explicitly designed to remove particles. All in-duct gas-phase air-cleaning devices can be tested using ANSI/ASHRAE Standard 145.2, although its use remains somewhat limited (ASHRAE 2016). There is no standardized *in situ* field-testing method for evaluating gas-phase air cleaner performance with a metric similar to CADR, although one study proposed a test method that used a single VOC (decane) as a representative gaseous pollutant source in a test house, and another extended a similar methodology to evaluate the removal of three VOCs in a test chamber (Howard-Reed et al. 2008; Kim et al. 2012; Sidheswaran et al. 2012).

### Sorbent Media

**Sorbent media air filters** use a material with a very high surface area called a sorbent to capture gaseous pollutants. Two main sorbent processes can be used to remove gaseous contaminants: a physical process known as adsorption and a chemical reaction called chemisorption. Both types of media can be tested using ANSI/ASHRAE Standard 145.1 (ASHRAE 2015c).

**Adsorption** results from the physical attraction of gas or vapor molecules to a surface. All adsorbents have limited capacities and thus require frequent maintenance. An adsorbent will generally adsorb molecules for which it has the greatest affinity and will allow other molecules to remain in the airstream. Adsorption occurs more readily at lower temperatures and humidity. Solid sorbents such as activated carbon, silica gel, activated alumina, zeolites, synthetic polymers, and porous clay minerals are useful because of their large internal surface area, stability, and low cost.

Activated carbon is the most common adsorbent used in HVAC systems and portable air cleaners to remove gaseous contaminants. It has the potential to remove most hydrocarbons, many aldehydes, organic acids through adsorption, and ozone through chemisorption. However, activated carbon is not especially effective against oxides of sulfur, hydrogen sulfide, low molecular weight aldehydes (e.g., formaldehyde), ammonia, and nitrogen oxide.

Adsorbent media filters can have high removal efficiency for many gaseous pollutants, but they can also have different removal efficiency for different gases at different concentrations (Kim et al. 2012). For example, tests performed at EPA measured the adsorption isotherms for three VOCs at concentrations of 100 parts per billion (ppb) to 200 ppb using three samples of activated carbon. The bed depth needed to remove the compounds was estimated assuming a 150 ppb concentration in the air, an exit concentration of 50 ppb, and a flow rate of 100 cfm across a 2-foot by 2-foot filter. The results of the study suggest that breakthrough of these chemicals would occur quickly in 6-inch deep carbon filters used for odor control (Ramanathan et al. 1988). Therefore, the thicker the media, the more efficient the filter will be for longer periods of time.

Adsorbent media can also be impregnated in thin layers onto fibrous air filter media to remove both gases and particles. For example, one study of the effects of various air-cleaner technologies on the sensory perception of human subjects demonstrated that an electret filter impregnated with carbon sorbent received the best ratings with respect to odor strength, nasal irritation, eye irritation, and overall air acceptability (Shaughnessy et al. 1994). However, such thin layers can become quickly saturated, and the filter can become a source of previously adsorbed pollutants (Miller et al. 1991). Gaseous pollutant adsorption to most adsorbent media does not generate any chemical byproducts, but adsorbent media filters require regular replacement or regeneration to restore sorbent sites and avoid breakthrough. Gas-phase filters that contain sorbents should generally be located downstream of particle air filters. The air filter reduces the amount of PM that reaches the sorbent, and the sorbent collects vapors that may be generated from liquid particles that collect on the particle filter.

**Chemisorption** occurs when gas or vapor molecules chemically react with sorbent material or with reactive agents impregnated into the sorbent. These impregnates react with gases and form stable chemical compounds that are bound to the media as organic or inorganic salts, or are broken down and released into the air as carbon dioxide, water vapor, or some material more readily adsorbed by other adsorbents.

A sorbent filter's behavior depends on many factors that can affect the removal of gaseous contaminants:

- Airflow rate and velocity through the sorbent
- Concentration of contaminants
- Presence of other gaseous contaminants
- Total available surface area of the sorbent (Some manufacturing techniques can significantly reduce a filter's total surface area.)
- Physical and chemical characteristics of the pollutants and the sorbent (such as weight, polarity, pore size, shape, volume, and the type and amount of chemical impregnation)
- Pressure drop
- Removal efficiency and removal capacity
- Temperature and relative humidity of the gas stream

### *Photocatalytic Oxidation (PCO)*

**PCO air cleaners** use a high-surface-area medium coated with a catalyst such as titanium dioxide to adsorb gaseous pollutants (Huang et al. 2016; Mo et al. 2009; Wang et al. 2007; Zhong and Haghighat 2015). When the photocatalyst is irradiated with UV light, a photochemical reaction takes place and hydroxyl radicals form on the media surface. The hydroxyl radicals oxidize gaseous pollutants adsorbed on the catalyst surface. This reaction, called PCO, converts organic pollutants into (ideally) carbon dioxide and water.

PCO air cleaners can transform a wide array of gaseous pollutants. However, PCO air cleaners are often ineffective in completely transforming gaseous pollutants in indoor air (Henschel 1998; Tompkins et al. 2005a, b) and are also known to generate harmful byproducts such as formaldehyde, acetaldehyde, nitrogen dioxide, and carbon monoxide (Hodgson et al. 2007). PCO air cleaners can also generate ozone when used with a UV-C lamp that lacks a coating to inhibit ozone generation. Therefore, some PCO air-cleaning devices use adsorbent media air filters downstream that may adsorb some of the generated byproducts. There are few field investigations to validate the performance of PCO air cleaners, and laboratory studies demonstrate high variability and often relatively low removal efficiency for many common indoor gases. For example, one study reported that PCO devices installed in portable air cleaners did not effectively remove any of the test VOCs present at the low concentrations normally found in indoor air (Chen at al. 2005). This study compared the VOC-removal efficiencies of 15 air cleaners that use different types of technology. A mixture of 16 VOCs commonly found indoors was used. The report indicated that the PCO devices studied might not work as advertised.

The usefulness of PCO air cleaners depends on the amount of catalyst, the amount of contact time between gaseous pollutants and the catalyst, and the amount of UV light that is delivered to the catalyst surface. If any one of these factors is not addressed in the design of the device, a PCO air cleaner may fail to destroy pollutants completely and instead produce new indoor pollutants including irritants. PCO of certain VOCs may create byproducts that are indoor pollutants if the system's design parameters and catalyst metal composition do not match the compound targeted for decomposition, particularly in the presence of multiple reactive compounds commonly found in residential settings. One study reported that no detectable byproducts formed during the PCO of 17 VOCs using titanium dioxide under the experimental conditions (Henschel 1998). However, two studies on the degradation of four chlorinated VOCs found byproducts including phosgene and chlorides (Alberci et al. 1998; Blake et al. 1993). In addition, the PCO of trichloroethylene in air using titanium dioxide as the catalyst yielded as byproducts carbon monoxide, phosgene, carbon dioxide, hydrogen chloride, and chlorine. However, these studies did not report the concentration of chlorinated precursor compounds or the concentrations of phosgene formed.

Several other studies have also explored the following aspects of PCO cleaners, often with mixed findings and suggestions for further research:

- How does UV light intensity and residence time affect PCO performance (Tompkins et al. 2005a)?
- How does the presence of other compounds such as toluene, benzene, ethanol, or siloxanes affect PCO performance (Tompkins et al. 2005a, b; Turchi et al. 1995; Zorn 2003)?
- How does the reaction temperature or water vapor content affect PCO performance (Zorn et al. 1999)?
- How can PCO systems be best engineered to optimized performance (Destaillats et al. 2012)?

A review of the literature suggests that more research is needed to further advance PCO as an effective technology in removing low levels of gaseous contaminants from the indoor air of residences (Chen et al. 2005; Tompkins et al. 2005 a, b). **The effectiveness of PCO air cleaners sold for use in homes remains largely undocumented.** And to date, there is no standard test method to compare and rate the effectiveness of PCO cleaners installed in residential HVAC systems or portable air cleaners.

### *Plasma*

**Plasma air cleaners** apply a high-voltage discharge to ionize incoming gases, breaking their chemical bonds and chemically altering them (Bahri and Haghighat 2014). Thermal plasma air cleaners generate a high-temperature plasma flame using high voltage and high current. Non-thermal plasma air cleaners accelerate electrons to generate reactive ions and radicals, which convert compounds by oxidation reactions. According primarily to controlled laboratory tests, plasma air cleaners can have high removal efficiency for some gases as well as particles, and they can also kill or deactivate airborne microorganisms. However, a number of harmful byproducts are known to form, including particles, ozone, carbon monoxide, and formaldehyde (Chen et al. 2009; Van Durme et al. 2009). Moreover, plasma emitted directly to indoor air contains ozone and other reactive oxygen species such as hydroxyl radicals, superoxides, and hydrogen peroxide. Plasma air cleaners are sometimes combined with other air-cleaning technologies, such as PCO or adsorbent media, but very little information exists on the performance of these systems in real indoor settings.

### *Intentional Ozone Generators*

**Ozone generators sold as air cleaners should not be used in occupied spaces.**

**Ozone generators sold as air cleaners**, which are typically designed to control odors, use UV lamps or electrical discharge to intentionally produce ozone. Ozone reacts with chemical pollutants to transform them into other compounds at high concentrations and can kill or deactivate biological pollutants.

However, ozone is a potent lung irritant. And as ozone reacts with chemical pollutants, it can produce harmful byproducts (Shaughnessy and Sextro 2006; U.S. EPA 2014; Wechsler 2006). If ozone concentrations are maintained below public health standards, it has little potential to remove indoor air contaminants. However, even at concentrations below public health standards, ozone reacts with chemicals emitted by such common indoor sources as household cleaning products, air fresheners, deodorizers, certain paints, polishes, wood flooring, carpets, and linoleum. The chemical reactions produce irritating and corrosive byproducts that may cause adverse health effects and may damage building materials, furnishings, and wiring. The ozone reaction byproducts that may result include ultrafine particles, formaldehyde, ketones, and organic acids (Destaillats et al. 2006; Sarwar et al. 2003; Waring 2014; Wechsler 2000; Wechsler and Shields 1999). Do not use ozone generators sold as air cleaners in occupied spaces. **No federal agency has approved ozone generators for use in occupied spaces.**

Ozone generators sold as air cleaners and marketed as duct-mounted or portable units use UV light or **corona discharge** to produce ozone, which is dispersed by a fan into occupied spaces (U.S. EPA 2014). Federal pesticide law requires manufacturers of ozone generators to list an EPA establishment number on the product's packaging. This number merely identifies the facility that manufactured the product. The presence of this number on a product's packaging does not imply that EPA endorses the product, nor does it imply that EPA has found the product to be safe or effective.

More information on ozone generators sold as air cleaners can be found at www.epa.gov/indoor-air-quality-iaq/ozone-generators-are-sold-air-cleaners.

### *Practical Considerations for Using Air Cleaners for Removing Gases*

Since many different gas-phase air-filtration devices are available, comparing and rating the effectiveness of installed gas-phase filters is difficult. ASHRAE has developed Standard 145.2 as a standard method for evaluating the effectiveness of gas-phase filtration devices installed in the ductwork of HVAC systems, but it is not widely used at this point in time (Shaughnessy and Sextro 2006; U.S. EPA 2014; Wechsler 2006).

Gas-phase filters are much less common than particle air-cleaning devices in homes because, currently, a properly designed and built gas-phase filtration system is too big for a typical residential HVAC system or portable air cleaner. Other factors that may contribute to the less frequent use of gas-phase filters in home HVAC systems are the filters' limited useful life, the fact that the sorbent material must be targeted to specific contaminants, the purchase price of the filters, and the costs of adapting them to residential applications, when possible, and of operating them once they have been installed.

Some gas-phase filters may remove, at least temporarily, a portion of the gaseous pollutants in indoor air. Although some gas-phase air filters—if properly designed, installed, used, and maintained—may effectively remove specific pollutants from indoor air, none is expected to remove adequately all of the gaseous pollutants in a typical home. For example, carbon monoxide is not readily captured by adsorption or chemisorption (Shaughnessy et al. 1994).

Because of their compact design, particle air filters that use impregnated media for additional gaseous pollutant removal are available for residential HVAC systems and portable air cleaners. They use sorbent particles of carbon, permanganate alumina, or zeolite incorporated into fibrous filter media. Such filters generally range from 1/8 inch to 2 inches thick. They provide a combination of particulate and gas-phase filtration with a minor increase in pressure drop across the filter. Their use in an existing HVAC system does not require extensive or expensive modifications to the system. However, their useful service life varies according to indoor pollution concentrations and exposure time. Breakthrough of the contaminants back into the room can take place very quickly in the thin layer impregnated with sorbents, resulting in a short service life for the filter, which must be replaced frequently. Thus, these devices usually have limited effectiveness in removing odors.

### *Removal of Radon and Its Progeny*

EPA does not recommend air cleaning to reduce the health risks associated with radon and the decay products of radon gas (known as radon progeny). The Agency recommends the use of source-control technologies to prevent radon from entering residential structures. The most effective radon control technique is active soil depressurization (ASD) (U.S. EPA 2006). An ASD system uses an electric fan to minimize radon entry by drawing air from under the slab/floor and venting it to the outside above the building's roofline.

A limited number of studies have investigated air cleaners' effectiveness in removing radon and its progeny. They compared the removal efficiencies of various air cleaners, including mechanical air filters, ESPs, and ionizers equipped with fans, and the risk reduction the air cleaners achieve. However, the degree of risk reduction found by these studies has been inconsistent.

## SELECTING AND USING A PORTABLE AIR CLEANER

Key parameters that influence the effectiveness of portable air cleaners include not only the fractional removal efficiency for a particular pollutant, but also the airflow rate through the air cleaner and the proximity of the air cleaner to the occupant and any pollutant sources. A helpful parameter for understanding the effectiveness of portable air cleaners is the **CADR**. The CADR is a measure of a portable air cleaner's delivery of relatively clean air, expressed in cfm. For example, an air cleaner that has a CADR of 250 for dust particles can reduce dust particle levels to the same concentration as would be achieved by adding 250 cfm of clean air to the space. The CADR is the product of the fractional removal efficiency for a particular pollutant and the airflow rate through the air cleaner. The higher the CADR the more particles the air cleaner will remove and the larger the area it can serve. A CADR can theoretically be measured and calculated for either gases or particles; however, current test standards only rate, and most manufacturers only report, CADRs for the removal of particles.

Consider an example that quantifies the effectiveness of an air-cleaning device in removing pollutants from an occupied space. The result depends on three factors: its fractional efficiency, the amount of air being filtered, and the path that the clean air follows after it leaves the filter. For example, a filter may remove 99 percent of the contaminant from the air that passes through it (i.e., have 99-percent efficiency). However, if the airflow rate through the filter is only 10 cfm in a typical room of approximately 1,000 cubic feet (e.g., approximately 10 feet by 12 feet by 8 feet), the filter will be relatively ineffective at removing contaminants from the air (i.e., 10 times less effective than if the airflow rate were 100 cfm).

## Clean Air Delivery Rates (CADRs) for Portable Air Cleaners

A voluntary standard is available for comparing the performance of portable air filters in a room at steady-state conditions during a controlled laboratory test: ANSI/AHAM AC-1-2015 (AHAM 2015). It was developed by the Association of Home Appliance Manufacturers (AHAM), a private voluntary standard-setting trade association, and is recognized by the American National Standards Institute (ANSI). The standard compares the effectiveness of portable air cleaners in a room size test chamber, as measured by the CADR. In addition to developing and maintaining this standard test method, AHAM has a portable air cleaner certification program. The organization lists AHAM certified air cleaners and their CADRs on its website at www.ahamverifide.org/search-for-products/room-air-cleaners. AHAM's online directory of certified portable air cleaners allows searches by certified CADR ratings, suggested room sizes, manufacturers, or brand names.

The AHAM CADR rating is based on the removal of three size ranges of particles as they pass through the portable air cleaner. These size ranges span a broad range of actual particle types and dimensions that overlap with each other, but they correspond to airborne contaminants that are of potential interest to consumers. Particles removed to achieve the "clean air" referred to in the CADR are described as pollen (particles ranging from 5 to 11 µm), dust (particles ranging from 0.5 to 3 µm), and tobacco smoke (particles ranging from 0.09 to 1 µm). These three pollutants are used as examples to represent large-, medium-, and small- sized particles, respectively.

Note that although AHAM uses tobacco smoke particles to represent smaller airborne particles, air cleaning is not an effective way to address environmental tobacco smoke. There are thousands of particulate and gaseous chemical compounds, including many known carcinogens, in tobacco smoke that cannot be removed effectively by air cleaning.

Also, note that **the CADR labeled on product packaging is typically the highest CADR achievable, which typically occurs at the highest airflow setting.** While lower airflow settings may have lower noise production, the CADR may not be known (but it could be considerably lower than the highest advertised and thus significantly less effective at pollutant removal).

Despite their differences, measured CADRs for each of the three tested particle size ranges are typically similar to each other for a specific air cleaner. For example, Figure 9 shows CADRs for more than 350 individual air cleaners tested by the AHAM standard and reported on the AHAM website: www.ahamdir.com. Figure 10 shows the AHAM recommended maximum room size (in square feet) for each air cleaner shown in Figure 9 (also as reported on the AHAM website).

On average, CADRs for pollen are typically approximately 5 percent greater than dust CADRs, while CADRs for tobacco smoke are approximately 4 percent lower than dust CADRs. Therefore, to understand how an air cleaner will remove small particles such as those that make up $PM_{2.5}$, tobacco smoke CADRs should be used as the most conservative estimate.

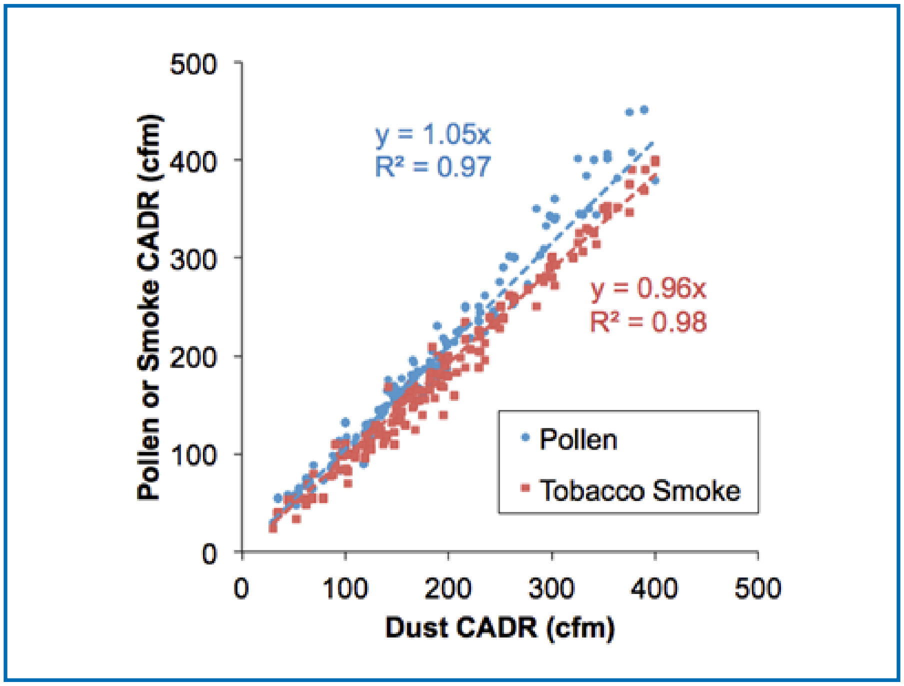

Figure 9. Comparison of CADRs for pollen, dust, and tobacco smoke particles for over 350 air cleaners tested and reported on the AHAM website: www.ahamdir.com/aham_cm/site/pages/index.html.

The ANSI/AHAM AC-1 test method also provides a way to recommend what room size an air cleaner should be specified for. The room size recommendation is calculated based on an 80-percent reduction in steady-state particle concentrations in the three size ranges of the AHAM test. This level of effectiveness assumes a flow rate of clean air that is four to five times the volume of the room dimensions used during the test. Said another way, if the unit is placed in a larger space than specified by its CADR rating, it can be expected to fall short of 80-percent reduction, and if placed in a smaller space, the unit may achieve a higher percent reduction (assuming in all cases that particle generation stays at a constant rate).

Based on the removal of tobacco smoke particles alone, Table 2 summarizes the linear fits to the data in Figure 10 to approximate the minimum CADR that would be required for various room sizes from 100 to 600 square feet. As examples, the resulting approximations of the maximum room size that a 20 cfm, 150 cfm, and 300 cfm CADR portable air cleaner would be most appropriate for are 30, 225, and 450 square feet, respectively. For reference, 30 square feet would be equivalent to a 5-foot by 6-foot room; 225 square feet would be equivalent to a 15-foot by 15-foot room; and 450 square foot would be equivalent to a 25-foot by 18-foot room in a typical one-story home.

**Table 2. Portable Air Cleaner Sizing for 80% Percent Steady-State Particle Removal**

| **Room area (square feet)** | 100 | 200 | 300 | 400 | 500 | 600 |
|---|---|---|---|---|---|---|
| **Minimum CADR (cfm)** | 65 | 130 | 195 | 260 | 325 | 390 |

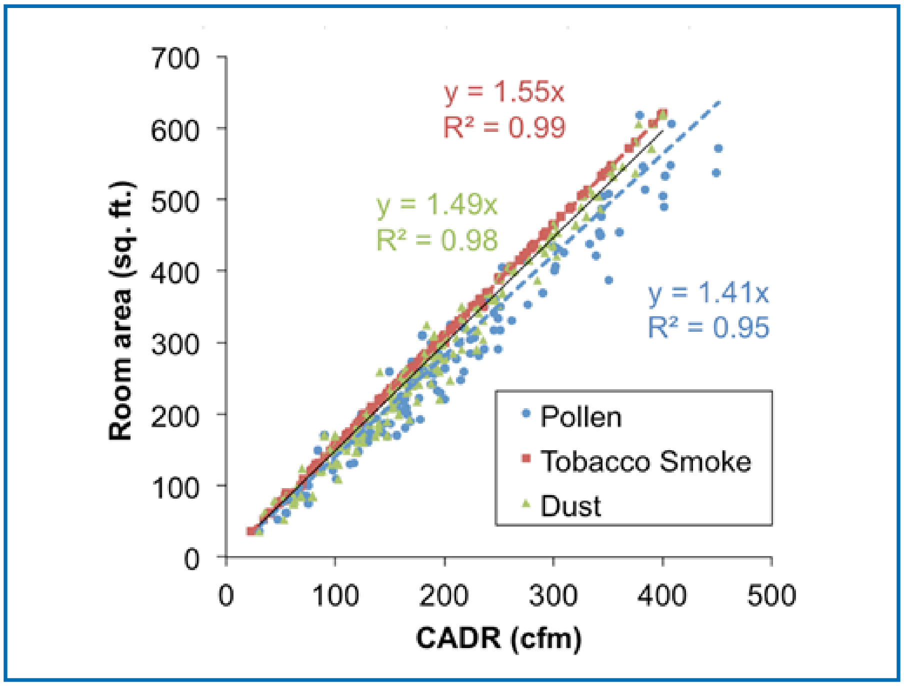

Figure 10. Maximum room size (in square feet) for which each air cleaner from Figure 9 is most appropriate (for each tested particle size category), as reported on the AHAM website: www.ahamdir.com/aham_cm/site/pages/index.html.

Many of the portable air cleaners AHAM has tested have moderate-to-high CADR ratings for small particles (Shaughnessy and Sextro 2006). **It is also important to note that a portable air cleaner's removal rate also competes with other removal processes occurring in the space, including deposition of particles on surfaces, sorption of gases, indoor air chemical reactions, and outdoor air exchange. Thus, while a portable air cleaner may not achieve its rated CADR under all circumstances, the CADR value does allow comparisons among portable air cleaners.**

In addition to evaluating CADRs for the particle size ranges involved in the AHAM test standard, studies to date have also assessed portable air cleaners' performance in removing tobacco smoke particles; diesel exhaust particles; larger airborne particles including those that contain cat, dog, and dust mite allergens; and fine and ultrafine particles (Bascom et al. 1996; Battistoni and Fava 1993; Consumers Union 2003; Custovic et al. 1998; De Blay et al. 1991; Green at al. 1999; Institute of Medicine 2000; Molgaard et al. 2014; Ongwandee and Kruewan 2013; Peck et al. 2016; Sultan et al. 2011; Van der Heide et al. 1999; Waring et al. 2008; Wood et al. 1998). These studies have generally demonstrated that CADRs for fine and ultrafine particles commonly range from less than approximately 20 cfm for ionizers and PCO portable air cleaners to between approximately 150 and 300 cfm for many HEPA and ESP portable air cleaners, depending on the size of the device.

## Portable Air Cleaner Noise

Some intervention studies involving the use of portable air cleaners have noted that portable air-cleaning units were used less frequently over time. Fewer operating hours reduces their effectiveness and, therefore, their potentially positive effect on indoor air quality and health outcomes. One study specifically noted that occupants reported excessive noise as the reason for turning off air cleaners at night (Sulser et al. 2009). Further intervention studies speculated that operating noise was a reason that air cleaners were turned off during sleeping hours (Batterman et al. 2012, 2013). That noise is a factor in consumer behavior is consistent with the observation that consumer packaging of portable air cleaners frequently includes descriptors such as "quiet". Intervention studies do not indicate what noise levels would encourage more hours of use. However, as of 2017, quantified operating noise is not a factor in the performance ratings of portable air cleaner ratings in the United States, nor are the noise values measured during performance tests commonly available to consumers on product packaging. Quantification of the operating noise of air cleaners could be a useful foundation for better informed consumer choices.

## Practical Considerations for Using Portable Air Cleaners

**Indoor particle concentrations are not constant over time.** Some indoor pollutants are periodically generated from sources such as hobby and craft materials or cooking food, and high concentrations can continue to last for long periods of time even after the source is gone. Others may infiltrate from episodic outdoor sources such as wildfire emissions (for recommendations on air cleaning to reduce exposure to wildfire smoke inside homes, refer to the EPA's 2016 document *Wildfire Smoke: A Guide for Public Health Officials*, available online at www3.epa.gov/airnow/wildfire_may2016.pdf). Therefore, a portable air cleaner would need to be operating both during and after these intermittent pollutant sources to have a meaningful effect on pollutant concentrations and exposures.

The placement of any portable air cleaner will affect its performance. For example, if there is a specific, identifiable source of pollutants, such as office appliances or other point sources, the unit should be placed so its intake is near that source. If there is no specific source, the air cleaner should be placed where it will direct clean air into the breathing zone of the occupants.

The air cleaner should not be situated where walls, furniture, curtains, and other obstructions will block the intake and outlet. Manufacturer instructions may indicate that the air cleaner be placed a certain distance from any objects that might obstruct airflow. Additionally, a portable air cleaner will be much more effective for a specific room when any exterior doors and windows in a room are closed.

**Regular filter media replacement and/or cleaning are essential for ensuring performance.** Follow manufacturer's instructions for filter replacement and/or cleaning.

**Some portable air cleaners sold to consumers are ENERGY STAR® qualified.** Earning the ENERGY STAR® means that a product meets strict energy efficiency guidelines set by EPA and the U.S. Department of Energy. The ENERGY STAR® disclaimer label, which includes the following statement, is placed on the product packaging of ENERGY STAR® qualified air cleaners: "This product earned the ENERGY STAR® by meeting strict energy efficiency guidelines set by the U.S. EPA. EPA does not endorse any manufacturer claims of healthier indoor air from the use of this product." For more detailed information on the approximate energy costs of operating portable air cleaners, refer to Table 3.

**Information about portable air cleaners is available from the *Consumer Reports* magazine/website.** Consumers Union is a nonprofit organization that provides product reviews and ratings. The details of the test method(s) used by Consumers Union to evaluate the performance of air-cleaning devices are not publically available. Consumers Union rates air cleaners based on a variety of criteria including noise.

**Caution should be exercised during replacement and cleaning of filter media and other air cleaner components.** During cleaning or replacement of air cleaners, an effort should be made to ensure that pollutants are not re-emitted into the air and do not come into contact with skin. To minimize exposures, excessive movement or air drafts should be avoided when filters are removed. Using an N-95 respirator (such as those sold for home improvement projects) and gloves can help provide additional protection during cleaning or filter replacement. Used filters should be placed in sealed plastic bags or containers for disposal.

**Noise may also be a consideration in selecting a portable air cleaner that contains a fan.** Portable air cleaners that do not have fans typically are much less effective than units that have them. In tests by Consumers Union, the largest portable air cleaners were the noisiest on their most effective high-speed settings (Consumers Union 2002). Recent peer-reviewed studies have also confirmed this same finding (Peck et al. 2016). However, some performed more quietly at low speed than many smaller cleaners do on high. Some larger portable units operating at low speed were found to be quiet enough for most households (Consumers Union 2003).

## SELECTING AND USING A FURNACE FILTER OR OTHER IN-DUCT AIR CLEANER

In addition to fractional removal efficiency metrics for furnace filters such as MERV, MPR, FPR, or HEPA, the effectiveness of furnace filters and in-duct air cleaners is influenced by several other key parameters and practical design and operation considerations.

### Practical Considerations for Using In-Duct Air Cleaners

**Removal of pollutants is often limited by system operation.** Although fractional removal efficiency ratings are an important indicator of potential performance, reduction of pollutant concentrations is a strong function of system effectiveness. The effectiveness of an in-duct filter or other air cleaner is a function of many parameters in addition to the fractional removal efficiency of the filter or air cleaner, including the airflow rate through the system relative to the size of the space and the HVAC system runtime. In most homes, central forced air heating and cooling systems only operate to meet heating and cooling needs. Although quite limited to date, experimental studies have demonstrated that typical central HVAC runtimes average less than 20 to 25 percent in most residential building types in most climate zones (James et al. 1997). Also, in some locations, such as where air-conditioning is not needed or where air-conditioning is provided by window air conditioners, central HVAC systems may not operate at all for many months of the year. Low system runtimes can greatly limit the effectiveness of an in-duct air cleaner simply by not passing air through it long enough to yield substantial reductions in indoor pollutant concentrations (Stephens 2015; Zhao et al. 2015). Because of low system runtimes, experimental data and theoretical predictions indicate that for particle removal, medium- to high-efficiency furnace filters, such as some MERV 12 filters and most MERV 13 to 16 filters, are likely to be almost as effective as HEPA filters in reducing the concentrations of most sizes of indoor particles, including those linked to health effects (Fisk et al. 2003; Zhao et al. 2015). Continuous operation of the HVAC fan will improve air circulation and air cleaning, but this operation mode also increases electrical energy consumption and its cost (NAFA 2007). For more detailed information on the approximate energy costs of operating HVAC systems with in-duct air cleaners and filters, refer to Table 3.

**Not all HVAC system fans can accommodate high-efficiency filters without affecting system performance.** Existing residential HVAC systems may not have enough fan or motor capacity to accommodate higher pressure drop filters without reducing airflow to the point where cooling or heating capacity is lost or good air mixing is sacrificed. These shortcomings can lead to increased risk of component failure and/or comfort problems in the space (Proctor 2012; Proctor et al. 2011; Walker et al. 2013). Therefore, in new installations, the HVAC manufacturer's information should be checked to determine whether it is feasible to use high-efficiency (and high pressure drop) filters, given the intended design, size, and velocity of the supply and return duct systems. In existing homes, performance of the entire installed system with respect to airflow rate versus equipment airflow and pressure capabilities can be measured to ensure that the system can accommodate the increased pressure drop imposed by adding a high-efficiency air filter; this should be done by a professional. Simply installing a high-efficiency filter is no guarantee that it will work as intended. Concerns about HVAC system performance are lessened or eliminated by use of high-efficiency filters with low airflow resistance, due to extensive pleating of filter media, increased filter thickness, and the use of electrostatically charged media. Such filters are increasingly available.

**In-duct air-cleaning devices should be installed such that bypass airflow is prevented.** Air filters should be installed so that the directional arrow printed on the side of the filter points in the direction of airflow within the system. Incorrectly designed or installed filter frames can cause bypass airflow, which significantly decreases filter effectiveness. Bypass airflow can also result from return duct leakage. If air from unconditioned spaces enters through the return duct, it can circumvent the filter, if the filter is installed at a return grille, rather than at the base of an air-handling unit. It is recommended that HVAC ducts be well sealed for return grille installations. High-efficiency filters require well-sealed frames to prevent leaks.

Table 3. Approximations of Annual Electricity Use and Electricity Costs for Operating Several Portable Air Cleaners Based on Power Draw Measurements Reported in the Literature and Assumptions for 20-, 50-, or 100-Percent Runtime

| Air cleaner type | Reference | Power draw (W) | Airflow rate (cfm) | Annual electricity use (kWh) | | | Annual electricity costs[1] | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Assumed runtime | | | | | |
| | | | | 20% | 50% | 100% | 20% | 50% | 100% |
| ESP | Waring et al. (2008) | 102 | 500 | 179 | 447 | 894 | $21 | $54 | $107 |
| HEPA 1 | | 206 | 182 | 361 | 902 | 1,805 | $43 | $108 | $217 |
| HEPA 2 | | 103 | 340 | 180 | 451 | 902 | $22 | $54 | $108 |
| Ion generator 1 | | 8 | 36 | 14 | 35 | 70 | $2 | $4 | $8 |
| Ion generator 2 | | 5 | <18 | 9 | 22 | 44 | $1 | $3 | $5 |
| HEPA 1 | Sultan et al. (2011) | 167 | 267 | 293 | 731 | 1,463 | $35 | $88 | $176 |
| HEPA 2 | | 226 | 571 | 396 | 990 | 1,980 | $48 | $119 | $238 |
| Fibrous electret | | 135 | 463 | 237 | 591 | 1,183 | $28 | $71 | $142 |
| HEPA 3 + activated carbon | | 98 | 146 | 172 | 429 | 858 | $21 | $52 | $103 |
| ESP | | 98 | 473 | 172 | 429 | 858 | $21 | $52 | $103 |
| Ion generator 1 | | 46 | 112 | 81 | 201 | 403 | $10 | $24 | $48 |
| Ion generator 2 | | 45 | 382 | 79 | 197 | 394 | $9 | $24 | $47 |
| Plasma + HEPA | | 110 | 344 | 193 | 482 | 964 | $23 | $58 | $116 |
| PCO 1 | | 444 | 913 | 778 | 1,945 | 3,889 | $93 | $233 | $467 |
| PCO 2 | | 14 | 8 | 25 | 61 | 123 | $3 | $7 | $15 |
| UVGI | | 16 | 12 | 28 | 70 | 140 | $3 | $8 | $17 |

[1] Assuming $0.12/kWh constant electricity cost.

For existing systems, installing a higher efficiency or HEPA filter may require modifications to the existing ductwork to permit the installation of the thicker filter. In addition, a more powerful fan may be needed to overcome the higher pressure drop. Electronic air cleaners and UV lamps should have an accessible power supply and an indicator showing when electrical service is off. The installation of UV lamps requires the addition of access holes into the duct, and the holes must be properly sealed to maintain HVAC efficiency. To avoid electrical and mechanical hazards, make sure air-cleaning devices that require an electrical power supply are listed on the Underwriters Laboratories website (www.ul.com) or with another independent safety testing laboratory.

**In-duct air-cleaning devices require sufficient access for inspection during use, repair, and maintenance.** In-duct air cleaners should be selected to match operating conditions, such as type of pollutant to be removed and allowable pressure drop. Filters and sorbents must be replaced regularly, in accordance with manufacturer's specifications. Electronic air cleaner efficiency decreases as the collecting plates become loaded with particles, so the plates must be cleaned, sometimes frequently, as required by the manufacturer. The cleanings should be scheduled to keep the unit operating at peak efficiency. Special attention must be given to cleaning the ionizing wires of electronic air cleaners designed to target specific contaminants.

**Turn the power off while servicing or cleaning powered in-duct air cleaners and central HVAC systems.** During cleaning or replacement of air cleaners or filters, an effort should be made to ensure that pollutants are not re-emitted into the air and do not come into contact with skin. To minimize exposures, excessive movement or air drafts should be avoided when filters are removed. Using an N-95 respirator and gloves can help provide additional protection during cleaning or filter replacement. Used filters should be placed in sealed plastic bags or other containers for disposal.

## APPROXIMATIONS OF OPERATIONAL ELECTRICITY COSTS OF PORTABLE AND IN-DUCT AIR CLEANERS

Detailed life cycle cost analyses of all types of portable and in-duct air cleaners and systems described in this document were not found in the literature, although Table 3 provides approximations of the operational electricity costs of using various portable and in-duct air cleaners. Waring et al. (2008) and Sultan et al. (2011) reported electrical power draw measurements for several types of portable air cleaners, including HEPA air cleaners (average of approximately 160 watts [W)], ion generators (average of approximately 25 W), ESPs (average of approximately 100 W), plasma (one unit combined with HEPA at approximately 110 W), PCO (average of approximately 229 W with a wide range), and UVGI (one small unit at 16 W). In general, the units with higher airflow rates also had higher power draws and were more effective air cleaners for removing ultrafine particles compared to the units with lower airflow rates and lower power draws. These air cleaners, power draws, and airflow rates are summarized in the first portion of Table 3.

Also shown in Table 3 is an approximation of the number of kilowatt-hours (kWh) and the annual electricity costs required to power selected portable air cleaners for 20, 50, and 100 percent of the hours of the year, assuming constant power draws and an average electricity cost of $0.12 per kWh. The estimated annual electricity costs for running these portable air cleaners 100 percent of the time range from less than $10 per year for a small ionizer unit to more than $450 per year for a large PCO unit. The average annual electricity costs for running portable HEPA air cleaners 100 percent of the time are just under $200 per year, with individual units ranging from just over $100 to nearly $250 per year.

For comparison, the blower fan in a typical central air-handling unit in a residential HVAC system, which commonly moves between 500 and 2,000 cfm when operating, draws between about 250 and 600 W (with an average of approximately 450 W) (Stephens et al. 2010). Running an average air-handling unit drawing approximately 450 W for 100 percent of the year would cost approximately $475, which is approximately $380 higher than the cost of running the same unit for a typical fractional runtime of approximately 20 percent to meet only heating and cooling needs (which is approximately $95). Although these cost estimates do not consider filter replacement costs, maintenance costs, or the incremental costs of changes in HVAC energy use (based on other aspects such as changes in air cleaner pressure drop over time, fan airflow rates, or heating and cooling system runtimes (Fazli et al. 2015), typically, the operational electricity cost of most portable air cleaners will likely be lower than operating central HVAC fans for the same amount of time. Note that these are approximations and the power draw of specific air cleaners and air-handling units will vary.

## WILL AIR CLEANING REDUCE HEALTH EFFECTS FROM INDOOR AIR POLLUTANTS?

In 2000, the Institute of Medicine Committee on the Assessment of Asthma and Indoor Air of the National Academy of Sciences reviewed literature on the effects of particle air cleaners on allergy and asthma symptoms and concluded that: “The results of existing experimental studies are inadequate to draw firm conclusions regarding the benefits of air cleaning for asthmatic and allergic individuals… Air cleaners are helpful in some situations in reducing allergy or asthma symptoms, particularly seasonal symptoms, but it is clear that air cleaning, as applied in the studies, is not consistently and highly effective in reducing symptoms” (Institute of Medicine 2000). Since the year 2000, technologies have advanced, and several additional studies have further investigated the impact of portable air cleaners on health outcomes or biomarkers of cardiovascular and respiratory health outcomes. Several of these studies were originally summarized in detail in Fisk (2013).

This document includes a modified version of the summary and a subjective assessment of the strength of the study design for residential air cleaner and health intervention studies from Fisk (2013). In addition, several more recent studies have also been summarized. Only those studies that focused on air cleaner interventions in residences were included in this document; studies of interventions in commercial buildings (Skulberg et al. 2005; Wargocki et al. 2008) were excluded because of the differences in the nature of indoor pollutant sources and HVAC system technologies in commercial buildings.

### Evidence for the Impacts of Air Cleaners on Indoor Pollutant Concentrations

Several recent studies have shown that the use of portable air cleaners with CADRs of about 100 to 300 cfm in living rooms and/or bedrooms can substantially reduce indoor concentrations of PM of both indoor and outdoor origin, often reducing indoor $PM_{2.5}$ concentrations by around 50 percent on average (e.g., Allen et al. 2011; Barn et al. 2008; Bräuner et al. 2008; Butz et al. 2011; Chen et al. 2015; Cui et al. 2018; Kajbafzadeh et al. 2015; Karottki et al. 2013; Lanphear et al. 2011; Park et al. 2017; Shao et al. 2017; Weichenthal et al. 2013; Xu et al. 2010).

Fewer studies have investigated the impact of portable air cleaners on gaseous pollutant concentrations or portable air cleaner use patterns over time. One study demonstrated that the use of a portable HEPA air cleaner with an activated carbon media filter also reduced indoor nitrogen dioxide concentrations in residences immediately after follow-up, although the reductions diminished over time, likely as occupants began to operate the air cleaners less often (Paulin et al. 2014). The same type of behavior was also observed in another study in which most people used their portable air cleaners when researchers were visiting often early in the study, but usage declined to only about one-third of households after researchers stopped visiting (Batterman et al. 2012). These results further confirm the importance of maintaining and actually operating any type of air-cleaning device.

A few experimental studies have also demonstrated that higher efficiency central HVAC fibrous media air filters such as MERV 13 or above can reduce indoor particle concentrations (Héroux et al 2010; Singer et al. 2016). Although they remain limited in number, they tend to confirm several existing modeling studies that demonstrate similar predicted outcomes (Azimi et al. 2016; Brown et al. 2014; MacIntosh et al. 2010; Myatt et al. 2008; Zhao et al. 2015).

Overall, field-testing and simulation studies show that high-efficiency duct-mounted and high-CADR portable air cleaners can reduce levels of airborne particles and, in some cases, gaseous pollutants in a home. High-efficiency fibrous media filters (e.g., with high MERV or HEPA rated) and activated carbon sorbent media filters have generally been shown to be the most effective while having the fewest limitations or adverse consequences.

## Evidence for the Impacts of Air Cleaners on Health Outcomes and/or Biomarkers of Health Outcomes

Studies investigating the impact of air cleaners on health outcomes and/or biomarkers of health outcomes are divided into two categories: (1) intervention studies of respiratory health outcomes in homes with subjects with allergies or asthma and (2) intervention studies of primarily cardiovascular health outcomes in homes not targeting subjects with allergies or asthma. The first group of studies is summarized in Table 4 and the second group of studies is summarized in Table 5. Each study is also summarized in more detail in a subsequent section at the end of this document.

### *Summary of the Impacts on Allergy and Asthma Health Outcomes*

A total of eight intervention studies that investigated the impact of using air cleaners in homes on respiratory health outcomes and/or changes in allergy or asthma symptoms in subjects with allergies or asthma are summarized in Table 4. Table 4 includes five studies reported in Fisk (2013) as well as two additional studies published since then and one prior study that was not included in Fisk (2013). Six studies investigated portable high-efficiency (typically HEPA) particle filters, one study investigated a bedroom outdoor air supply unit without a filter, and one study investigated a central in-duct UVGI unit. All eight studies reported statistically significant improvements in at least one health endpoint, including but not limited to objective and self-reported outcomes such as peak expiratory flow, bronchial inflammation markers, medication use, or symptoms scores. However, the magnitudes of improvements were often modest, and typically a number of other measured health outcomes were either not affected or the observed changes were not statistically significant. Changes in indoor pollutant concentrations, when measured, were generally large and statistically significant for measures such as $PM_{2.5}$ or total VOC (typically approximately 50-percent reductions in concentrations), but not for allergen or other microbial counts. These studies and others also suggest that the delivery of filtered air close to the breathing zone (for example, operating an air cleaner in a bedroom of sleeping allergic or asthmatic occupants) appears to be more effective than central HVAC or living room air filtration (Sublett 2011). Despite some effectiveness limitations for allergenic particles, the evidence indicates that air cleaners can be somewhat effective for reducing allergy or asthma symptoms in susceptible populations, although the magnitude of possible improvements is not very large.

### *Summary of the Impacts on Cardiovascular Health Outcomes*

A total of 11 intervention studies that investigated the effect of using air cleaners in homes on primarily cardiovascular health outcomes and markers of these same health outcomes in subjects without allergies or asthma are summarized in Table 5. Measured health outcomes include lung function, exhaled breath condensate, blood pressure, and/or heart rate, while markers of health outcomes include biomarkers of microvascular endothelial function, inflammation, oxidative stress, and/ or lung damage. Table 5 includes four studies reported in Fisk (2013) and seven additional studies published since then. Eight studies investigated portable high-efficiency (typically HEPA) particle filters, two studies investigated either central in-duct or window air-conditioner mounted particle filters with recirculation air, and one study investigated a window-mounted unit with outdoor air ventilation supply. Ten studies involved short-term health outcomes, while only one study involved long-term (yearlong) health outcomes.

Ten of the 11 intervention studies found a significant improvement in at least one measured cardiovascular health outcome or marker of cardiovascular health outcomes, including all of the studies with strong experimental designs. The magnitude of measured improvements in short-term health outcomes or markers was typically between 5 and 10 percent compared to control groups or conditions. The evidence of a beneficial effect was generally stronger and more consistent for studies in locations with higher particle concentrations. It should be noted that health benefits from lower exposure to airborne particles, even in healthy people, are more clearly accrued over long periods of time (years) rather than during the short duration (days to weeks) of these intervention studies (Pope and Dockery 2006). The results of these short-term studies are therefore likely capturing only a fraction of the expected benefits. In fact, in the one long-term study, some changes in health outcomes (e.g., blood pressures) were of similar magnitude to those observed in short-term studies, while changes in other health outcomes (e.g., markers of inflammation and oxidative stress) were much greater (e.g., approximately 50 percent) (Chuang et al. 2017).

### *Summary of Health Intervention Studies and Their Limitations*

Of the 20 residential intervention studies reviewed, 19 found statistically significant reductions in indoor exposures to indoor $PM_{2.5}$, $PM_{10}$, and/or particle number counts with the use of air cleaners, while levels of allergens in air or in dust were reduced in only one out of three studies reviewed that measured allergens. Most of the airborne PM exposure reductions with HEPA or other high-efficiency portable air cleaners were on the order of approximately 50 percent or higher. Only three studies investigated the use of central in-duct air cleaners, and reductions in PM exposures were not as consistently large.

Nineteen out of 20 residential intervention studies also found statistically significant associations between the introduction and use of air cleaners (and typically reduced indoor exposures) and at least one measure of health outcomes or marker of health outcomes. However, most of the health improvements were relatively modest in magnitude and, when multiple outcomes were measured, typically only a fraction of health outcomes or biomarkers of health outcomes were impacted.

Although these intervention studies suggest positive effects of air cleaners on health outcomes, caution must be taken when interpreting many of their results. For one, some studies on the health benefits of air cleaning involve multiple interventions such as use of mattress and pillow covers, exclusion of pets from the bedroom, weekly baths for pets, or vacuum cleaning, and thus are not necessarily useful in determining the effects of air cleaners alone. Additionally, multiple objective health outcomes typically were measured, but typically only a fraction of measured outcomes had significant changes, and sometimes with inconsistent diurnal patterns or lag periods between exposures and outcomes, whereas the others were either unchanged or the changes were non-significant.

Nevertheless, results from the studies reviewed herein continue to suggest, similar to Fisk (2013), that particle filtration in homes (primarily by portable air cleaners with appropriately sized CADRs) can typically reduce indoor PM concentrations of various sources and sizes by an average of approximately 50 percent, whereas allergen levels in dust are less affected. Using air cleaners has also been linked to reductions in some allergy and asthma symptoms, and lowering indoor PM concentrations with air cleaners has been shown to beneficially impact some markers of cardiovascular effects associated with exposure to indoor PM of both indoor and outdoor origin.

In addition to these intervention studies, there is sufficient evidence that reducing exposure to airborne particles in outdoor air has long-term and short-term benefits to cardiovascular and respiratory health, among others (U.S. EPA 2009). Given what is known, it is reasonable and logical to assume that, because much of human exposure to particles of outdoor origin actually occurs indoors and because air cleaning can substantially reduce indoor exposures to these particles, reduced mortality and morbidity associated with outdoor particle exposure could be achievable with the use of improved air cleaning. Several studies have estimated that potential health benefits of using particle filtration to lower indoor exposures to PM of outdoor origin, including wildfire emissions, are large, and the estimated financial benefits far exceed the estimated costs (Fisk and Chan 2017a, b; Montgomery et al. 2015; Zhao et al. 2015). Another recent modeling study came to similar conclusions for using activated carbon filters in homes to reduce indoor ozone of outdoor origin (Aldred et al. 2015).

No intervention studies to date were found that investigated the effects of gas-phase filtration, ESPs, ionizers, PCO, or plasma systems in portable or in-duct air cleaners in homes on indoor pollutant concentrations and associated health symptoms. The scarcity of data results in little scientific evidence to evaluate whether these devices are associated with a reduction in health symptoms.

## Table 4. Intervention Studies of Primarily Respiratory Health Outcomes in Homes With Subjects With Allergies or Asthma

| Study | Brehler et al. (2003) | Francis et al. (2003) | Bernstein et al. (2006) | Sulser et al. (2009) |
|---|---|---|---|---|
| Subjects | 44 adults with allergies and/or asthma | 30 adults allergic to cats or dog allergen | 19 mold-sensitized asthmatic children, age 5 to 17 years | 30 asthmatic children sensitive to pet allergen |
| Type of building | Homes (24 rural, 20 urban) | Homes with cats or dogs | Homes with central forced air HVAC systems | Homes with high cat or dog allergen levels in dust |
| Exposures focus | General particles, pollens | Pet allergen | Allergens in dust, bacterial, and fungal counts in air and dust | Pet allergen |
| First filter location, type, and CADR | Bedroom outdoor air supply (fresh air, no filter) | Bedroom (HEPA, unknown CADR) | In-duct central HVAC (CREON2000 UVGI with HEPA pre-filter) | Bedroom (220 cfm) |
| Second filter location, type, and CADR | n/a | Living room (HEPA, unknown CADR) | n/a | Living room (220 cfm) |
| Gas-phase filtration | No | No | No | No |
| Intervention period | 2 weeks | 12 months | 8 weeks | 12 months |
| Reduction in exposures | Not reported | • SS and substantial reductions in airborne cat and dog allergen in both groups<br>• Reductions in intervention group not SS relative to reductions in control group | • Small but not SS reduction in mold and bacterial counts in indoor air with UVGI unit versus placebo<br>• No SS difference in allergens or molds in house dust samples | No SS change in cat and dog allergen concentration in dust |
| Change in allergy and asthma symptoms | Subjects with seasonal allergy:<br>• Nose[a] ↓ (30%) ↔<br>• Eyes[a] ↓ (42%) ↔<br>• Lung ↔<br>Subjects with perennial allergy:<br>• Nose ↔<br>• Eyes ↔<br>• Lung ↔ | n/a | First treatment period only:<br>• Asthma symptoms ↓<br>• Asthma medication use ↓ | Nasal ↓<br>Nocturnal ↓<br>Pediatric quality of life score ↔ |
| Change in objective health outcomes | • Peak expiratory flow (PEF, a measure of how fast a person can exhale) in morning ↓ (5%)<br>• PEF in daytime ↔ | • Bronchial hyper-reactivity and/or asthma treatment requirements ↓<br>• Forced expiratory volume (FEV, how much air a person can exhale during a breath) ↔<br>• Forced vital capacity (total amount of air exhaled during an FEV test) ↔ | Both treatment periods:<br>• Peak expiratory flow (PEF) rate variability ↓ (~2% mean; ~59% median) | • Forced expiratory volume (FEV) ↔<br>• Eosinophil cationic protein (inflammation marker) ↔<br>• Non-SS trend toward improved bronchial hyper-responsiveness |
| Assessment of study strength | Strong (crossover, placebo, randomized order of exposure) | Moderate (random assignment to intervention vs. control group, no placebo) | Moderate (random assignment, placebo, crossover design), but small sample size | Strong (control group with placebo, random assignment to groups) |
| Author(s) main conclusion(s) | Recommends fresh air filtration systems in bedrooms. | "Small but significant improvement in combined asthma outcome." | "Central UV irradiation was effective at reducing airway hyper-responsiveness manifested as peak expiratory flow rate variability and some clinical symptoms." | "Although HEPA air cleaners retained airborne pet allergens, no effect on disease activity...was observed." |

Table 4 (continued). Intervention Studies of Primarily Respiratory Health Outcomes in Homes With Subjects With Allergies or Asthma

| Study | Xu et al. (2010)[e] | Butz et al. (2011) | Lanphear et al. (2011) | Park et al. (2017)[e] |
|---|---|---|---|---|
| Subjects | 30 children with asthma | 85 children with asthma[b] | 215 children with asthma | 16 children with asthma and/or allergic rhinitis |
| Type of building | Homes in New York state | Homes with smokers | Homes with smokers | Homes in California |
| Exposures focus | General particles and gases | Environmental tobacco smoke | Environmental tobacco smoke | General particles |
| First filter location, type, and CADR | Bedrooms (HEPA, ~150 cfm, with ~3 air changes per hour of outdoor air ventilation) | Bedroom (HEPA, 225 cfm) | Bedroom (HEPA, 220 cfm) | Living room (HEPA with activated carbon, ~600 cfm) |
| Second filter location, type, and CADR | n/a | Living room (HEPA, 225 cfm) | Main activity room (HEPA, 220 cfm) | Bedroom (HEPA with activated carbon, ~450 cfm) |
| Gas-phase filtration | No | Yes (activated carbon) | Yes (activated carbon and potassium permanganate zeolite) | Yes (activated carbon) |
| Intervention period | 6 weeks | 6 months | 12 months | 12 weeks |
| Reduction in exposures | • 72% ($PM_{2.5\text{–}10}$)<br>• 59% (TVOC) | • Intervention group: SS 19.9 and 8.7 μg/m$^3$ (59% and 46%) decreases in $PM_{2.5}$ and $PM_{10}$, respectively versus control group<br>• Control group: 3.5 and 2.4 μg/m$^3$ (9% and 14%) increases in $PM_{2.5}$ and $PM_{10}$, respectively<br>• No SS changes in air nicotine or urine cotinine concentrations | • SS 25% reduction in particle counts >0.3 μm in intervention group relative to 5% reduction in control group<br>• No SS reductions in particle counts >5 μm or airborne nicotine | 43% ($PM_{2.5}$) |
| Change in allergy and asthma symptoms | n/a | • Symptom-free days[c] ↓ (10%)<br>• Slow activity days ↔<br>• Nocturnal cough ↔<br>• Wheeze ↔<br>• Tight chest ↔ | • Asthma symptoms ↔ | • Asthma control test scores ↑ (~45%)<br>• Nasal symptom scores ↓ (~30%) |
| Change in objective health outcomes | • Peak expiratory flow (PEF) ↑<br>• Exhaled breath nitrate concentration (pulmonary inflammation marker) ↓<br>• Exhaled breath condensate pH (pulmonary inflammation marker) ↑ | n/a | • Unscheduled asthma-related visits to a healthcare provider ↓ (25%)<br>• Exhaled nitric oxide (inflammation indicator) ↔<br>• Medication use ↔ | • Peak expiratory flow (PEF) ↑ (~100%) |
| Assessment of study strength | Weak (all participants received crossover intervention, with randomized different timings; effect size is difficult to interpret) | Moderate (random assignment to intervention vs. control group, no placebo) | Strong (control group with placebo, random assignment to groups) | Weak (randomized control and intervention groups, small sample size of 8 homes per group, no placebo, no crossover) |
| Author(s) main conclusion(s) | "Air cleaning in combination with ventilation can effectively reduce symptoms for asthma sufferers."[d] | Air cleaners reduce particles and symptom-free days but do not prevent exposure to secondhand smoke. | Air cleaners promising "as part of multi-faceted strategy to reduce asthma morbidity." | "Reducing indoor $PM_{2.5}$ with air purifiers may be an effective means of improving clinical outcomes in patients with allergic diseases." |

SS = statistically significant; Symbols: ↑ Increase (SS unless otherwise noted), ↓ Decrease (SS unless otherwise noted), ↔ No change

[a] Improved in morning log but not subsequently in daytime log.

[b] Excluding subjects in group with air cleaners plus health coach.

[c] SS improvement in symptom-free days when subjects with air cleaners, both with and without a health coach, were compared to controls.

[d] In reality, the study did not report changes in asthma symptoms, but rather *indicators* of asthma symptoms.

[e] Not reviewed in Fisk (2013).

Table adapted from Fisk (2013) with permission from the publisher.

**Table 5. Intervention Studies of Primarily Cardiovascular Health Outcomes in Homes Not Targeting Subjects With Allergies or Asthma**

| Study | Bräuner et al. (2008) | Allen et al. (2011) | Lin et al. (2011) | Weichenthal et al. (2013) |
|---|---|---|---|---|
| Subjects | 41 healthy non-smoking adults age 60–75 | 45 adults | 60 healthy non-smoking young adults (students) | 37 adults and children, 6 with asthma |
| Type of building | Urban homes within 350 m of a major road in Denmark | 25 homes in a small city in Canada | Homes in Taiwan | First Nations homes in Canada, most with smoking |
| Exposures focus | General particles | Wood smoke | General particles | General particles, tobacco smoke |
| First filter location, type, and CADR | Bedroom (HEPA, ~320 cfm) | Bedroom of each home (HEPA, 150 cfm) | Central HVAC filter (3M Filtrete) | Main living area (224 cfm) |
| Second filter location, type, and CADR | Living room (HEPA, ~320 cfm) | Living room (HEPA, 300 cfm) | n/a | n/a |
| Gas-phase filtration | No | No | No | No |
| Intervention period | 2 days | 1 week | 4 weeks | 1 week |
| Exposure concentration without treatment | 12.6 $\mu$g/m$^3$ (PM$_{2.5}$ geometric mean)<br>9.4 $\mu$g/m$^3$ (PM$_{2.5-10}$ geometric mean)<br>10,016 cm$^{-3}$ (count 10–700 nm) | 11.2 $\mu$g/m$^3$ (PM$_{2.5}$ mean) | 22.8 ± 12.2; 24.5 ± 13.0 $\mu$g/m$^3$ (PM$_{2.5}$ mean) | 49.0 $\mu$g/m$^3$ (PM$_{10}$)<br>42.5 $\mu$g/m$^3$ (PM$_{2.5}$)<br>37.5 $\mu$g/m$^3$ (PM$_1$) |
| Reduction in exposures | 63% (PM$_{2.5}$ geometric mean)<br>51% (PM$_{10}$ geometric mean)<br>68% (count 10–700 nm) | 60% PM$_{2.5}$<br>74% levoglucosan (wood smoke marker) | ~20% reduction in PM$_{2.5}$ | 54% (PM$_{10}$)<br>61% (PM$_{2.5}$)<br>62% (PM$_1$) |
| Change in objective health outcomes | Microvascular function (coronary event predictor) ↓ (8%)<br>Hemoglobin ↓ (1%)<br>Inflammation biomarker ↔<br>Biomarker of coagulation ↔ | Reactive hyperemia index (coronary event predictor) ↓ (9%)<br>C-reactive protein (inflammation marker) ↓ (33%)<br>Oxidative stress ↔ | Systolic blood pressure ↓ (11%)<br>Diastolic blood pressure ↓ (7%)<br>Heart rate ↓ (7%) | Systolic blood pressure ↓ (7%)<br>Diastolic blood pressure ↓ (6%)<br>Forced expiratory flow (PEF) ↓ (6%)<br>Forced vital capacity ↔<br>Peak expiratory flow ↓ (8%)<br>Reactive hyperemia index (coronary event predictor) ↔ |
| Assessment of study strength | Strong (blinded, placebo-controlled intervention, within-subject, randomized order of exposure | Strong (crossover, placebo, randomized order of exposure) | Weak (intervention periods always followed periods without intervention) | Strong (randomized double blind crossover with placebo) |
| Author(s) main conclusion(s) | Filtration of recirculated air may be a feasible way of reducing the risk of cardiovascular disease. | Predictors of cardiovascular morbidity can be favorably influenced by reducing particles with air cleaners. | Air filtration can reduce indoor PM$_{2.5}$ concentrations and modify the effect of PM$_{2.5}$ on blood pressure and heart rate in a healthy, young population. | Reducing indoor PM may contribute to improved lung function in First Nation communities. |

**Table 5 (continued). Intervention Studies of Primarily Cardiovascular Health Outcomes in Homes Not Targeting Subjects With Allergies or Asthma**

| Study | Karottki et al. (2013)[e] | Chen et al. (2015)[e] | Kajbafzadeh et al. (2015)[e] | Padró-Martínez et al. (2015)[e] |
|---|---|---|---|---|
| Subjects | 48 elderly nonsmoking adults | 35 healthy university students | 83 healthy adults | 20 non-smoking adults |
| Type of building | 27 homes in Denmark | Dormitories in Shanghai, China | Homes in Vancouver, British Columbia, Canada | Public housing units within 200 m of major interstate in Somerville, Massachusetts |
| Exposures focus | General particles | Indoor particles of outdoor origin | Traffic and woodsmoke particles | Traffic-related and general indoor particles |
| First filter location, type, and CADR | Living room (HEPA, unknown CADR) | Center of the room (Filtrete, 141, 116, and 97 cfm for pollen, dust, and smoke) | Living room (HEPA, 300 cfm for smoke) | Window mounted in living rooms (MERV 17, 170 cfm with outdoor air ventilation) |
| Second filter location, type, and CADR | Bedroom (HEPA, unknown CADR) | n/a | Bedroom (HEPA, 150 cfm for smoke) | n/a |
| Gas-phase filtration | No | No | No | No |
| Intervention period | 2 weeks | 2 days | 1 week | 3 weeks |
| Exposure concentration without treatment | 8 $\mu g/m^3$ ($PM_{2.5}$ median)<br>7,669 $cm^{-3}$ (count) | 96.2 $\mu g/m^3$ ($PM_{2.5}$ mean) | 7.1 $\mu g/m^3$ ($PM_{2.5}$ mean) | 11,660 $cm^{-3}$ (count, mean of medians) |
| Reduction in exposures | ~50% ($PM_{2.5}$)<br>~30% (10–300 nm particle number) | 57% ($PM_{2.5}$) | 40% ($PM_{2.5}$) | 47% (7 nm to 3 µm number concentrations, or PNC) |
| Change in objective health outcomes | Microvascular function ↑[a] ↔<br>Lung function ↔<br>Biomarkers of systemic inflammation ↔ | Circulatory inflammatory markers:<br>• Monoctyle chemoattractant protein-1 ↓ (18%)<br>• Interleukin-1β ↓ (68%)<br>• Myeloperoxidase ↓ (33%)<br>Circulatory coagulation markers:<br>• Soluble CD40 ligand ↓ (65%)<br>Systolic blood pressure ↓ (3%)<br>Diastolic blood pressure ↓ (5%)<br>Fractional exhaled nitrous oxide ↓ (17%)<br>Several other biomarkers of inflammation, coagulation, vasoconstriction or lung function ↔ | Biomarkers of systemic inflammation:<br>• C reactive protein ↓[b]<br>• Interleukin-6 ↔<br>• Band cells ↔<br>Microvascular endothelial function ↔<br>Reactive hyperaemia index ↔ | Biomarkers of systemic inflammation and coagulation:<br>• Interleukin-6 (IL-6) ↑<br>• C reactive protein ↔<br>• Tumor necrosis factor alpha-receptor II (TNF-RII) ↔<br>• Fibrinogen ↔<br>Systolic blood pressure ↔<br>Diastolic blood pressure ↔ |
| Assessment of study strength | Strong (randomized, double-blind, crossover intervention) | Strong (randomized, double-blind crossover with placebo) | Strong (randomized, single-blind crossover with placebo) | Moderate (randomized, double-blind crossover with placebo; small sample sizes) |
| Author(s) main conclusion(s) | "Substantial exposure contrasts in the bedroom" observed. | The study "demonstrated clear cardiopulmonary benefits of indoor air purification among young, healthy adults in a Chinese city with severe ambient particulate air pollution." | The "association between C-reactive protein and indoor $PM_{2.5}$ among healthy adults in traffic-impacted areas is consistent with the hypothesis that traffic-related particles (even at low concentrations) play an important role in the cardiovascular effects of the urban PM mixture." | "HEPA filtration remains a promising, but not fully realized intervention." Associations between decreased PNC and increased IL-6 could be due to confounding factors, interference with anti-inflammatory medication use, or exposure misclassification due to time-activity patterns. |

## Table 5 (continued). Intervention Studies of Primarily Cardiovascular Health Outcomes in Homes Not Targeting Subjects With Allergies or Asthma

| Study | Chuang et al. (2017)[d] | Shao et al. (2017)[d] | Cui et al. (2018)[e] |
|---|---|---|---|
| Subjects | 200 healthy adults aged 30 to 65 years | 35 elderly adults | 70 non-smoking healthy adults aged 10 to 26 years |
| Type of building | Homes in Taipei | Homes in Beijing | Homes in a Shanghai suburb |
| Exposures focus | General particles and gases | General particles (much from outdoors) | General particles |
| First filter location, type, and CADR | Living room (3M Filtrete MPR 1000/MERV 11 in window air-conditioners) | Living room (Philips AC4374, HEPA and activated carbon with CADR of 215 cfm) | Living area (mostly dorms) (Amway Atmosphere, HEPA, and activated carbon with airflow rate of 100 cfm) |
| Second filter location, type, and CADR | Master and guest bedrooms (3M Filtrete MPR 1000/MERV 11 in window air-conditioners) | Bedroom (Philips AC4016, HEPA and activated carbon with CADR of 177 cfm) | n/a |
| Gas-phase filtration | No | Yes | Yes |
| Intervention period | 1 year | 2 weeks | 1 day (overnight) |
| Exposure concentration without treatment | • 21.4 µg/m$^3$ ($PM_{2.5}$ mean)<br>• 1.22 ppm (TVOC mean) | 60 µg/m$^3$ ($PM_{2.5}$ mean) | • 33.2 µg/m$^3$ ($PM_{2.5}$ mean)<br>• 5938 #/cm$^3$ (count mean) |
| Reduction in exposures | • ~40% ($PM_{2.5}$ mean)<br>• ~65% (TVOC mean) | ~60% ($PM_{2.5}$ mean) | • ~72% ($PM_{2.5}$ mean)<br>• ~59% (PM count mean) |
| Change in objective health outcomes | • Systolic blood pressure ↓ (7%)<br>• Diastolic blood pressure ↓ (6%)<br>• High sensitivity-C-reactive protein (hs-CRP, a marker of inflammation) ↓ (50%)<br>• 8-hydroxy-2′-deoxyguanosine (8-OHdG, a marker of oxidative stress) ↓ (53%)<br>• Fibrinogen (marker of blood coagulation) ↔ | • IL-8 (systemic inflammation) ↓ (58%)[d]<br>• Exhaled breath condensate measures ↔<br>• Lung function measures ↔<br>• Blood pressure ↔<br>• Heart rate variability ↔ | Airway impedance ↓ (7%)<br>Airway resistance ↓ (7%)<br>Small airway resistance ↓ (20%)<br>Von Willebrand factor (vWF) ↓ (27%)<br>FEV1 and FVC ↔<br>Blood pressure ↔<br>IL-6 ↔ |
| Assessment of study strength | Strong (randomized, blind, crossover intervention with large sample size and long sample duration)[c] | Moderate (randomized, blind, crossover intervention), but short duration and small sample size | Strong (randomized, blind, crossover intervention with medium/large sample size but short duration) |
| Author(s) main conclusion(s) | "…air pollution exposure was associated with systemic inflammation, oxidative stress and elevated blood pressure." And "the long-term filtration of air pollution with an air conditioner filter was associated with cardiovascular health of adults." | "…results showed that indoor air filtration produced clear improvement on indoor air quality, but no demonstrable changes in the cardio-respiratory outcomes of study interest observed in the seniors living with real-world air pollution exposures." | "A single overnight residential air filtration, capable of reducing indoor particle concentrations substantially, can lead to improved airway mechanics and reduced thrombosis risk." |

SS = statistically significant, m$^3$ = cubic meters; Symbols: ↑ Increase (SS unless otherwise noted), ↓ Decrease (SS unless otherwise noted), ↔ No change

[a] SS effects on microvascular function (~6% improvement on average) were observed among subjects not taking any vasoactive drugs when controlling for decreases indoor $PM_{2.5}$ concentrations, suggesting that improvements in vascular function were linked to the effectiveness of the air purifiers in each bedroom.

[b] A SS increase only occurred in the traffic-impacted homes, not in woodsmoke-impacted homes.

[c] The authors noted that while the intent was to blind the intervention (Filtrete) and control (coarse gauze) filters, the participants were not entirely blinded because the two filters looked very different.

[d] Measured in the combined group (both chronic obstructive pulmonary disease [COPD] and non-COPD); the COPD group also experienced a 70% reduction in IL-8.

[e] Not reviewed in Fisk (2013).

Table adapted from Fisk (2013) with permission from the publisher.

### *Detailed Descriptions of Health Intervention Studies*

Each of the intervention studies summarized in Table 4 that investigated the effects of using air cleaners in homes on objective respiratory health outcomes and/or changes in allergy or asthma symptoms in subjects with allergies or asthma is described in more detail below.

1. Brehler et al. (2003) conducted a randomized, controlled, double-blind, two-period crossover study to investigate the effectiveness of fresh air filtration systems installed in the bedrooms of 44 adult volunteers in Germany suffering from hay fever. The filtrations systems were used for a total of 4 weeks in each home: 2 weeks with an active filter and 2 weeks with a placebo. The combined ventilation and filtration systems used a fan ducted to the outside to bring in outdoor air to provide ventilation, and the outdoor air was filtered using a European F7 filter class (approximately equivalent to MERV 13). Outdoor air ventilation flow could be controlled between approximately 500 and 2,000 cfm. No indoor exposure measurements were made. There was a significant decrease in nighttime hay fever symptoms and an increase in morning peak expiratory flow rates, although no effects were observed in volunteers who also had perennial allergies.
2. Francis et al. (2003) conducted a randomized parallel-group study in the United Kingdom to investigate the clinical effects of placing portable air cleaners in the living room and bedroom of 30 asthmatic adults sensitized to and sharing a home with cats or dogs for 12 months. The study group included air cleaners and the use of HEPA filter vacuum cleaners, while the control group included the use of HEPA filter vacuum cleaners alone. The air cleaners had HEPA filters with an unknown CADR (Honeywell Model DA-5018). Measured clinical effects included measures of airway responsiveness, treatment requirement, lung function, and peak flow, results of which were combined into a single combined asthma outcome. Measurements of reservoir and airborne allergen were taken before and after the interventions. A statistically significant improvement in combined asthma outcomes was observed in 10 out of 15 subjects in the active group compared to only three out of 15 subjects in the control group after 12 months of intervention. There were no significant differences between the active and control groups for changes in measures of lung function, reservoir pet allergen, or airborne pet allergen.
3. Bernstein et al. (2006) conducted a double-blind, placebo-controlled crossover trial to investigate the effects of UV irradiation units with a HEPA pre-filter (CREON2000 units) installed in central forced air HVAC systems in the homes of 19 mold-sensitized asthmatic children, age 5 to 17 years. The study lasted 28 weeks involving 8 weeks with the UVGI unit operating and 8 weeks with the placebo operating. The order in which the systems were used was randomized among the study group. Clinical outcome measurements included morning and evening peak expiratory flow rates and variability, changes in forced expiratory volume in 1 second, changes in total rhino-conjunctivitis and asthma symptom scores and quality-of-life scores, and changes in medication use. Airborne mold and bacterial counts were also measured. Controls had a sham blue light installed in the HVAC system. There was a small

but not significant reduction in mold and bacterial counts in indoor air with the UVGI unit operating, while there was no significant difference in allergens or molds in house dust samples. The authors reported a statistically significant improvement in peak expiratory flow rate variability with the UVGI unit compared to the placebo for both treatment periods (the mean improvement was 2 percent, whereas the median improvement was approximately 59 percent). Also, during only the first treatment period, there was a statistically significant improvement in asthma symptom scores, the number of days with asthma symptoms, total asthma medication use, and peak expiratory flow rate variability in subjects receiving the UVGI units compared to the placebo units. No significant differences were observed between the UVGI units and placebo units from other clinical or environmental outcome measurements. The authors concluded that "central UV irradiation was effective at reducing airway hyper-responsiveness manifested as peak expiratory flow rate variability and some clinical symptoms."

4. Sulser et al. (2009) conducted a randomized controlled trial of 30 asthmatic children with sensitization to cat and/or dog allergens to test the effect of HEPA air cleaners (IQ Air Allergen 100 with a CADR of approximately 220 cfm) placed in the living room and bedroom on pulmonary function, allergy symptoms, and allergen levels in house dust (Sulser et al. 2009). After 6 to 12 months, there was no significant change in lung function (as measured by peak expiratory flow) or in the use of medication; however, there was a slight improvement in bronchial sensitivity. There was no change in allergen concentrations in dust samples. Overall, the study concluded that the effectiveness of these air cleaners as asthma therapy is doubtful.

5. Xu et al. (2010) conducted a field study in which a combined outdoor air ventilation supply and HEPA filtration unit was installed in the bedrooms of children with physician-diagnosed asthma for a period of 6 weeks at a time. The unit provided approximately three air changes per hour of ventilation air from outdoors and approximately nine air changes per hour of recirculation flow through the filter (i.e., a CADR of approximately 150 cfm). Exhaled breath condensate was collected every sixth day and analyzed for nitrate and pH, and peak expiratory flow was also measured. Indoor air measurements included $PM_{10}$, carbon monoxide, carbon dioxide, and TVOC in each bedroom. Indoor $PM_{10}$ and TVOC concentrations decreased with the operation of the device by an average of 72 and 59 percent, respectively. Exhaled breath condensate nitrate concentrations decreased significantly and peak expiratory flows increased significantly with operation of the unit.

6. Butz et al. (2011) tested the use of a portable air cleaner and a health coach intervention to reduce secondhand smoke exposure in children with asthma residing with a smoker. The air cleaners used were Holmes Harmony Air Purifier HAP650 with an activated carbon filter and a pleated HEPA filter and a CADR of 225 cfm. The portable air cleaners were installed in the child's bedroom and in the living room of his or her home. They measured indoor PM, nicotine, and urine cotinine concentrations and tracked the number of days with asthma symptoms in the children. Randomly assigned study

groups included those that received only air cleaners, air cleaners plus a health coach, or a delayed air cleaner installation (i.e., the control). Each group contained approximately 40 children, and the study lasted 6 months. $PM_{2.5}$ and $PM_{10}$ concentrations were significantly lower in both air cleaner groups compared to the control group, but no differences were found in indoor air nicotine or urine cotinine concentrations. The introduction of a health coach provided no additional reduction in PM concentrations. Symptom-free days were significantly increased in both air cleaner groups compared with the control group, by an average of approximately 10 percent. The study concluded that although the use of air cleaners reduced indoor PM concentrations and increased symptom-free days, it was not adequate to prevent exposure to secondhand smoke.

7. Lanphear et al. (2011) conducted a double-blind, randomized trial to test the effects of HEPA air cleaners on unscheduled asthma visits and symptoms among children with asthma exposed to secondhand smoke. The HEPA air cleaners (Austin Healthmate, with what appears to be a CADR of 220 cfm) also contained carbon-potassium permanganate-zeolite filter inserts to adsorb gases. Two air cleaners were installed; one in the child's bedroom and one in the main living area. A total of 225 children were enrolled in the study; 110 were assigned to the intervention group with an active HEPA air cleaner, and 115 to the control group with a sham air cleaner. Children in the intervention group had approximately 18 percent fewer unscheduled asthma visits than the control group, corresponding with a 25-percent reduction in particle concentrations (>0.3 μm) in the intervention group compared to a 5-percent reduction in the control group. There were no statistically significant differences in parent-reported asthma symptoms, exhaled nitric-oxide levels, air nicotine levels, or cotinine levels between groups.
8. Park et al. (2017) evaluated the effectiveness of portable air cleaners for reducing indoor $PM_{2.5}$ concentrations and health outcomes in children with asthma and/or allergic rhinitis in 16 homes in California. Air cleaners were installed in the living room and bedrooms of the subjects during a 12-week study duration. The air cleaners used a three-step filtering system: dust filter, activated carbon filter, and HEPA filter (Samsung Models AX7000 and AX9000, with CADRs of approximately 450 cfm and approximately 600 cfm). Eight homes received air purifiers, and eight homes did not. The average indoor $PM_{2.5}$ concentration was 43 percent lower in the air cleaners group (from 7.4 to 4.3 $\mu g/m^3$). At 12 weeks, the air cleaners group showed improvements in childhood asthma control test scores and mean evening peak flow rates, whereas the control group showed deterioration in the same measures. Total and daytime nasal symptoms scores were also significantly lower in the air cleaners group.

Each of the intervention studies summarized in Table 5 that investigated the effects of using air cleaners in homes on primarily cardiovascular health outcomes and/or markers of cardiovascular health outcomes—including lung function, exhaled breath condensate, blood pressure, heart rate, and/or several biomarkers of microvascular endothelial function, inflammation, oxidative stress, and/or lung damage—is described in more detail below.

1. Bräuner et al. (2008) investigated the effects of controlled exposure to indoor air particles on microvascular function and biomarkers of inflammation and oxidative stress in a healthy elderly population living in apartments in Denmark. A total of 21 non-smoking couples participated in a randomized, double-blind, crossover study with two consecutive 48-hour exposures to either particle-filtered or non-filtered air. HEPA filter air cleaners with a flow rate of 540 $m^3$/hr (approximately 320 cfm) were placed in the living room and bedroom in each apartment. Indoor air filtration significantly improved microvascular function by approximately 8 percent, and the mass concentration of $PM_{2.5}$ was more important than the total number concentration of particles 10 to 700 nm.
2. Allen et al. (2011) deployed portable HEPA air filters and placebo filtration in a randomized crossover intervention study of 45 healthy adults in a woodsmoke-impacted community during consecutive 7-day periods of filtered and non-filtered air each. The air cleaners were installed in the main activity room of the house (with a CADR of 300 cfm for tobacco smoke) as well as in the participants' bedrooms (with a CADR of 150 cfm for tobacco smoke). They measured indoor $PM_{2.5}$ concentrations using integrated gravimetric sampling and evaluated endothelial function and measures of oxidative stress and systemic inflammation as markers of cardiovascular health. HEPA filters reduced indoor $PM_{2.5}$ concentrations in 24 of 25 homes, with a mean reduction of 60 percent. Concentrations resulting from both indoor and outdoor-infiltrated sources were significantly reduced. Air filtration was associated with improved endothelial function and decreased concentrations of inflammatory biomarkers but not markers of oxidative stress. Specifically, HEPA filtration was associated with a 9.4 percent increase in reactive hyperemia index, an indicator of microvascular endothelial function, and a 32.6 percent decrease in C-reactive protein, an indicator of inflammation.
3. Lin et al. (2011) evaluated whether the use of improved central air conditioner filters (3M Filtrete) would reduce indoor $PM_{2.5}$ and impact blood pressure and heart rate in a young, healthy population of 60 students in Taiwan. Blood pressure and heart rate were monitored continuously for 48 hours at approximately 2-week intervals over the course of four home visits within a 1.5-month period each. $PM_{2.5}$ concentrations were measured at 1-minute intervals during each study period. TVOCs were also measured. Indoor $PM_{2.5}$ concentrations and participant blood pressure and heart rate were higher during the first two visits without a filter than the last two visits with the filter.
4. Weichenthal et al. (2013) conducted a crossover study on a First Nations reserve in Manitoba, Canada, of portable electrostatic air cleaners installed in the main living area of 20 homes with 37 residents. Lung function, blood pressure, and endothelial function measures were collected at the beginning and end of each week-long measurement period. The air cleaners were 3M Filtrete FAP03-RS Ultra Clean Air Purifiers with a CADR of 224 cfm for smoke. A placebo was installed for the control weeks. Indoor pollutant measurements included integrated $PM_1$, $PM_{2.5}$, and $PM_{10}$; polycyclic aromatic hydrocarbons; several VOCs; and nitrogen dioxide. Average indoor $PM_{2.5}$ concentrations were

almost 50 percent lower with the filters installed, although concentrations were still much higher than outdoors because of a high prevalence of indoor smoking. Portable air cleaner use was associated with statistically significant increases in lung flow, decreases in systolic blood pressure, and decreases in diastolic blood pressure. Consistent inverse associations were also observed between indoor $PM_{2.5}$ and lung function. The study concluded that commercially available portable air cleaners may offer substantial reductions in indoor PM concentrations and that such reductions may be associated with improved lung function, but that efforts aimed at improving indoor air quality should begin with reducing indoor sources such as smoking in these communities.

5. Karottki et al. (2013) conducted a randomized, double-blind crossover intervention study with consecutive 2-week periods with or without a portable HEPA air cleaner (with an unknown flow rate and CADR) installed in the living room and bedroom of 48 elderly nonsmoking adults in 27 homes to investigate their effects on respiratory and cardiovascular health by measures of inflammation and vascular dysfunction. Health outcome measures included blood pressure; microvascular and lung function; and hematological, inflammation, monocyte surface and lung cell damage markers measured from collected blood samples. The air cleaners reduced indoor $PM_{2.5}$ mass concentrations and particle number concentrations by approximately 50 and 30 percent on average, respectively, although the effectiveness varied by home. There were no statistically significant differences in microvascular and lung function or the biomarkers of systemic inflammation with and without the HEPA filter installed. However, there was a small impact when filtration was considered in conjunction with indoor $PM_{2.5}$ concentrations, resulting in improved microvascular function in homes with lower indoor $PM_{2.5}$ concentrations.

6. Chen et al. (2015) conducted a randomized, double-blind crossover trial of short-term portable air cleaner interventions in the dormitories of 35 healthy college students in Shanghai, China. Students were randomized into two groups and alternated the use of true or sham air purifiers for 48 hours with a 2-week interval in between. The air cleaners had a CADR of 141 for pollen, 116 for dust, and 97 for smoke and three fan speeds. Fourteen biomarkers of inflammation, coagulation, and vasoconstriction; lung function; blood pressure; and fractional exhaled nitric were measured as markers of cardiopulmonary impacts. On average, air purification resulted in a 57 percent reduction in $PM_{2.5}$ concentrations when filters were operating. Air purification was significantly associated with decreases in several circulating inflammatory and thrombogenic biomarkers, decreases in systolic and diastolic blood pressure, and decreases in fractional exhaled nitrous oxide. The effects on lung function and vasoconstriction biomarkers were beneficial but not statistically significant.

7. Kajbafzadeh et al. (2015) conducted a randomized, single-blind crossover intervention study to evaluate the effects of portable HEPA air cleaners on indoor $PM_{2.5}$ concentrations, endothelial function, and systemic inflammation among 83 healthy adults in Vancouver, British Columbia, Canada, living in traffic- or woodsmoke-impacted areas. HEPA filtration, including one located in the

living room (Honeywell Model 50300 with a CADR of 300 cfm for smoke) and one located in the bedroom (Honeywell 18150 with a CADR of 150 cfm for smoke), was associated with a 40 percent decrease in indoor $PM_{2.5}$ concentrations, but there was no relationship between $PM_{2.5}$ exposure and endothelial function. There was an association between indoor $PM_{2.5}$ concentrations and a measure of systemic inflammation in homes in areas affected by vehicle traffic but not by woodsmoke.

8. Padró-Martínez et al. (2015) conducted a randomized, double-blind crossover trial of the effects of HEPA air filter units in the living rooms of 19 public housing units located within 200 m of a highway on particle number concentrations, blood pressure, and blood biomarkers of cardiovascular health. The air cleaners were HEPAiRx units with a MERV 17 filter and an airflow rate of approximately 170 cfm. Particle number concentrations were reduced by 21 to 68 percent in the apartments, but there were no significant differences in blood pressure or three of four biomarkers, while one biomarker actually increased with the filtration units. The study noted the importance of using larger sample sizes and better understanding time-activity patterns that also contribute to exposures.
9. Chuang et al. (2017) conducted a randomized, blind crossover trial of the effects of high-efficiency window-mounted air-conditioning filters (3M Filtrete with 1000 MPR/MERV 11) installed in 200 homes in Taipei. One hundred adult participants were randomly assigned to an air filtration or control group, and six home visits were conducted per year. The control and intervention groups were then switched after 1 year. Indoor pollutant measurements included 24-hour monitoring of $PM_{2.5}$ and TVOC concentrations. Blood pressure was monitored for each participant during each visit. The morning following air pollution monitoring, blood samples were collected and analyzed for biological markers of cardiovascular health, including high sensitivity-C-reactive protein (hs-CRP), 8-hydroxy-2′-deoxyguanosine (8-OHdG, a marker of oxidative stress), and fibrinogen. Indoor $PM_{2.5}$ and TVOC concentrations were lower in the filtration intervention groups by approximately 40 and 65 percent, on average. Lower $PM_{2.5}$ and TVOC concentrations were also correlated with lower blood pressure and lower levels of hs-CRP and 8-OHdG (with no statistically significant changes in fibrinogen levels).
10. Shao et al. (2017) conducted a randomized crossover trial of the effects of portable air filtration units on indoor $PM_{2.5}$ and biomarkers of respiratory and systemic inflammation, oxidative stress, lung function, and blood pressure and autonomic nervous system function in 35 non-smoking elderly participants with and without chronic obstructive pulmonary disease (COPD) in Beijing. Portable air cleaners with HEPA and activated carbon filters (Philips AC4374 with a CADR of 215 cfm in the living room and Philips AC4016 with a CADR of 177 cfm in the bedrooms) were installed for a 2-week period in addition to a 2-week sham installation period. Measurements were conducted in 20 households. Pollutant monitoring included 10-day integrated indoor $PM_{2.5}$ and black carbon concentrations, along with elemental analysis of $PM_{2.5}$ concentrations. Clinical outcomes included measures of respiratory inflammation and oxidative stress (e.g., exhaled breath condensate),

systemic inflammation (e.g., fibrinogen, C-reactive protein, interleukin-6, interleukin-8), lung function (e.g., forced expiratory volume), and blood pressure and heart rate variability. The 10-day average indoor $PM_{2.5}$ concentrations were approximately 60 percent lower in the intervention group. The only significant change in health endpoints was that interleukin-8, a measure of systemic inflammation, was reduced in the filtration group (both the total group and the COPD group). There were no significant improvements in lung function, blood pressure, or heart rate variability the following short-term air cleaner interventions.

11. Cui et al. (2018) conducted a double-blind, randomized crossover study of the effects of portable air filtration on markers of cardiopulmonary health outcomes in 70 non-smoking healthy adults, aged 19 to 26 years, during overnight (~13 hour) periods in homes in a suburb of Shanghai, China. Each participant received both true and sham indoor air filtration, with true and sham sessions separated by a 2-week washout interval. Participants received a commercially available air purifier with a HEPA and activated carbon filters and an airflow rate of approximately 100 cfm. Participants were a combination of healthy adults and nursing students living in dormitory rooms. Each session started at 6 p.m. on a Saturday, and participants stayed and slept in their dorms with doors and windows closed until the next morning. The ordering of true and sham filtration was randomly assigned. Pollutant exposure measurements included $PM_{2.5}$, particle number (i.e., 10 nm to 1 μm), ozone, and $NO_2$. Measured markers of health outcomes included: lung function by spirometry and impulse oscillometry; respiratory inflammation by fractional exhaled nitric oxide; cardiovascular function by pulse wave analysis and systolic and diastolic blood pressure; systemic inflammation and coagulation by blood sampling and analysis for interleukin-6, soluble P-selectin (sCD62P), and von Willebrand factor (vWF); and systemic oxidative stress by urine sampling and analysis for urinary free malondialdehyde (MDA). Outdoor $PM_{2.5}$ concentrations ranged from 18.6 to 106.9 $\mu g/m^3$ during the study. Compared to sham filtration, true filtration decreased the indoor $PM_{2.5}$ and total particle number concentrations by 72.4 percent and 59.2 percent on average, respectively. True filtration significantly improved lung function measured immediately after the end of filtration, as measured by lowered airway impedance and resistance as indicators of airway mechanics. No significant improvements for spirometry indicators were observed. True filtration also significantly lowered vWF by 26.9 percent on average 24 hours after the end of the filtration period, indicating reduced risk for thrombosis. Finally, in analyses stratified by male and female participants, vWF and interleukin-6 were both significantly reduced in males while pulse pressure was significantly decreased in females. The authors concluded that a single period of overnight residential air filtration was capable of reducing indoor particle concentrations substantially and led to improved airway mechanics and reduced thrombosis risk.

## RESEARCH NEEDS

Research needs on duct-mounted and portable air-cleaning technology effectiveness:

- Conduct long-term health intervention studies of portable and in-duct air cleaners.
- Collect field measurements of pollutant removal effectiveness and conduct health intervention studies for those air-cleaning technologies that have not yet been comprehensively studied, such as PCO, plasma, UVGI, sorbent technologies, and other technologies that are currently being marketed to consumers.
- Investigate what aspects of product design and operation affect how and why consumers operate portable and in-duct air cleaners along the entire life cycle of an air cleaner (e.g., runtimes, noise, maintenance, filter changes) and how that impacts effectiveness.
- Develop and validate air cleaner test standards that specifically address indoor $PM_{2.5}$, ultrafine particles, and speciated VOCs.
- Develop and validate accurate pollutant sensors for incorporating into effective and economical consumer-grade holistic air-cleaning systems (e.g., ability to accurately measure concentrations of ultrafine particles, $PM_{2.5}$, and speciated VOCs over long periods of time).
- Assess the pollutant removal effectiveness (e.g., for fine and ultrafine particles) of ductless residential HVAC systems such as mini-split systems.
- Collect field measurements of pollutant removal effectiveness and conduct health intervention studies on emerging air-cleaning technologies such as passive material coatings and bio-walls.

## FURTHER RESOURCES

Association of Home Appliance Manufacturers (AHAM): www.aham.org

ASHRAE position document on filtration and air cleaning: www.ashrae.org/about/position-documents

CADR information: www.ahamverifide.org/search-for-products/room-air-cleaners/what-is-the-clean-air-delivery-rate-cadr

California Air Resources Board Certified Air Cleaning Devices: www.arb.ca.gov/research/indoor/aircleaners/certified.htm

*Consumer Reports*: www.consumerreports.org

EPA’s Indoor Air Quality website: www.epa.gov/indoor-air-quality-iaq

EPA’s Radon website: www.epa.gov/radon

EPA’s “Ozone Generators that are Sold as Air Cleaners”: www.epa.gov/indoor-air-quality-iaq/ozone-generators-are-sold-air-cleaners

EPA’s “Should You Have the Air Ducts in Your Home Cleaned?”: www.epa.gov/indoor-air-quality-iaq/should-you-have-air-ducts-your-home-cleaned

EPA’s “Wildfire Smoke: A Guide for Public Health Officials”: www3.epa.gov/airnow/wildfire_may2016.pdf

National Air Filtration Association (NAFA): www.nafahq.org

# ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| 8-OHdG | 8-hydroxy-2′-deoxyguanosine |
| AHAM | Association of Home Appliance Manufacturers |
| ANSI | American National Standards Institute |
| ASD | active soil depressurization |
| CADR | clean air delivery rate |
| CDC | Centers for Disease Control and Prevention |
| cfm | cubic feet per minute |
| COPD | chronic obstructive pulmonary disease |
| EPA | U.S. Environmental Protection Agency |
| ESP | electrostatic precipitator |
| FPR | Filter Performance Rating |
| hs-CRP | high sensitivity-C-reactive protein |
| HVAC | heating, ventilating, and air-conditioning |
| IEC | International Electrotechnical Commission |
| ISO | International Organization for Standardization |
| kWh | kilowatt-hour |
| µm | micrometer |
| $m^3$ | cubic meter |
| MERV | Minimum Efficiency Reporting Value |
| MPR | Microparticle Performance Rating |
| NAFA | National Air Filtration Association |
| nm | nanometer |
| PCO | photocatalytic oxidation |
| PM | particulate matter |
| $PM_{2.5}$ | fine particulate matter smaller than 2.5 µm in diameter |
| $PM_{10}$ | coarse particulate matter smaller than 10 µm in diameter |
| ppb | parts per billion |
| RRNC | radon-resistant new construction |
| TVOC | total volatile organic compounds |
| UV | ultraviolet |
| UVGI | ultraviolet germicidal irradiation |
| VOC | volatile organic compound |
| vWF | von Willebrand Factor |
| W | watts |

# GLOSSARY

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| **Acute** | Having a rapid onset and following a short but potentially severe course. |
| **Adsorption** | The physical process that occurs when liquids, gases, or suspended matter adhere to the surfaces or in the pores of a material. |
| **Air cleaner** | A device used to remove particulate or gaseous impurities from the air; examples include fibrous filter media combined with a fan, sorbent media combined with a fan, electrostatic precipitator, ion generator, ultraviolet germicidal irradiation cleaner, and photocatalytic oxidation cleaner. |
| **Air filter** | A device that removes particulate material from an airstream. |
| **Airflow resistance** | See pressure drop. |
| **Allergen** | A chemical or biological substance (e.g., pollen, animal dander, house dust mite proteins) that can cause an allergic reaction characterized by hypersensitivity (an exaggerated immune response). |
| **Allergic respiratory disease** | A collection of health conditions, including allergies and asthma, that are characterized by nasal or bronchial symptoms that can be triggered by environmental exposures. |
| **Allergy** | An exaggerated or pathological immune reaction to breathing, eating, or touching substances that have no comparable effect on the average individual. |
| **American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)** | ASHRAE is a global professional society that focuses on building systems, energy efficiency, indoor air quality, refrigeration, and sustainability technologies. |
| **Asthma** | A usually chronic inflammatory disorder of the airways characterized by intermittent episodes of wheezing, coughing, and difficulty breathing, sometimes associated with an allergy to inhaled substances. |
| **Bacterial spore** | Inactive stage of bacteria, with a thick protective coating that allows the bacteria to survive harsh environmental conditions. |
| **Chemisorption** | A process whereby a chemical substance adheres to a surface through the formation of a chemical bond. |
| **Chronic** | Marked by long duration, by frequent recurrence over a long time, and often by slowly progressing seriousness. |
| **Clean air delivery rate (CADR)** | A measure of air cleaner performance, defined as the amount of contaminant-free air delivered by the device, expressed in cubic feet per minute (cfm). CADRs are always the measurement of a unit's performance as a complete system. |

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| **Corona discharge** | An electrical discharge brought on by the ionization of a fluid surrounding a conductor, which occurs when the potential gradient exceeds a certain value. |
| **Dander** | Minute scales of skin. Dander also may contain hair or feathers. |
| **Disinfection** | The process of any reduction or prevention of growth in a microbial population with no percentage efficiency specified. |
| **Double-blind study** | A type of clinical trial study design in which the study participants and the investigators do not know the identity of the individuals in the intervention and control groups until data collection has been completed. |
| **Effectiveness (of an air cleaner)** | A measure of the ability of an air-cleaning device to remove pollutants from the space it serves. |
| **Efficiency (of an air cleaner)** | A measure of the ability of an air-cleaning device to reduce the concentration of pollutants in the air that passes once through the device. Also referred to as “single-pass” efficiency. |
| **Electret media** | Fibrous filter media with an electrostatic charged initially applied to enhance particle removal. |
| **Electrostatic precipitator (ESP)** | A type of air cleaning technology that removes particles by an active electrostatic charging process that requires electricity to charge particles that become attracted and adhere to oppositely charged plates. |
| **Fibrous media air filter** | A type of air filter that removes particles by capturing them onto fibrous fiber materials. |
| **Filter Performance Rating (FPR)** | A proprietary filter efficiency rating metric. |
| **HEPA (high-efficiency particulate air) filter** | An extended surface mechanical air filter having a minimum fractional particle removal efficiency of 99.97 percent for all particles of 0.3 µm diameter, with high efficiency for both larger and smaller particles. |
| **Ionizer (air cleaner)** | An air-cleaning device that uses a high-voltage wire or carbon fiber brushes to electrically charge air molecules, which produces negative ions onto which airborne particles attach and become charged. The charged particles can attach to nearby surfaces such as walls or furniture, or to one another, and settle faster. Also called an “ion generator.” |
| **Minimum Efficiency Reporting Value (MERV)** | A filter efficiency rating metric resulting from laboratory testing following ASHRAE Standard 52.2. |
| **Mold spore** | Tiny reproductive structures produced by vegetative mold. |
| **Microparticle Performance Rating (MPR)** | A proprietary filter efficiency rating metric. |

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| **Ozone** | Chemical symbol $O_3$; An unstable allotrope of oxygen that is formed naturally from atmospheric oxygen by electric discharge or exposure to ultraviolet radiation and is also produced in the lower atmosphere by the photochemical reaction of certain pollutants. It is poisonous at sufficiently high concentrations. |
| **Particle** | A small discrete mass of solid or liquid matter that remains individually dispersed in gas or liquid emissions (usually considered to be an atmospheric pollutant). |
| **Photocatalytic oxidation (PCO)** | An air cleaner technology that uses a high-surface-area medium coated with a catalyst such as titanium dioxide that adsorbs and reacts with gaseous pollutants when irradiated with UV light. |
| **Placebo effect** | A usually, but not necessarily, beneficial effect attributable to an expectation that an action such as a treatment will have a desired outcome. |
| **Plasma air-cleaning technology** | An air-cleaning technology that uses a high-voltage discharge to ionize incoming gases, which breaks their chemical bonds and chemically alters gaseous pollutants. |
| **Pressure drop** | The difference in pressure between two points of a fluid (such as air) in a system. Pressure drop occurs when frictional forces act on a fluid as it flows through a system. |
| **Radon** | A colorless, odorless, radioactive gas that can be found in indoor air. It comes from radium in natural sources such as rock, soil, ground water, natural gas, and mineral building materials (e.g., granite countertops). As uranium breaks down, it releases radon, which in turn produces short-lived radioactive particles called "progeny," some of which attach to dust particles. |
| **Rhinitis** | Inflammation of the mucous membrane lining of the nose. |
| **Sorption** | The common term used for adsorption or chemisorption interactions. |
| **Ultrafine particles** | Particles smaller than 0.1 µm. |
| **Ultraviolet (UV) light** | An electromagnetic radiation with a wavelength from 10 nm to 400 nm, shorter than that of visible light but longer than X-rays. |
| **UV-A** | Long-wave UV radiation (315 to 400 nm). |
| **UV-B** | Mid-wavelength UV radiation (280 to 315 nm). |
| **UV-C** | Short-wave UV radiation (100 to 280 nm). |
| **Vegetative bacteria and molds** | Microorganisms that are in the growth and reproductive stage (i.e., not spores). |
| **Volatile organic compounds (VOCs)** | Chemicals that contain carbon and are vaporous at room temperature and pressure. |

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