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Personal Interventions to Reduce Exposure to Outdoor Air Pollution

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Abstract

Unhealthy levels of air pollution are breathed by billions of people worldwide, and air pollution is the leading environmental cause of death and disability globally. Efforts to reduce air pollution at its many sources have had limited success, and in many areas of the world, poor air quality continues to worsen. Personal interventions to reduce exposure to air pollution include avoiding sources, staying indoors, filtering indoor air, using face masks, and limiting physical activity when and where air pollution levels are elevated. The effectiveness of these interventions varies widely with circumstances and conditions of use. Compared with upstream reduction or control of emissions, personal interventions place burdens and risk of adverse unintended consequences on individuals. We review evidence regarding the balance of benefits and potential harms of personal interventions for reducing exposure to outdoor air pollution, which merit careful consideration before making public health recommendations with regard to who should use personal interventions and where, when, and how they should be used.

INTRODUCTION

Ambient air pollutants include air pollutants such as $PM_{2.5}$ (particulate matter less than 2.5 microns in aerodynamic diameter), ozone, oxides of nitrogen and sulfur, and carbon monoxide, as well as hundreds of hazardous air pollutants that are less frequently monitored. Outdoor-source air pollution has been implicated in specific mortality and morbidity from an ever-growing number of diseases, including cancer and cardiovascular, developmental, reproductive, endocrine, and neurodegenerative diseases (91). In a recent analysis, an estimated 8.9 million deaths globally were attributable to $PM_{2.5}$ alone in 2015 (15). With increasing awareness of harmful outdoor air pollution concentrations, there has been among the general public an increasing interest in and use of personal interventions to reduce exposure and risk of adverse health effects.

Personal interventions are defined here as behavioral or technological interventions that are under the direct control of individuals and are intended to reduce exposure to, and health risks from, outdoor air pollution. The main personal interventions are avoiding air pollution sources, staying indoors, filtering indoor air, reducing physical activity, and using respirators or other face masks. Beyond the sphere of personal decisions and actions, public health officials are called on to consider personal interventions when making recommendations or acting to protect public health. To date, reviews of personal interventions for air pollution have focused on the need for evidence to support clinical decision-making, which involves a patient's individual susceptibilities and circumstances as well as knowledge of the effectiveness and safety of interventions (3, 17, 35, 54, 65, 73). Public health interventions at the individual level may require an even higher level of evidence for effectiveness and safety before promulgating recommendations, guidelines, or regulations that may affect millions of individuals.

The scope of this review is limited to personal interventions to reduce exposure to outdoor-source air pollution, while recognizing that indoor sources must be considered when addressing total exposure to air pollution. Also outside the scope of this review are exposure to air pollution in indoor workplaces and exposure to pollen and mold spores, as well as interventions to modify susceptibility using pharmacological agents or natural products. Most of the assessment of personal interventions for outdoor air pollution has been done in the context of middle- and high-income countries. Although the basic principles underlying the interventions may be broadly applicable, they should be applied cautiously to local conditions.

GUIDANCE ON PERSONAL INTERVENTIONS MAY VARY BASED ON CONSIDERATION OF AMBIENT POLLUTION LEVELS

An expert workshop sponsored by the American Thoracic Society (ATS) was held in 2018 to discuss the overall effectiveness and safety of personal interventions to reduce exposures and health risks of outdoor air pollution (56), focusing largely on considerations for individuals living in countries with relatively higher incomes and lower pollution levels. In early 2019, an expert consultation was convened by the World Health Organization (WHO) to discuss similar topics, but with a broader focus on global populations, including nations with relatively low incomes and high pollution levels (100). It is noteworthy that the two expert panels came to somewhat different conclusions on interpreting the appropriateness of personal interventions such as using face masks or reducing physical activity that may be more likely to have adverse effects with long-term application. Any difference in the two reports' conclusions was not due to consideration of a different body of scientific evidence or major differences of opinion between the expert groups, but rather was a recognition of how consideration of personal interventions may vary depending on whether elevated pollution levels are unusual and episodic in low-pollution locations versus regularly occurring in high-pollution locations. For example, while both panels acknowledged the need for caution in recommending the use of respirators due to potential adverse effects, the WHO panel concluded that more evidence was needed to recommend respirators for use by the general population in chronically high-pollution locations, whereas the ATS panel allowed that respirators may be effective for reducing exposure to short-term, episodic elevations in particulate matter air pollution concentrations.

CHANGES IN AIR QUALITY MAY MODIFY GUIDANCE ON PERSONAL INTERVENTIONS

More than half of the world's population was exposed to increased levels of $PM_{2.5}$ between 2010 and 2016 (85). Average concentrations decreased substantially in North America and Europe during this time period while increasing in Asia, Africa, and South America (1, 32). Given the steady improvement in ambient air pollution concentrations in the United States and other developed regions of the world, understanding long-term trends in ambient air quality provides an important context when considering the role of personal interventions to reduce the health impacts of outdoor air pollution. Here, we briefly consider the primary causes of the recent improvements in air quality in the United States, which are likely to continue over the next several years even without further policy action.

Large improvements in air quality in the United States following the 1970 Clean Air Act or the 1990 amendments to the Clean Air Act are often cited in support of the positive impact of the Act and resulting regulatory actions by federal and state air quality managers (25, 93, 94). However, improvements in air quality are not only detectable over long time periods, but also readily observable over the last decade (25). Paradoxically, over the last 20 years, a majority of respondents to surveys of the general public consistently believed that the quality of the environment is worsening, even as air quality has consistently improved over this same time period (29).

The most direct impact on ambient air quality in the United States in recent years occurred as a result of macroeconomic forces that led to a dramatic reduction in energy production from coal power plants. Since its peak in the late 2000s, electricity production from coal has been cut by more than 50%, with many of the remaining coal power plants scheduled for retirement over the next 10 years (92). Looking forward, continued improvement in air quality will not be due primarily to changes in energy mix, but rather will be due largely to the ongoing turnover of fleets of light-duty vehicles, heavy-duty vehicles, locomotives, and other internal combustion engines, which will largely continue even without additional policy intervention. The anticipated impact of retiring older-model-year engines is substantial because the vast majority of emissions from the on-road and nonroad sectors are generated by a small percentage of older-model-year vehicles. Turnover to newer, cleaner engines can be accelerated by targeted interventions that address emissions from mobile sources, nonroad sources, and ports, with attendant health benefits (62). Last, as these major sources of anthropogenic emissions continue to decline, other sources of pollution are becoming more important. In particular, the contribution of emissions from wildland fires to both ambient particulate matter and ozone concentrations continues to increase as a major contributor not only to peak pollution levels but also to ambient conditions that occur throughout the year (78).

Changes in air quality over time are a relevant consideration that should inform guidance regarding the use of personal interventions. For example, elevated levels of air pollution in many parts of the United States now occur only episodically rather than being a regular occurrence. Short-term use of personal interventions may have very different benefit and risk profiles compared with long-term use. In addition, shrinking opportunities for further emission reductions may alter the balance of responsibility for reducing individual health risks associated with outdoor air pollution.

ADDITIONAL EMISSION REDUCTIONS ARE PREFERRED OVER THE NEED FOR PERSONAL INTERVENTIONS

Recent reviews of personal interventions for air pollution affirm that emission reduction strategies are more effective and efficient than individual action (17, 54, 100). These assertions have not been based on quantitative analysis of the changes in exposure levels that are possible through broad-based improvements in air quality versus targeted efforts at the individual level. Rather, they are premised on the general concept that even small improvements in air quality experienced by an entire population will result in greater population health benefits than even potentially larger reductions in exposures among a relatively small at-risk subpopulation utilizing efficacious behavioral modifications (72, 84).

Effective personal interventions for air pollution interrupt exposure pathways from the source to the dose of air pollution (**Figure 1**). In evaluating alternative strategies, consideration should be given to the balance of overall effectiveness, including benefit, burden, cost, and potential harms. Compared with upstream interventions to reduce air pollution at its source, personal interventions place a greater burden of potential adverse effects or unintended consequences on individuals, as discussed below. Moreover, the effectiveness of behavioral modifications is limited by the degree to which these modifications are successfully adopted by individuals. Reliance on behavioral modifications that are less likely to be accessed and used by under-resourced individuals may widen disparities. More generally, the preference for emission reductions also takes into account the fairness of placing the responsibility for improvement on the source of the problem rather than requiring those affected to bear the burden of protecting themselves.

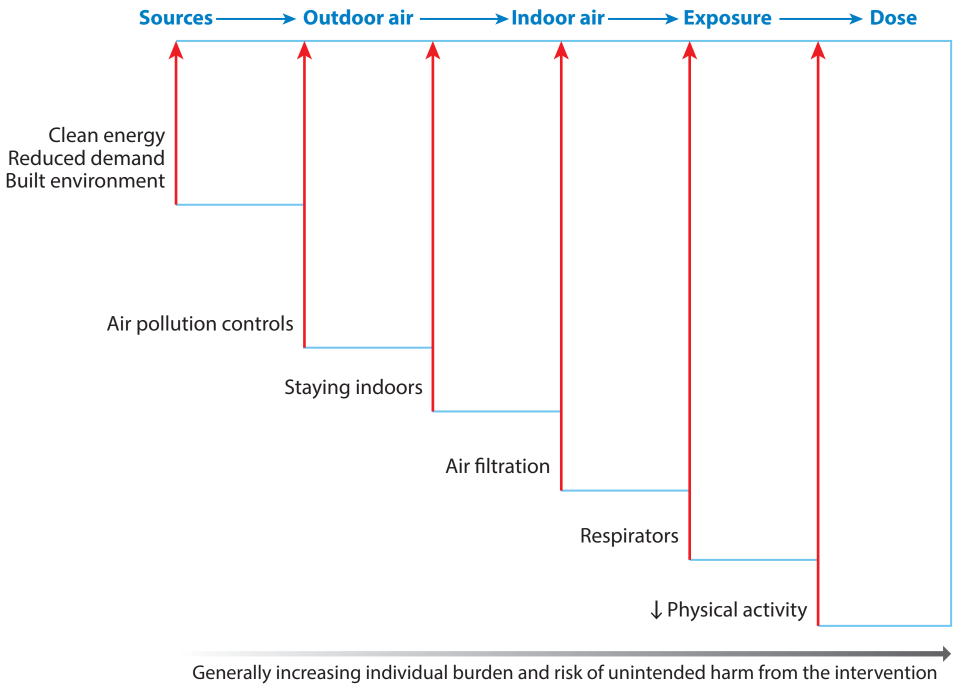

Figure 1

Successful interventions for air pollution interrupt exposure pathways. Personal interventions provide multiple barriers to reduce exposure after the failure of emission reductions and source controls to limit population exposures to air pollutants to concentrations that fall below thresholds for harm.

TARGETED EMISSION REDUCTIONS TO ADDRESS HOT-SPOT LOCATIONS SHOULD BE A PRIORITY MOVING FORWARD

Spatial variability in air pollution concentrations occurs not only at the national level, in which air pollution concentrations can vary by an order of magnitude or more, but also at finer scales within the same metropolitan area. "Hot spots" of higher pollution concentrations occurring within the same air shed can result from the close proximity to large emission sources or can result from the combined impact of multiple local emission sources, such as industrial or traffic sources. These areas of higher local air pollution often occur in communities with higher percentages of lower-income or minority populations. The excess health impacts that result from these disparities can be further exacerbated by social vulnerabilities and biological susceptibilities that can have interactive and additive effects with environmental exposures (63).

Given the current regulatory, environmental, and technological landscape, the utilization of improved exposure assessment approaches to identify hot spot locations combined with targeted interventions to reduce emission levels that impact these areas should be a primary goal for every air quality management agency in the United States and other similarly situated countries. These targeted interventions provide the greatest opportunities for improving health outcomes in the near term in situations where few options are available for large, broad-based improvements in air quality. Moreover, circumstances that would require individuals living in areas with elevated air pollutant concentrations to use personal interventions to lower their exposure levels to those of the broader community are an important equity issue and a primary environmental justice concern.

WHY IS CONSIDERATION OF PERSONAL INTERVENTIONS NECESSARY?

Even after all feasible actions have been taken to reduce emissions of harmful air pollutants, there will still remain a need for some individuals to consider the use of personal interventions to reduce exposures. This need may be due to pollution episodes caused by discrete events (e.g., wildland fires, dust storms) or due to heightened susceptibility to air pollution levels that may be relatively harmless for less susceptible individuals. By definition, the use of personal interventions places burdens on the individual, whether it be the risk of adverse health effects, discomfort, inconvenience, cost, or some other consideration that may make the use of personal interventions undesirable. The balancing of these burdens with the benefits of pollution reduction needs to be considered carefully by the individual and their health care provider.

The following sections provide a summary of the most commonly available personal interventions and the key issues to be considered when balancing the potential benefits, harms, and trade-offs that stem from the use of personal interventions for reducing exposure to and health risk from air pollution.

ROOM FOR IMPROVEMENT IN THE DEVELOPMENT, EVALUATION, AND USE OF RISK COMMUNICATION TOOLS

Improving risk communication with regard to the locations and times of peak pollution concentrations, as well as providing relevant day-to-day information on health risks associated with days that have moderate pollution levels, is an underutilized strategy for local air quality agencies to help reduce the health burdens of outdoor air pollution (23). Even as pollution levels continue to improve, the dissemination of high-quality risk communication information is needed to allow individuals to make informed decisions on the use of personal interventions that will reduce their total exposure levels (49).

For risk communication to have a positive influence on public health outcomes, the risk communication information needs to be timely, accurate, and accessible and provide information in ways that are useful to a wide range of individuals with different levels of susceptibility and risk profiles (22). Unfortunately, rigorous evaluation of risk communication tools often occurs only after these tools have been put into public use, if at all (14, 99). This failure to validate risk communication information not only creates obstacles to introducing updated or revised risk communication tools, but also can result in the communication of information that does not lead to effective mitigation of health risks (71).

Improved exposure assessment based on spatial and temporal variations in air quality is one area where risk communication can be improved. In addition, more focused efforts to adequately evaluate risk communication tools (i.e., air quality indices and their weightings of multiple air pollutants) are needed to validate that increasing index values are consistently associated with higher health risks (24, 57). The small number of validation studies that have been carried out often fail to assess how seasonal differences in pollution mixtures and concentrations may result in indices performing well for only part of the year. Finally, health messaging that accompanies reported air quality index information has room for improvement to be more evidenced based and more informative for individuals with a wide range of susceptibility to varying levels of outdoor air pollution (20, 28).

PERSONAL INTERVENTIONS TO REDUCE EXPOSURE TO AND RISK FROM OUTDOOR AIR POLLUTION

Staying Indoors

Staying indoors and sheltering in place has been a mainstay of advice for extreme air pollution events such as wildfires (55, 96). Moreover, the public may generally assume that air pollution is an outdoor problem and that they are well protected indoors, especially in their homes (44). Nonetheless, outdoor air pollution enters buildings, with widely varying efficiency, through openings and gaps in the building envelope and through open windows or doors and mechanical ventilation systems (5). Indoor concentrations of outdoor air pollutants may also be reduced by deposition on surfaces and chemical reactions. Although concentrations of outdoor air pollutants are lower indoors, most exposure to outdoor air pollution among US residents occurs in the microenvironments where they spend >90% of their time, including homes (about 70%), workplaces, schools, vehicles, etc. (46).

Total indoor $PM_{2.5}$ includes both indoor- and outdoor-source $PM_{2.5}$. A review of 77 studies that included more than 4,000 homes found that the average ratio of total indoor to outdoor $PM_{2.5}$ was ~1.0 (19). Considering only outdoor sources, the ratio of indoor to outdoor $PM_{2.5}$ averaged 0.55. In contrast with $PM_{2.5}$, ozone is a strong oxidant gas that is destroyed by chemical reactions in the air and on surfaces indoors, resulting in indoor/outdoor ozone ratios that vary from ~0.2 to 0.8, depending on building ventilation and other factors (12). These values suggest that, although the benefits of staying indoors to reduce exposure to outdoor air pollution may be diminished by indoor pollution sources, when outdoor air pollution is elevated, staying indoors can substantially reduce exposure to outdoor air pollutants. The higher the concentrations of outdoor air pollution, the greater the benefit of staying indoors in terms of both absolute and relative reduction in total exposure to outdoor-source air pollutants. Additional time spent indoors is unlikely to lead to substantial reduction in total daily exposure when outdoor air pollution levels are moderately elevated, given the proportion of time that most people in industrialized societies spend indoors at baseline. When outdoor air pollutant levels are elevated to more extreme levels (e.g., several times the usual levels), staying indoors can help to avoid short-term, peak-level exposures as well as substantially reduce total exposure.

Advice to stay indoors is not without potential unintended consequences. In addition to increased exposure to indoor-source pollutants, advice to stay indoors in hot climates may lead to heat stress in the absence of air conditioning and, if followed for prolonged periods of time, to reduced benefits from physical activity and nature contact, as well as to social isolation (74). These adverse effects may affect vulnerable, low-income communities disproportionately. Additional advice to mitigate potential adverse effects includes avoiding burning candles or incense, limiting cooking, and encouraging outdoor activity when air quality is good. Finally, the benefits of staying indoors may not be available to outdoor workers, the homeless, and people who live or work in drafty buildings with high levels of pollutant infiltration.

Air Cleaners

Residential air cleaners can reduce indoor concentrations of air pollutants arising from both indoor and outdoor sources. Air cleaners vary greatly in technology, capacity, cost, energy usage, maintenance requirements, and by-products. The two main types of residential filters are portable air cleaners and filters mounted in the ducts of an existing central air conditioning system. A 2018 US Environmental Protection Agency (EPA) review of air cleaners concluded that high-efficiency fibrous filters [high minimum efficiency reporting value (MERV) or high-efficiency particulate air (HEPA) rated] are the most effective and have the fewest limitations or adverse consequences (95). Filters in central forced air systems may be less effective, owing to intermittent operation on demand for heating or cooling (2). In a study in homes of children with asthma, portable HEPA air cleaners were found to be more effective than filters in central air systems (12).

Activated carbon filters are the only technology that has been found to be partially effective for removing gases without producing potentially harmful by-products (95). Adsorbents added to fibrous filters to remove gases generally have low capacity and limited service life (95). Electronic air cleaners, including electrostatic precipitators, ionizers, and plasma air cleaners, which create electrically charged particles or gases to remove them from the air, can also produce harmful concentrations of ozone (59). The California Air Resources Board mandates testing of air cleaners to ensure that ozone production does not reach hazardous levels, but there is currently no national regulation.

Reductions in total $PM_{2.5}$ concentrations ranging from 20% to ~70% have been observed in studies of residential HEPA or equivalent filters (26, 42, 43, 64, 70, 86). However, air filtration is efficacious for lowering PM concentrations only insofar as sufficient contaminated air flows through the filter. Higher-efficiency filters, such as the HEPA filters (99.97% efficient for 0.3 micron particles), require more pressure to move air through the filter. Given the same fan, an air cleaner with a less efficient but lower-resistance filter may paradoxically have a higher clean air delivery rate (CADR). To be efficacious, portable air cleaners must have an adequate CADR for the size of the interior space. The overall effectiveness of air cleaners in reducing occupants' exposure to indoor PM of outdoor origin will depend on usage and maintenance as well as efficacy.

Relatively few studies have considered changes in health outcomes resulting from interventions to reduce indoor pollutant concentrations. Improvement in childhood asthma symptoms and/or control has been reported in several studies, which may be attributable to a reduction in allergens as well as air pollutants (16, 39, 53, 90). Cardiovascular outcomes examined in air cleaner studies have been limited to short-term changes in surrogate biomarkers. The 2018 US EPA report reviewed 11 studies that included portable air cleaners ($N = 8$) and other air filter configurations ($N = 3$), such as higher-efficiency, duct-mounted filters in central air systems. Ten studies reported at least one significant biomarker change compared with control periods, including C-reactive protein (CRP), microvascular function, interleukin-6 (IL-6), and blood pressure, but with inconsistency across the studies (95). A systematic review of effects of home particle filtration on blood pressure changes included 10 trials that enrolled 604 participants and found a significant reduction in mean systolic blood pressure of −3.94 mm Hg [95% confidence interval (CI), −7.00 to −0.89] (98). Additional study is needed to confirm short-term improvement in blood pressure and to begin to examine long-term effects, including actual health outcomes.

Except for the potential generation of harmful by-products, such as ozone, by some electronic air cleaners as well as low-level fan noise, air cleaners generally appear to have low potential for adverse effects. However, the cost of purchasing and operating air cleaners (hundreds of US dollars per year) is a factor that limits their use and may exacerbate environmental health disparities when some people lack the economic means to pay for the improvements.

Modifying Physical Activity: Intensity, Time, and Place

The inhaled dose of air pollutants is determined by the pulmonary ventilation rate (minute ventilation) as well as the air concentration of the pollutant. During moderate exertion, minute ventilation (volume of air inhaled per minute) can increase by more than tenfold. Shifting outdoor physical exertion to locations and times at which air pollutant levels are lower will reduce the inhaled dose of air pollution (68). However, we know of no studies showing that advising patients or the general public to modify physical activity when air quality is poor results in improvement in health outcomes. Several lines of evidence from observational epidemiological studies and risk assessment models have suggested long-term cardiovascular and respiratory benefits of physical activity, despite exercise taking place in near-roadway environments with higher levels of traffic-related air pollution (4, 48). However, the potential long-term health effects of exercising when air pollutant concentrations are elevated remain uncertain since results from the Southern California Children's Health Study suggested almost two decades ago that children playing three or more sports per week in high-ozone communities were three times as likely to develop asthma compared with those exercising in low-ozone communities (61). In other studies, the acute pulmonary benefits of physical exertion among healthy adults and adults with chronic obstructive pulmonary disease (COPD) and asthma were greater when exposures to traffic-related air pollutants were lower but were not completely reversed in highly polluted environments (47, 50, 88).

In light of the proven health benefits of physical activity, it is important to carefully assess potential benefits and harms of recommendations on where and when to reduce activity. Recommendations to temporarily reduce the degree of exertion and to modify the location of physical activity (such as indoors instead of outdoors on high pollution days or away from pollution sources) should be balanced with encouragement to engage in physical activity when and where air quality is good. For example, choosing a walking or cycling route away from motor vehicle traffic can reduce exposure to traffic-related air pollutants, which typically fall to background levels within ∼400 m of major roadways (10). Likewise, avoiding later-day ozone by exercising in the morning can preserve the benefits of physical activity while minimizing exposure to ozone.

Respirators or Face Masks

Face masks, as discussed here, are air-filtering/air-purifying devices worn on the face, covering the nose and mouth, that provide widely varying levels of protection from inhalation of air pollution. Face masks may include respirators certified by governmental agencies for workplace protection, unregulated respirators, dust masks, surgical masks, cloth masks, and other improvised masks. Filtering face piece respirators (FFRs), in which the entire face piece is composed of the filtering medium, include the N95 in the United States, the KN95 in China, and the FFP2 in the European Union. The filtering material in face masks typically provides protection only against airborne particles, although some may include adsorbents, such as activated charcoal, for removal of gases. Unlike surgical masks and other loose-fitting face coverings, N95 and similar respirators are designed to achieve a very close facial fit and very efficient filtration of airborne particles (>95% removal by the filter material, for the maximum penetrating particle size of approximately 0.3 microns; smaller as well as larger particles are more efficiently removed). To maintain a tight fit and a high level of protection, respirators must be used correctly.

In principle, the efficacy of face masks for reducing exposure to particle pollution is a function of the efficiency of the filter material times the proportion of inhaled air that actually passes through the filter (76). If the face mask does not have a tight seal against the face, the contaminated air will tend to take the path of least resistance and flow through the gaps in the face seal instead of through the filter during inhalation (33). Improper size and use, facial structure, and beards can break a respirator's face seal. Prior to the use of respirators that rely on a tight face seal, the Occupational Safety and Health Administration (OSHA) and other occupational safety agencies require worker training and fit-testing, which assesses total particle penetration through the filter material and face seal leaks. Training and fit-testing are generally not available to the general public. A poorly fitted FFR may provide some protection and user face seal checks can improve fit (97), but the effectiveness of respirators used by the general public to reduce exposure to ambient air pollution is not known (38).

Regardless of the level of evidence regarding effectiveness and safety, people are already using face masks to reduce exposure to air pollution. Face masks have been commonly used in some parts of the world with more extreme air pollution levels. In the United States, nonoccupational use of face masks by the public has been far less common, until the recent wildfires and the coronavirus disease 2019 (COVID-19) pandemic. Unlike face masks that are most useful as source control to prevent the spread of COVID-19, face masks for air pollution are intended to protect the wearer. As face masks have become normalized in many urban areas of the world, some level of increased use for air pollution will likely persist after the pandemic abates.

Limited evidence from seven small crossover trials suggests that the use of FFRs during short-term exposures to high ambient air pollution may provide cardiovascular health benefits (34, 51, 52, 66, 87, 102). However, only one of these studies used a sham respirator to blind subjects and investigators and to avoid potential confounding by other effects of wearing a respirator (34). End points were limited to acute changes in biomarkers such as heart rate variability and blood pressure before and after the intervention. Four studies (51, 52, 66, 87) found lower blood pressure with the use of respirators, and two studies found no change in blood pressure (34). Three studies found higher heart rate variability (a positive effect) (51, 53, 87), but one did not (34). No controlled studies have assessed the impact of wearing respirators or face masks on chronic exposure or on clinical health outcomes with either short-term or repeated, long-term use. No studies have examined the potential benefits of using loose-fitting face masks for reducing exposure or risk from air pollution. Effectiveness in the general population is expected to be limited by discomfort with long-term use, and respirators are usually not worn during sleep.

The increased cardiac and respiratory work due to dead space and resistance that accompanies the use of respirators may have the potential to precipitate adverse cardiopulmonary events, especially with heavy exertion. Individuals who have conditions that confer increased susceptibility to air pollution, such as heart and lung disease, may also be at greater risk of adverse effects from wearing a respirator (55). Although medical clearance prior to using respirators has been required for decades by OSHA and other occupational health regulatory agencies, evidence-based standards for who can safely wear a respirator are lacking (11).

Much of the burden and potential adverse effects of face masks are attributable to the tight face seal that is essential for high levels of protection. The cavity between the interior surface of a tight-fitting respirator and the surface of the face adds physiological dead space, which is filled with air that is close to body temperature, with 100% relative humidity, and contains end-tidal air with carbon dioxide (CO_2) concentrations of up to 5% (50,000 ppm) and diminished oxygen concentration. Respirators increase the work of breathing resulting from resistance to air movement through the filtering material, although the charged electret filter material typically used in today's FFRs offers less resistance compared with earlier FFRs (101). Reported adverse effects of wearing a respirator include discomfort (heat, sweating, perceived difficulty breathing), mild physiological stress, headache, dermatitis, and psychological distress (including claustrophobia) (40).

A recent systematic review and meta-analysis of the downsides of using face masks for reducing virus transmission in any setting found that several randomized controlled trials (RCTs) measured discomfort, but most only recorded spontaneously reported events or did not report any events (7). After observational studies were included, high rates of headaches, difficulty breathing, and skin reactions were reported, in some cases in a majority of users. Duration of use increased both discomfort and nonadherence. Other studies suggested adverse psychological effects, including fear, stigma, isolation/loneliness, and reduced empathy (7). Several studies have reported greatly increased risk of new onset or exacerbated chronic headache (13, 58, 69) and facial dermatitis (18, 27, 37) with FFR use among health care workers. An additional concern about the use of face masks is that they may give the user a false sense of security, potentially leading to higher exposure than would occur in the absence of the face mask.

In contrast with reports of adverse effects in observational studies, several laboratory studies have found that the use of respirators under controlled conditions for short time periods (hours) by healthy people, including pregnant women, was well-tolerated with little effect on cardiopulmonary physiology (45, 79, 81, 82, 83). Increased blood pressure among 10 men wearing FFRs with moderate exertion in a study published in 1991 may not be applicable to today's lower-resistance FFRs (41). The potential adverse effects of rebreathing CO_2 at relatively high levels appear to deserve further study (6, 77, 79). Only a few studies have focused on groups that may be at increased risk of adverse effects, finding that respirators were well-tolerated for short periods by adults with respiratory conditions (8) and healthy children (30), although, in general, the likelihood and severity of adverse effects appears to increase with wear time (40). Little is known about the risks of adverse health effects arising from wearing respirators among the general public. Even relatively low-probability risks of adverse events may have public health significance when applied to large heterogeneous populations.

Loose-fitting face masks provide a smaller and more variable degree of protection than tight-fitting FFRs but are better tolerated, less likely to cause adverse effects, and more likely to be used. Experimental studies with loose-fitting face masks, including a wide variety of surgical masks, dust masks, and improvised masks (cloth masks, bandanas, etc.), have shown a wide range of filtration efficiencies for the filter fabric, ranging from near 0% to about 70% for respirable-sized particles (67, 75). Few studies have attempted to measure efficacy during use, which takes into account inhaled air that bypasses the filter material. Compared with tight-fitting respirators, the use of surgical masks or other face coverings appears to be well-tolerated with minimal measurable physiological effects (80). This finding is consistent with a smaller dead space and lower breathing resistance, resulting from leaky face seals compared with tight-fitting FFRs. Very few studies have examined the effects of face masks among the general population or susceptible groups in everyday settings. Infants under 2 years old had no change in oxygen saturation or end-tidal CO_2 after 30 min of wearing a surgical face mask at rest but had significantly increased heart rate and breathing rate after 2 min walking compared with no mask (60).

Holm et al. (36) recently reviewed the literature regarding efficacy and safety of use of FFRs and other face masks among children to reduce exposure to PM emissions from wildfires. The authors argued persuasively that the benefit–risk balance favored the use of FFRs and surgical masks, even when poorly fitted and used without training, given estimates of 60–70% and 20% average reductions in exposure to PM (21, 89), respectively, and given evidence that suggests few and mild physiological effects in children and healthy adults when wearing these face masks. Because of their unreliable filtering efficiency, improvised face masks should not be recommended for controlling exposure to PM when higher-quality FFRs or surgical masks are available.

In summary, although protection is highly variable and usually limited to PM, face masks are an attractive option for exposure control, because they can be used in most environments. However, compared with other personal interventions for air pollution, face masks place greater burdens on the user (**Figure 1**). Use of respirators or other face masks for protection against air pollution appears to be straightforward and intuitive, but maximizing effectiveness and minimizing potential harms depend on complex interactions between multiple factors, beginning with assessing where and when to use a face mask, choosing an appropriate face mask, and using it properly. Current evidence supports some health benefits but also some health risks from the use of respirators among the general public, and more research is needed. For some (e.g., outdoor workers, homeless individuals), face masks may be the only available option to reduce exposure. At this time, short-term use of FFRs or surgical masks by the general public to reduce exposure to PM during extreme air pollution events such as wildfires seems justified, with the caveats that limiting exertion, staying indoors, and using air conditioning and/or air filtration should be prioritized, and individuals who have respiratory or cardiovascular conditions should consult with a health care provider.

DECISION-MAKING ABOUT PERSONAL INTERVENTIONS FOR AIR POLLUTION

Making decisions about public health action in the face of uncertainty is not new to public health practice. Witness the evolution of recommendations for personal prevention interventions for the COVID-19 pandemic, which included some of those considered here: avoidance of sources (social distancing), face masks, ventilation, and air cleaners. At the present time, decisions about which personal interventions for reducing exposure and risk from air pollution are advisable—for whom and where, when, and how to implement them—are fraught with uncertainty. Air pollution itself is complex, with many types and sources, variable mixtures, and personal exposure levels that vary in intensity, frequency, and duration as people move through microenvironments over space and time. Available information on personal exposure levels has varying degrees of accuracy and reliability. We know that, in general, the risk of a wide range of adverse outcomes increases with increased exposure, but individual susceptibility is only poorly understood and there are no risk stratification algorithms for air pollution. As reviewed here, there is uncertainty about the efficacy and effectiveness of personal interventions for exposure reduction, let alone for reduction in health risk. Finally, there is also uncertainty about the likelihood and severity of adverse effects or unintended consequences of the use of the available personal interventions in diverse populations.

Despite these uncertainties, decisions must be made. Even a nondecision is a decision in favor of the status quo. A few principles may inform approaches to decisions regarding personal interventions for air pollution. It has been suggested that public health ethics demands action in the face of uncertainty, which is always present when intervening in complex systems (9). Accordingly, when evidence is incomplete and inconclusive, acting to protect health on the basis of available information and theory is the right thing to do. The bias to act is also reflected in the precautionary principle, by which we should not wait for complete information and certainty before acting to prevent harm. However, the precautionary principle can also be applied to public health interventions that may cause harm (31). Precaution in acting is also consistent with the ancient admonition, "first do no harm." To avoid stalemate when both the benefits and harms of potential interventions are uncertain, decision theory can be used to weigh the balance of benefits, harms, and costs, in comparison with other potential courses of action, and prioritize those that have the most beneficial balance.

Applied to decisions about personal interventions for reducing exposure to and risks from air pollution, these principles may support a few generalizations. As noted above, upstream interventions to reduce air pollution at its source are almost always the most effective and efficient approach to reducing population exposure to pollution and risk. Leaving technical feasibility and cost aside, in theory, the counterfactual of absent or reduced exposure to a harmful agent would be expected to provide only benefit to the population, across the whole spectrum of individual susceptibility and risk (acknowledging that in the real world, economic cost and higher order effects on health are important considerations). The more the intervention itself alters or adds to other exposures and behaviors, the greater the potential is for unintentional adverse consequences and burden on individuals (84). Interventions that add additional exposures or change behavior demand additional scrutiny and evidence for effectiveness and safety to counterbalance uncertainty about unintended consequences before being applied to large populations. All of the personal interventions for air pollution have known potential benefits and harms that are somewhat uncertain, as well as potential unintended consequences, but using respirators and reducing physical activity may require greater certainty about benefits and risks, compared with staying indoors and using air filters. In all cases, consideration of the many caveats, as outlined in the discussion above about specific personal interventions, is warranted before recommending them to large populations. Finally, education can mitigate the likelihood of misuse of personal interventions for reducing air pollution exposure, and surveillance of outcomes following policy decisions can provide a basis for revision when necessary.

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LITERATURE CITED

1. Abera A, Friberg J, Isaxon C, Jerrett M, Malmqvist E, et al. 2021. Air quality in Africa: public health implications. *Annu. Rev. Public Health* 42:193–210
2. Alavy M, Siegel JA. 2019. IAQ and energy implications of high efficiency filters in residential buildings: a review (RP-1649). *Sci. Technol. Built Environ.* 25:261–71
3. Allen RW, Barn P. 2020. Individual- and household-level interventions to reduce air pollution exposures and health risks: a review of the recent literature. *Curr. Environ. Health Rep.* 7:424–40
4. Andersen ZJ, de Nazelle A, Mendez MA, Garcia-Aymerich J, Hertel O, et al. 2015. A study of the combined effects of physical activity and air pollution on mortality in elderly urban residents: the Danish diet, cancer, and health cohort. *Environ. Health Perspect.* 123:557–63
5. Azimi P, Stephens B. 2020. A framework for estimating the US mortality burden of fine particulate matter exposure attributable to indoor and outdoor microenvironments. *J. Expo. Sci. Environ. Epidemiol.* 30:271–84
6. Azuma K, Kagi N, Yanagi U, Osawa H. 2018. Effects of low-level inhalation exposure to carbon dioxide in indoor environments: a short review on human health and psychomotor performance. *Environ. Int.* 121:51–56

7. Bakhit M, Krzyzaniak N, Scott AM, Clark J, Glasziou P, Del Mar C. 2021. Downsides of face masks and possible mitigation strategies: a systematic review and meta-analysis. *BMJ Open* 11:e044364
8. Bansal S, Harber P, Yun D, Liu D, Liu Y, et al. 2009. Respirator physiological effects under simulated work conditions. *J. Occup. Environ. Hyg.* 6:221–27
9. Bayer R, Fairchild AL. 2004. The genesis of public health ethics. *Bioethics* 18:473–92
10. Beckerman B, Jerrett M, Brook JR, Verma DK, Arain MA, Finkelstein MM. 2008. Correlation of nitrogen dioxide with other traffic pollutants near a major expressway. *Atmos. Environ.* 42:275–90
11. Belafsky S, Vlach J, McCurdy SA. 2013. Cardiopulmonary fitness and respirator clearance: an update. *J. Occup. Environ. Hyg.* 10:277–85
12. Bennett DH, Kenyon N, Tancredi D, Schenker M, Fisk WJ, et al. 2018. *Benefits of high efficiency filtration to children with asthma*. Final Rep., Calif. Air Resour. Board, Calif. Environ. Prot. Agency, Sacramento. **https://ww2.arb.ca.gov/sites/default/files/classic/research/apr/past/11-324.pdf**
13. Bharatendu C, Ong JJY, Goh Y, Tan BYQ, Chan ACY, et al. 2020. Powered air purifying respirator (PAPR) restores the N95 face mask induced cerebral hemodynamic alterations among healthcare workers during COVID-19 outbreak. *J. Neurol. Sci.* 417:117078
14. Borbet TC, Gladson LA, Cromar KR. 2018. Assessing air quality index awareness and use in Mexico City. *BMC Public Health* 18:538
15. Burnett R, Chen H, Szyszkowicz M, Fann N, Hubbell B, et al. 2018. Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter. *PNAS* 115:9592–97
16. Butz AM, Matsui EC, Breysse P, Curtin-Brosnan J, Eggleston P, et al. 2011. A randomized trial of air cleaners and a health coach to improve indoor air quality for inner-city children with asthma and secondhand smoke exposure. *Arch. Pediatr. Adolesc. Med.* 165:741–48
17. Carlsten C, Salvi S, Wong GWK, Chung KF. 2020. Personal strategies to minimise effects of air pollution on respiratory health: advice for providers, patients and the public. *Eur. Respir. J.* 55:1902056
18. Chaiyabutr C, Sukakul T, Pruksaeakanan C, Thumrongtharadol J, Boonchai W. 2021. Adverse skin reactions following different types of mask usage during the COVID-19 pandemic. *J. Eur. Acad. Dermatol. Venereol.* 35:e176–78
19. Chen C, Zhao B. 2011. Review of relationship between indoor and outdoor particles: I/O ratio, infiltration factor and penetration factor. *Atmos. Environ.* 45:275–88
20. Chen R, Wang X, Meng X, Hua J, Zhou Z, et al. 2013. Communicating air pollution-related health risks to the public: an application of the Air Quality Health Index in Shanghai, China. *Environ. Int.* 51:168–73
21. Cherrie J, Apsley A, Cowie H, Steinle S, Mueller W, et al. 2018. Effectiveness of facemasks used to protect Beijing residents against particulate air pollution. *Occup. Environ. Med.* 75:446–52
22. Cromar K, Gladson L, Jaimes Palomera M, Perlmutt L. 2021. Development of a health-based index to identify the association between air pollution and health effects in Mexico City. *Atmosphere* 12:372
23. Cromar KR, Duncan BN, Bartonova A, Benedict K, Brauer M, et al. 2019. Air pollution monitoring for health research and patient care. An official American Thoracic Society workshop report. *Ann. Am. Thorac. Soc.* 16:1207–14
24. Cromar KR, Ghazipura M, Gladson LA, Perlmutt L. 2020. Evaluating the U.S. Air Quality Index as a risk communication tool: comparing associations of index values with respiratory morbidity among adults in California. *PLOS ONE* 15:e0242031
25. Cromar KR, Gladson LA, Ewart G. 2019. Trends in excess morbidity and mortality associated with air pollution above American Thoracic Society-recommended standards, 2008–2017. *Ann. Am. Thorac. Soc.* 16:836–45
26. Cui X, Li F, Xiang J, Fang L, Chung MK, et al. 2018. Cardiopulmonary effects of overnight indoor air filtration in healthy non-smoking adults: a double-blind randomized crossover study. *Environ. Int.* 114:27–36
27. Di Altobrando A, La Placa M, Neri I, Piraccini BM, Vincenzi C. 2020. Contact dermatitis due to masks and respirators during COVID-19 pandemic: what we should know and what we should do. *Dermatol. Ther.* 33:e14528
28. Dorevitch S, Karandikar A, Washington GF, Walton GP, Anderson R, Nickels L. 2008. Efficacy of an outdoor air pollution education program in a community at risk for asthma morbidity. *J. Asthma* 45:839–44

29. Gallup. 2021. Environment. *Gallup*. **https://news.gallup.com/poll/1615/environment.aspx**
30. Goh DYT, Munn MW, Lee WLJ, Teoh OH, Rajgor DD. 2019. A randomized clinical trial to evaluate the safety, fit, comfort of a novel N95 mask in children. *Sci. Rep.* 9:18952
31. Goldstein BD. 2001. The precautionary principle also applies to public health actions. *Am. J. Public Health* 91:1358–61
32. Gómez Peláez LM, Santos JM, de Almeida Albuquerque TT, Reis NC Jr., Andreão WL, de Fátima Andrade M. 2020. Air quality status and trends over large cities in South America. *Environ. Sci. Policy* 114:422–35
33. Grinshpun SA, Yermakov M, Reponen T, Simmons M, LeMasters GK, Ryan PH. 2014. Traffic particles in ambient air of a major US urban area: Has anything changed over a decade? *Aerosol Air Q. Res.* 14:1344–51
34. Guan T, Hu S, Han Y, Wang R, Zhu Q, et al. 2018. The effects of facemasks on airway inflammation and endothelial dysfunction in healthy young adults: a double-blind, randomized, controlled crossover study. *Part. Fibre Toxicol.* 15:30
35. Hadley MB, Baumgartner J, Vedanthan R. 2018. Developing a clinical approach to air pollution and cardiovascular health. *Circulation* 137:725–42
36. Holm SM, Miller MD, Balmes JR. 2021. Health effects of wildfire smoke in children and public health tools: a narrative review. *J. Expo. Sci. Environ. Epidemiol.* 31:1–20
37. Hu K, Fan J, Li X, Gou X, Li X, Zhou X. 2020. The adverse skin reactions of health care workers using personal protective equipment for COVID-19. *Medicine* 99:e20603
38. Huang W, Morawska L. 2019. Face masks could raise pollution risks. *Nature* 574:29–30
39. James C, Bernstein DI, Cox J, Ryan P, Wolfe C, et al. 2020. HEPA filtration improves asthma control in children exposed to traffic-related airborne particles. *Indoor Air* 30:235–43
40. Johnson AT. 2016. Respirator masks protect health but impact performance: a review. *J. Biol. Eng.* 10:4
41. Jones JG. 1991. The physiological cost of wearing a disposable respirator. *Am. Ind. Hyg. Assoc. J.* 52:219–25
42. Kajbafzadeh M, Brauer M, Karlen B, Carlsten C, van Eeden S, Allen RW. 2015. The impacts of traffic-related and woodsmoke particulate matter on measures of cardiovascular health: a HEPA filter intervention study. *Occup. Environ. Med.* 72:394–400
43. Karottki DG, Spilak M, Frederiksen M, Gunnarsen L, Brauner EV, et al. 2013. An indoor air filtration study in homes of elderly: cardiovascular and respiratory effects of exposure to particulate matter. *Environ. Health* 12:116
44. Kelly FJ, Fussell JC. 2019. Improving indoor air quality, health and performance within environments where people live, travel, learn and work. *Atmos. Environ.* 200:90–109
45. Kim J-H, Benson SM, Roberge RJ. 2013. Pulmonary and heart rate responses to wearing N95 filtering facepiece respirators. *Am. J. Infect. Control* 41:24–27
46. Klepeis NE, Nelson WC, Ott WR, Robinson JP, Tsang AM, et al. 2001. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *J. Expo. Anal. Environ. Epidemiol.* 11:231–52
47. Kubesch N, De Nazelle A, Guerra S, Westerdahl D, Martinez D, et al. 2015. Arterial blood pressure responses to short-term exposure to low and high traffic-related air pollution with and without moderate physical activity. *Eur. J. Prev. Cardiol.* 22:548–57
48. Kubesch NJ, Therming Jorgensen J, Hoffmann B, Loft S, Nieuwenhuijsen MJ, et al. 2018. Effects of leisure-time and transport-related physical activities on the risk of incident and recurrent myocardial infarction and interaction with traffic-related air pollution: a cohort study. *J. Am. Heart Assoc.* 7:e009554
49. Kyrkilis G, Chaloulakou A, Kassomenos PA. 2007. Development of an aggregate Air Quality Index for an urban Mediterranean agglomeration: relation to potential health effects. *Environ. Int.* 33:670–76
50. Laeremans M, Dons E, Avila-Palencia I, Carrasco-Turigas G, Orjuela-Mendoza JP, et al. 2018. Black carbon reduces the beneficial effect of physical activity on lung function. *Med. Sci. Sports Exerc.* 50:1875–81
51. Langrish JP, Li X, Wang S, Lee MMY, Barnes GD, et al. 2012. Reducing personal exposure to particulate air pollution improves cardiovascular health in patients with coronary heart disease. *Environ. Health Perspect.* 120:367–72

52. Langrish JP, Mills NL, Chan JK, Leseman DL, Aitken RJ, et al. 2009. Beneficial cardiovascular effects of reducing exposure to particulate air pollution with a simple facemask. *Part Fibre Toxicol*. 6:8
53. Lanphear BP, Hornung RW, Khoury J, Yolton K, Lierl M, Kalkbrenner A. 2011. Effects of HEPA air cleaners on unscheduled asthma visits and asthma symptoms for children exposed to secondhand tobacco smoke. *Pediatrics* 127:93–101
54. Laumbach R, Meng Q, Kipen H. 2015. What can individuals do to reduce personal health risks from air pollution? *J. Thorac. Dis.* 7:97–107
55. Laumbach RJ. 2019. Clearing the air on personal interventions to reduce exposure to wildfire smoke. *Ann. Am. Thorac. Soc.* 16:815–18
56. Laumbach RJ, Cromar KR, Adamkiewicz G, Carlsten C, Charpin D, et al. 2021. Personal interventions for reducing exposure and risk for outdoor air pollution: an official American Thoracic Society workshop report. *Ann. Am. Thorac. Soc.* 18:1435–43
57. Li X, Xiao J, Lin H, Liu T, Qian Z, et al. 2017. The construction and validity analysis of AQHI based on mortality risk: a case study in Guangzhou, China. *Environ. Pollut.* 220:487–94
58. Lim ECH, Seet RCS, Lee K-H, Wilder-Smith EPV, Chuah BYS, Ong BKC. 2006. Headaches and the N95 face-mask amongst healthcare providers. *Acta Neurol. Scand.* 113:199–202
59. Liu W, Huang J, Lin Y, Cai C, Zhao Y, et al. 2020. Negative ions offset cardiorespiratory benefits of $PM_{2.5}$ reduction from residential use of negative ion air purifiers. *Indoor Air* 31:220–28
60. Lubrano R, Bloise S, Testa A, Marcellino A, Dilillo A, et al. 2021. Assessment of respiratory function in infants and young children wearing face masks during the COVID-19 pandemic. *JAMA Netw. Open* 4:e210414
61. McConnell R, Berhane K, Gilliland F, London SJ, Islam T, et al. 2002. Asthma in exercising children exposed to ozone: a cohort study. *Lancet* 359:386–91
62. Meng Y-Y, Su SG, Chen X, Molitor J, Yue D, Jerrett M. 2021. *Improvements in air quality and health outcomes among California Medicaid enrollees due to goods movement actions*. Rep. 205, Health Effects Inst., Boston. **https://www.healtheffects.org/system/files/meng-rr205-report.pdf**
63. Morello-Frosch R, Zuk M, Jerrett M, Shamasunder B, Kyle AD. 2011. Understanding the cumulative impacts of inequalities in environmental health: implications for policy. *Health Aff.* 30:879–87
64. Morishita M, Adar SD, D'Souza J, Ziemba RA, Bard RL, et al. 2018. Effect of portable air filtration systems on personal exposure to fine particulate matter and blood pressure among residents in a low-income senior facility a randomized clinical trial. *JAMA Internal Med.* 178:1350–57
65. Morishita M, Thompson KC, Brook RD. 2015. Understanding air pollution and cardiovascular diseases: Is it preventable? *Curr. Cardiovasc. Risk. Rep.* 9:30
66. Morishita M, Wang L, Speth K, Zhou N, Bard RL, et al. 2019. Acute blood pressure and cardiovascular effects of near-roadway exposures with and without N95 respirators. *Am. J. Hypertens.* 32:1054–65
67. Mueller W, Horwell CJ, Apsley A, Steinle S, McPherson S, et al. 2018. The effectiveness of respiratory protection worn by communities to protect from volcanic ash inhalation. Part I: filtration efficiency tests. *Int. J. Hyg. Environ. Health* 221:967–76
68. Nyhan M, McNabola A, Misstear B. 2014. Comparison of particulate matter dose and acute heart rate variability response in cyclists, pedestrians, bus and train passengers. *Sci. Total Environ.* 468–469:821–31
69. Ong JJY, Bharatendu C, Goh Y, Tang JZY, Sooi KWX, et al. 2020. Headaches associated with personal protective equipment—a cross-sectional study among frontline healthcare workers during COVID-19. *Headache* 60:864–77
70. Park H-K, Cheng K-C, Tetteh AO, Hildemann LM, Nadeau KC. 2017. Effectiveness of air purifier on health outcomes and indoor particles in homes of children with allergic diseases in Fresno, California: a pilot study. *J. Asthma* 54:341–46
71. Peaslee M, Nelson J, Reed E, Sexton L. 2020. Effect of air quality alerts on intended behavior change. In *Advances in Physical, Social & Occupational Ergonomics*, ed. W Karwowski, RS Goonetilleke, S Xiong, RHM Goossens, A Murata, pp. 386–93. Cham, Switz.: Springer
72. Perlmutt L, Stieb D, Cromar K. 2017. Accuracy of quantification of risk using a single-pollutant Air Quality Index. *J. Expo. Sci. Environ. Epidemiol.* 27:24–32

73. Rajagopalan S, Brauer M, Bhatnagar A, Bhatt DL, Brook JR, et al. 2020. Personal-level protective actions against particulate matter air pollution exposure: a scientific statement from the American Heart Association. *Circulation* 142:e411–31
74. Ren J, Li B, Yu D, Liu J, Ma Z. 2016. Approaches to prevent the patients with chronic airway diseases from exacerbation in the haze weather. *J. Thorac. Dis.* 8:E1–7
75. Rengasamy S, Eimer B, Shaffer RE. 2010. Simple respiratory protection—evaluation of the filtration performance of cloth masks and common fabric materials against 20–1000 nm size particles. *Ann. Occup. Hyg.* 54:789–98
76. Rengasamy S, Eimer BC. 2011. Total inward leakage of nanoparticles through filtering facepiece respirators. *Ann. Occup. Hyg.* 55:253–63
77. Rhee MSM, Lindquist CD, Silvestrini MT, Chan AC, Ong JJY, Sharma VK. 2021. Carbon dioxide increases with face masks but remains below short-term NIOSH limits. *BMC Infect. Dis.* 21:354
78. Rice MB, Henderson SB, Lambert AA, Cromar KR, Hall JA, et al. 2021. Respiratory impacts of wildland fire smoke: future challenges and policy opportunities. An official American Thoracic Society workshop report. *Ann. Am. Thorac. Soc.* 18:921–30
79. Roberge RJ, Coca A, Williams WJ, Powell JB, Palmiero AJ. 2010. Physiological impact of the N95 filtering facepiece respirator on healthcare workers. *Respir. Care* 55:569–77
80. Roberge RJ, Kim J-H, Benson SM. 2012. Absence of consequential changes in physiological, thermal and subjective responses from wearing a surgical mask. *Respir. Physiol. Neurobiol.* 181:29–35
81. Roberge RJ, Kim J-H, Palmiero A, Powell JB. 2015. Effect of pregnancy upon facial anthropometrics and respirator fit testing. *J. Occup. Environ. Hyg.* 12:761–66
82. Roberge RJ, Kim J-H, Powell JB. 2014. N95 respirator use during advanced pregnancy. *Am. J. Infect. Control* 42:1097–100
83. Roberge RJ, Kim J-H, Powell JB, Shaffer RE, Ylitalo CM, Sebastian JM. 2013. Impact of low filter resistances on subjective and physiological responses to filtering facepiece respirators. *PLOS ONE* 8:e84901
84. Rose G. 1985. Sick individuals and sick populations. *Int. J. Epidemiol.* 14:32–38
85. Shaddick G, Thomas ML, Mudu P, Ruggeri G, Gumy S. 2020. Half the world's population are exposed to increasing air pollution. *npj Clim. Atmos. Sci.* 3:23
86. Shao D, Du Y, Liu S, Brunekreef B, Meliefste K, et al. 2017. Cardiorespiratory responses of air filtration: a randomized crossover intervention trial in seniors living in Beijing: Beijing Indoor Air Purifier StudY, BIAPSY. *Sci. Total Environ.* 603–604:541–49
87. Shi J, Lin Z, Chen R, Wang C, Yang C, et al. 2017. Cardiovascular benefits of wearing particulate-filtering respirators: a randomized crossover trial. *Environ. Health Perspect.* 125:175–80
88. Sinharay R, Gong J, Barratt B, Ohman-Strickland P, Ernst S, et al. 2018. Respiratory and cardiovascular responses to walking down a traffic-polluted road compared with walking in a traffic-free area in participants aged 60 years and older with chronic lung or heart disease and age-matched healthy controls: a randomised, crossover study. *Lancet* 391:339–49
89. Steinle S, Sleeuwenhoek A, Mueller W, Horwell CJ, Apsley A, et al. 2018. The effectiveness of respiratory protection worn by communities to protect from volcanic ash inhalation. Part II: Total inward leakage tests. *Int. J. Hyg. Environ. Health* 221:977–84
90. Sublett JL. 2011. Effectiveness of air filters and air cleaners in allergic respiratory diseases: a review of the recent literature. *Curr. Allergy Asthma Rep.* 11:395–402
91. Thurston GD, Kipen H, Annesi-Maesano I, Balmes J, Brook RD, et al. 2017. A joint ERS/ATS policy statement: What constitutes an adverse health effect of air pollution? An analytical framework. *Eur. Respir. J.* 49:1600419
92. US EIA (Energy Inf. Adm.). 2021. *Monthly energy review*. Rep., US EIA, Washington, DC. **https://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf**
93. US EPA (Environ. Prot. Agency). 1997. *The benefits and costs of the Clean Air Act, 1970 to 1990: retrospective study*. Rep., US EPA, Washington, DC. **https://www.epa.gov/clean-air-act-overview/benefits-and-costs-clean-air-act-1970-1990-retrospective-study**
94. US EPA (Environ. Prot. Agency). 2011. *Benefits and costs of the Clean Air Act 1990–2020, the second prospective study*. Rep., US EPA, Washington, DC. **https://www.epa.gov/clean-air-act-overview/benefits-and-costs-clean-air-act-1990-2020-second-prospective-study**

95. US EPA (Environ. Prot. Agency). 2018. *Residential air cleaners: a technical summary*. EPA 402-F-09-002, US EPA, Washington, DC. **https://www.epa.gov/sites/default/files/2018-07/documents/residential_air_cleaners_-_a_technical_summary_3rd_edition.pdf**
96. US EPA (Environ. Prot. Agency). 2021. *Wildfire smoke: a guide for public health officials. Revised 2019*. EPA-452/R-21-901, US EPA, Research Triangle Park, NC. **https://www.airnow.gov/sites/default/files/2021-09/wildfire-smoke-guide_0.pdf**
97. Viscusi DJ, Bergman MS, Zhuang Z, Shaffer RE. 2012. Evaluation of the benefit of the user seal check on N95 filtering facepiece respirator fit. *J. Occup. Environ. Hyg.* 9:408–16
98. Walzer D, Gordon T, Thorpe L, Thurston G, Xia Y, et al. 2020. Effects of home particulate air filtration on blood pressure: a systematic review. *Hypertension* 76:44–50
99. Wen X-J, Balluz L, Mokdad A. 2009. Association between media alerts of air quality index and change of outdoor activity among adult asthma in six states, BRFSS, 2005. *J. Community Health* 34:40–46
100. WHO (World Health Organ.). 2020. *Personal interventions and risk communication on air pollution*. Meet. Rep., WHO, Geneva. **https://www.who.int/publications/i/item/9789240000278**
101. Xu J, Xiao X, Zhang W, Xu R, Kim SC, et al. 2020. Air-filtering masks for respiratory protection from $PM_{2.5}$ and pandemic pathogens. *One Earth* 3:574–89
102. Yang X, Jia X, Dong W, Wu S, Miller MR, et al. 2018. Cardiovascular benefits of reducing personal exposure to traffic-related noise and particulate air pollution: a randomized crossover study in the Beijing subway system. *Indoor Air* 28:777–86