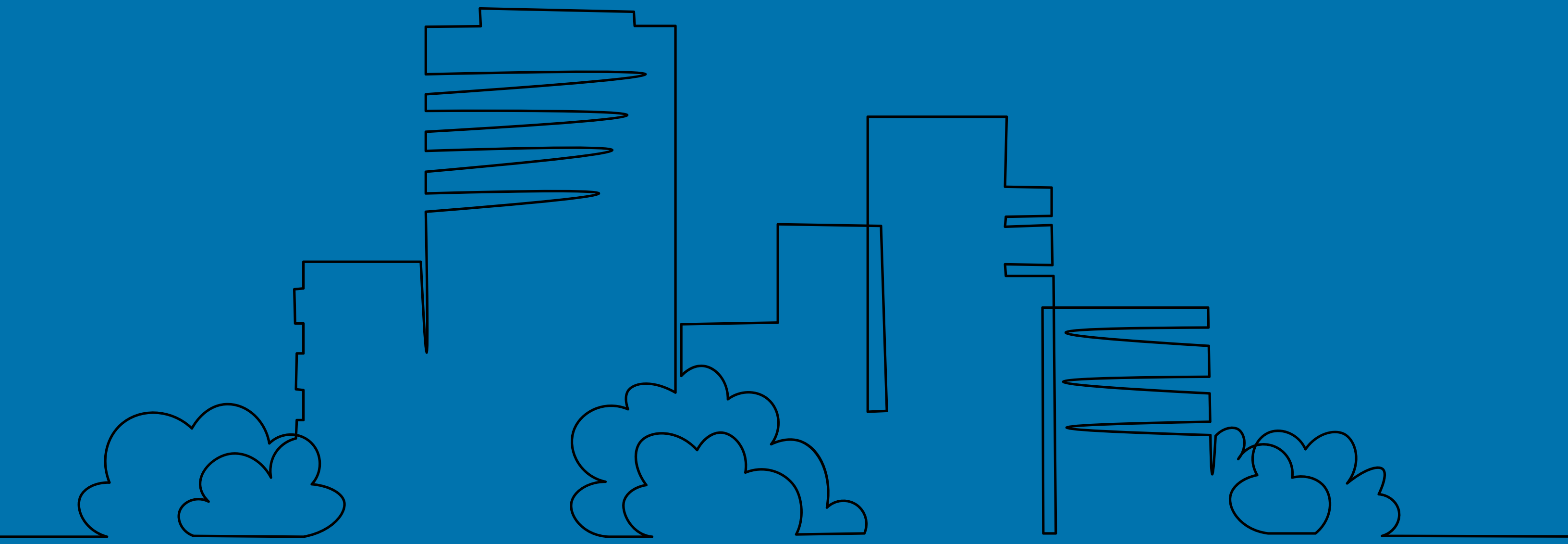
The Lancet COVID-19 Commission
Task Force on Safe Work, Safe School, and Safe Travel

# Proposed Non-infectious Air Delivery Rates (NADR) for Reducing Exposure to Airborne Respiratory Infectious Diseases

NOVEMBER 2022



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# Executive Summary

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and other respiratory pathogens are effectively transmitted through the inhalation exposure route indoors, mostly in places with inadequate ventilation and filtration. Current building standards, however, promote bare-minimum ventilation and filtration targets that do not protect against infectious disease transmission. There is urgency in setting new minimum standards that can help reduce respiratory disease risk indoors and promote better health overall. Yet, to date, leading organizations have not established clear health-based targets for use outside of healthcare settings. There also remains significant confusion regarding which metric to use (volumetric flow rate of air per volume of the room, per person, or per floor area). The important scientific debates about metrics and targets must continue. However, while there is debate about the "best" metric to use, and there is debate about the specific targets for each, there is no debate that the current targets are too low.

To advance this conversation around health-based ventilation targets for airborne respiratory pathogens, the Lancet COVID-19 Commission Task Force on Safe Work, Safe School, and Safe Travel reviewed the scientific evidence around ventilation and disease transmission for SARS-CoV-2 and other airborne pathogens. We found that when we look at the totality of evidence – and despite differences across studies, experts, and metrics – there is coalescence around ventilation targets above current minimums. Based on this assessment, the Task Force proposes the following Non-infectious Air Delivery Rates (NADR) for Reducing Exposure to Airborne Respiratory Infectious Diseases, which are feasible and achievable right now with existing and widely available approaches and technologies. Note that these proposed NADRs are not intended to replace existing targets for healthcare or residential settings.

TABLE 1.
**Proposed Non-infectious Air Delivery Rates (NADR) for Reducing Exposure to Airborne Respiratory Diseases; The Lancet COVID-19 Commission Task Force on Safe School, Safe Work, and Safe Travel**

| | **Volumetric flow rate per volume** | **Volumetric flow rate per person** | | **Volumetric flow rate per floor area** | |
|---|---|---|---|---|---|
| | ACHe | cfm/person | L/s/person | cfm/ft$^2$ | L/s/m$^2$ |
| Good | 4 | 21 | 10 | 0.75 + ASHRAE minimum outdoor air ventilation | 3.8 + ASHRAE minimum outdoor air ventilation |
| Better | 6 | 30 | 14 | 1.0 + ASHRAE minimum outdoor air ventilation | 5.1 + ASHRAE minimum outdoor air ventilation |
| Best | > 6 | > 30 | > 14 | >1.0 + ASHRAE minimum outdoor air ventilation | > 5.1 + ASHRAE minimum outdoor air ventilation |

# 1. Background on Air Ventilation, Filtration, and Disinfection to Reduce Infectious Disease Transmission

There are three main routes of transmission of respiratory pathogens, including SARS-CoV-2 [1], [2]. Airborne or aerosol transmission involves inhalation of the virus, which is carried in respiratory particles up to 100 µm in size ("airborne transmission"). For the purpose of mitigation, airborne transmission should be subdivided into two categories: short-range at a distance <1-2 m and long-range at a distance >1-2 m. Transmission can also occur by the spray of large droplets directly onto the external mucus membranes (eyes, nostrils, lips), which occurs only at very close distances ("spray transmission"). If a surface becomes contaminated with virus, someone could touch it and transfer it to their mucus membranes, potentially initiating infection ("fomite transmission"). These definitions of modes of transmission have been shown to be more accurate than the traditionally defined modes that include droplet, droplet nuclei or airborne at long distance only, and contact (either direct or involving fomites) [3].

There are many ways to reduce the risk of pathogen transmission through the above-mentioned routes. For example, spray transmission can be minimized by, among other things, physical distancing, physical barriers, mask-wearing, and face shields. Transmission by touch can be minimized through frequent cleaning and disinfection of commonly touched objects, through the use of automatic or touchless alternatives (e.g., automatic doors), and through frequent hand washing. Long-range aerosol transmission can be minimized by, among other things, mask-wearing, increasing outdoor air ventilation to dilute the concentration of respiratory aerosol particles that contain the virus, filtering air in a room or building, or disinfection of infectious aerosols in indoor air using germicidal ultraviolet light (GUV). To some extent, these strategies also reduce the risk of short-range aerosol transmission [4], [5].

Buildings and their heating, ventilation, and air conditioning (HVAC) systems play a critical role in minimizing the transmission of airborne infectious diseases. Many different types of building HVAC systems are used in the United States (U.S.), and they are usually designed and operated under American National Standards Institute and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ANSI/ASHRAE) standards; however, most of these standards, particularly in buildings other than healthcare facilities, have not been designed to reduce the risk of transmission of airborne infectious diseases. Such guidelines also do not exist elsewhere. These standards or guidelines are voluntary, and are not typically followed in all states unless they are adopted and explicitly written into a building code.

In this report, we discuss ventilation, filtration, and air disinfection techniques for reducing the transmission of airborne infectious diseases indoors and discuss common building HVAC systems, current standards, and how the standards are set. Next, we describe different approaches for calculating the equivalent delivery rates of non-infectious air (i.e., air that is free of infectious bioaerosols) and compare their pros and cons. Then, we summarize key studies supporting the benefits of ventilation, filtration, and disinfection against transmission of SARS-CoV-2 and other infectious respiratory pathogens as well as their benefits beyond infectious respiratory diseases in Appendix A. This review informed the development of the non-infectious air delivery rate (NADR) targets presented in Table 1 in the Executive Summary.

## 1-1. VENTILATION

Ventilation is defined as the process of supplying/ distributing outdoor air to or removing air from a space for the purpose of controlling contaminant levels, humidity, or temperature within the space [6]. Increasing the ventilation rate in a building dilutes the concentration of infectious airborne particles and decreases the risk of long-range transmission and, at some level, short-range transmission of airborne pathogens. Ventilation in buildings can be divided into three categories: infiltration, natural ventilation, and mechanical ventilation.

Infiltration is unintentional introduction of outdoor air to indoor spaces through the cracks and small holes of buildings and mechanical systems driven by pressure differences between outdoor and indoor air. Older buildings and mechanical systems usually have more air leakage, while cracks and holes are often fewer in newer buildings and mechanical systems. Temperature differences between indoors and outdoors (which set up pressure differences) and pressure differences between indoors and outdoors established by wind across the building envelope (which is also affected by wind direction) are among the factors that influence the infiltration rate in buildings

Natural ventilation is the uncontrolled, but intentional, air movement in and out of open windows or doors, and other purpose-built openings. Although opening windows and doors provides natural ventilation, this means of ventilation may be less effective than mechanical ventilation because it can be unpredictable and is based on many factors outside the control of the building and occupants, such as outdoor air temperature, wind direction, wind speed, and pressure differentials.

Mechanical ventilation provides controlled ventilation that forcibly brings outdoor air inside and distributes that fresh air to different areas of the building. Subtypes of mechanical ventilation include unit ventilation, whole-building ventilation, and spot ventilation. Single-room or unit ventilation systems use one or multiple fans along with particle filter(s) and coils to bring outdoor air into a single room, recirculate, filter, condition, and exhaust room air. Whole-building mechanical ventilation systems use one or more fans and duct systems to exhaust stale air and/or supply fresh air to the building. In commercial and health facilities, whole-building mechanical ventilation systems usually work with air handling units (AHUs) connected to ductwork distributed to most of the indoor spaces. These AHUs have an insulated box that contains a fan or blower, filter racks or chambers, and heating elements. Spot ventilation can improve the effectiveness of natural and whole-building ventilation by removing indoor air pollution and/or moisture at its source. Spot ventilation includes the use of localized exhaust fans, such as those used above kitchen ranges and in bathrooms. In some HVAC systems, a fraction of the indoor air is recirculated and mixed with the outdoor air coming in to save on cooling and heating energy costs.

There are four basic types of mechanical ventilation systems: exhaust, supply, balanced, and energy (or heat) recovery ventilation systems. Each of these systems can work continuously or intermittently depending on its design, and all of them can increase heating and cooling costs of buildings. Exhaust ventilation systems expel indoor air to the outdoors with one or more fans, while make-up air infiltrates through leaks in the building shell and through intentional, passive vents. Exhaust systems typically are not appropriate for hot, humid climates, as there is a risk of drawing hot outdoor air into interior spaces where it could reach cool surfaces, condense, and cause moisture problems. They can also drag outdoor air through parts of the building envelope that worsen indoor air quality, particularly in newer homes with poor ventilation. In residential buildings, the exhaust fans are often located in bathrooms. Supply ventilation systems use a fan to pressurize buildings, forcing outside air into the building while air leaks out of the building through holes in the shell, bathroom, and range fan ducts, and intentional vents (if any exist). Supply systems typically are not appropriate for cold climates, as there is a risk of heated indoor air being pushed through small holes and cracks in the building where it could reach cold exterior surfaces, condense, and cause moisture problems. Balanced ventilation systems, if properly designed and installed, introduce and exhaust approximately equal quantities of outdoor air and recirculated indoor air. While buildings using these systems are neither intentionally pressurized nor depressurized, some small pressure differences can exist, and often many public buildings are slightly pressurized to keep outdoor air from unintentionally infiltrating indoors. Balanced ventilation systems work well for all climates. Energy (heat) recovery ventilation systems are similar to balanced systems, moving approximately equal quantities of air into and out of buildings, but they use additional technology to reduce the heating and cooling load and improve comfort. The two most common supplemental systems are heat recovery ventilation (HRV) and energy recovery ventilation (ERV). HRV systems transfer heat from exhaust air to incoming air during the heating season and from incoming air to exhaust air in the cooling season. ERV systems transfer heat and moisture between the exhaust air and incoming air, providing additional savings in the summer by adjusting the moisture content of the incoming air in the winter and by adding moisture from the outgoing air to help avoid excessively dry indoor conditions.

## 1-2. FILTRATION

Air filtration is a relatively easy-to-use and flexible technology that is implemented widely to remove particles and gases from air streams [7]. A particulate air filter is composed of fibrous or porous materials, which remove aerosols and droplets from the air. Gaseous air filters use sorbent materials to remove gases such as volatile organic compounds (VOCs), carbon dioxide ($CO_2$), and ozone (O3) from the air. Filtration in indoor environments can help mitigate airborne transmission by removing airborne particles containing pathogens from air that is mechanically drawn through an air filter. The two most common uses are filters installed in an HVAC system to clean incoming outside air and/or recirculated air, and in a portable/movable air cleaner that is placed in a room [8]. The overall effectiveness of a filtration system at reducing particle concentrations depends on several factors including filter removal efficiency, airflow rate through the filter, size of the particles, and location of the filter in the HVAC system or room [9]. Three systems are regularly used in the U.S. for rating the removal efficiency of air filters: the Minimum Efficiency Reporting Value (MERV, ranging from 1 to 16), the Micro-particle Performance Rating (MPR, ranging from 100 to 2800), and the Filter Performance Rating (FPR, ranging from 1 to 10). The International Organization for Standardization (ISO) has also introduced a rating for air filters based on their effectiveness in removing different particle sizes [10].

A higher rating is assigned to filters that can remove more aerosol, including infectious aerosol, from the air. It is important to note that air filter removal efficiencies vary for different particle sizes. High-efficiency particulate air (HEPA) filters have the best removal performance among air filters; they remove more than 99.9% of particles of all sizes.

Portable air cleaners, also known as air cleaners, air purifiers, or air sanitizers, are designed to filter the air in a single room or area by mechanically recirculating the air through a filter. The performance of portable air cleaners is usually reported as clean air delivery rate (CADR). The CADR is the particulate free airflow rate that the air cleaner provides and depends on the filter efficiency and the fan flow rate. The higher the CADR, the more quickly the unit can remove particles from the air in a room and the larger the area it can serve. Portable air cleaners often achieve a high CADR by employing a higher fan flow rate and by using HEPA filters

HVAC system filtration is designed to filter air throughout a building using particle air filters only when the system is operating. In most cases, the systems run only when heating or cooling is needed (usually less than 50% of the time during heating and cooling seasons [11]. In order to achieve more filtration, systems may need to run for longer periods, which may increase electricity costs and result in less reliable humidity control during the cooling season. The filtration rate of the system also can be improved by choosing filters with higher MERV ratings. Sometimes lower-rated air filters in HVAC systems (e.g., MERV 8) are placed in the supply air from outside to protect equipment from large particles, and these are typically inefficient for small particles.

## 1-3. AIR DISINFECTION

Air disinfection using germicidal ultraviolet (GUV) is the use of ultraviolet (UV) energy to inactivate microorganisms. GUV fixtures emit UV-C energy, which has shorter wavelengths (i.e., 200 to 280 nm) than UV-A (i.e., 320 to 400 nm) and UV-B (i.e., 280 to 320 nm) rays. Exposure to UV-C poses less risk to human health compared to UV-A and UV-B rays; however, direct exposure to UV-C light can still be a health hazard to skin and eyes [12]. Although the entire UV spectrum can kill or inactivate many microorganisms, UV-C energy provides the most germicidal effect, with 265 nm being the optimum wavelength [13]. More recent studies also demonstrated the effectiveness of far UV-C light (207–222 nm) in deactivating pathogens with lower harm to exposed human tissues compared to UV-C light [14], [15].

GUV is used in some buildings, for example jails, homeless shelters, and hospitals in particular, and has been shown to be effective in disinfecting air containing bacteria and viruses such as *Mycobacterium tuberculosis*, influenza virus, and measles virus [16]. Air disinfection using GUV is usually recommended for indoor settings with high risk of transmission of airborne infectious diseases and in spaces where adequate ventilation cannot be maintained year-round, where ventilation is nonexistent or rates are low, and where there are limitations in using filtration systems [17]. Although air disinfection is effective at inactivating infectious bacteria and viruses in an aerosol, it does not physically remove particles and thus has minimal or no impacts on other types of indoor air pollutants, unlike ventilation and filtration which can reduce exposures to airborne pathogens and other air pollutants simultaneously inside buildings.

There are three common approaches for using GUV inside buildings: upper-room systems, in-duct systems for HVAC applications, and portable air cleaners equipped with UV lamps. Upper-room GUV is the approach that creates a disinfection zone above the heads of people in the room, thereby limiting direct exposure to UV. As air circulates in the room from thermal plumes, ceiling fans, and/or other means, infectious aerosols are inactivated by the GUV. This approach yields very high NADRs. Upper-room GUV is recommended for high-risk indoor settings including areas with an increased likelihood of the presence of infectious people and crowded spaces [17]. Upper-room GUV works best when the air in a room is well mixed. In-duct GUV systems are installed in supply air ducts to inactivate airborne viruses present in recirculated air. The successful design of an in-duct GUV system depends on air temperature, air velocity, and relative humidity. Portable GUV devices are generally air cleaners equipped with UV-C lamps that are designed to disinfect the air in a single room or area. Some healthcare facilities use high-wattage mobile GUV units that are able to disinfect air and surfaces in patient or emergency rooms in hospitals, but these units must be used only when the room is unoccupied. Some UV lamps including those contained in some photocatalytic oxidation (PCO) air cleaners generate ozone indoors, which is a respiratory hazard [18]. In order for a GUV system to be effective, there must be sufficient contact time between the pathogen and the UV light; this often presents a challenge for designing an effective in-duct or portable GUV system [19].

## 1-4. CURRENT STANDARDS FOR AIR VENTILATION, FILTRATION, AND DISINFECTION IN BUILDINGS

Air ventilation, filtration, and disinfection systems have been used in buildings for many decades to reduce the occupants' exposures to indoor air pollutants such as particulate matter (PM), VOCs, $CO_2$, nitrogen oxides (NOx), and infectious bioaerosols; therefore, similar to other building systems, there are standards and codes governing how they should be installed, operated, and maintained. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) is one of the internationally recognized organizations that have developed standards for building HVAC systems. Before the COVID-19 pandemic started, many building managers in the U.S. had already adopted at least some of their recommendations for ventilation and filtration systems.

The installation, operation, and maintenance of ventilation, filtration, and GUV disinfection systems are discussed in several ASHRAE standards and handbooks. This section summarizes some important aspects of relevant ASHRAE standards; further details can be found in the current versions of ASHRAE standards and guidelines.

The minimum ventilation rates for acceptable indoor air quality (IAQ) in non-residential and residential buildings are stated in ASHRAE Standards 62.1 and 62.2, respectively [6], [20]. These standards specify minimum ventilation rates and other measures intended to provide IAQ that is acceptable to human occupants and that minimizes adverse health effects. For non-residential buildings, Standard 62.1 specifies the minimum ventilation rate in occupants' breathing zone based on the building type (i.e., occupancy category), number of occupants, and floor area of the space. When the occupant number is not available, a default occupant density can be used for estimating the minimum ventilation rate. The required breathing zone ventilation rates per occupant and per floor area vary between 5 and 20 cfm/person and 0.06 and 0.48 cfm/ft$^2$, respectively, depending on the type of building and its occupants. For some specific indoor spaces such as animal facilities, kitchens, and parking garages, where occupants are potentially exposed to higher concentrations of air pollutants, the standard requires minimum exhaust rates between 0.25 and 3.00 cfm/ft$^2$ of floor area (Standard 62.1-2022).

## 1-4. CURRENT STANDARDS FOR AIR VENTILATION, FILTRATION, AND DISINFECTION IN BUILDINGS (CONTINUED)

For residential buildings, ASHRAE Standard 62.2 calculates the total required ventilation rate based on the floor area and the number of bedrooms. (We note that this approach to estimating the number of long-term residents in a dwelling does not fully account for shared bedrooms, and thus represents an important inequity within the current standard.) The standard requires a minimum total ventilation rate of 0.03 cfm/ft$^2$ of floor area and 7.5 cfm per occupant (i.e., number of bedrooms plus one) for residential buildings and allows infiltration credits and ventilation-rate reductions for particle filtration in residential buildings. ASHRAE also has developed more specific standards for ventilation system design and performance in commercial cooking operations [21] and healthcare facilities [22], as well as air quality within commercial aircraft that includes a combination of ventilation and high-efficiency particulate air (HEPA) filtration measures [23].

Filtration rate is a function of removal efficiency of air filters and the airflow rate passing through them. In general, ASHRAE provides recommendations for the minimum removal efficiency of air filters instead of suggesting a required airflow rate passing through the air filters. One exception is ASHRAE Standard 62.2, which describes potential ventilation rate reductions based on airflow rates through particle filters [18]. ANSI/ASHRAE Standard 52.2 establishes a test procedure for evaluating the performance of air cleaning devices as a function of particle size. This procedure has been used widely to determine the Minimum Efficiency Reporting Value (MERV) of air filters deployed in HVAC systems and air cleaning devices [24]. MERV ratings range from 1 to 16, and higher MERV ratings indicate higher particle removal efficiencies. HEPA filters, with more than 99.9% removal efficiency for all particle sizes, are more efficient than MERV 16 filters. ASHRAE recommends air filters with MERV ratings higher than 8 (or ISO $ePM_{10}$) in buildings located where the national standard or guideline for particulate matter smaller than 10 µm ($PM_{10}$) is exceeded. Similarly, MERV ratings not less than 11 (or ISO $ePM_{2.5}$) are recommended for air filters in buildings located where the national standard or guideline for particulate matter smaller than 2.5 µm ($PM_{2.5}$) is exceeded [6]. For capturing airborne particles that contain viruses and bacteria, MERV ratings higher than 13 (or ISO $ePM_1$) for air filters are recommended [9]. ASHRAE has more strict filtration recommendations for high-risk indoor environments including healthcare facilities and commercial aircraft. It is recommended that all air that is recirculated through an aircraft pass through a HEPA filter [23]. In healthcare facilities, ASHRAE recommendations for filtration depend on the function of the indoor space; MERV 8 air filters are recommended in non-critical spaces, and MERV 14, MERV 16 and HEPA air filters are recommended in high-risk indoor environments [22].

GUV devices and systems are placed in air-handling systems and in room settings for the purpose of air and surface disinfection. These systems do not remove particles or other indoor air pollutants; thus, they are only used for reducing the risk of exposure to infectious bioaerosols. Detailed descriptions of GUV components and systems are given in ASHRAE Handbook 2019 – HVAC Applications, Chapter 62: Ultraviolet Air and Surface Treatment and the ASHRAE Handbook 2016 – HVAC Systems and Equipment, Chapter 17: Ultraviolet Lamp Systems [25], [26]. However, other ASHRAE standards and documents also provide some recommendations for using GUV systems. ASHRAE 62.1 suggests that GUV lamps in supply air or space shall not transmit 185 nm wavelengths, which may generate ozone. ASHRAE Position Document on Filtration and Air Cleaning indicates that the most effective wavelength range for inactivation of microorganisms is between 220 and 300 nm, with peak effectiveness near 265 nm [27]. For upper room GUV systems, ASHRAE recommends a ceiling that is at least 8 ft (2.44 m) or higher and that the upper room area where the UV-C energy will be installed is free of obstructions (hanging televisions, signage, framing soffits, etc.) that might misdirect the UV energy [28].

# 2. Different Approaches for SARS-CoV-2 Risk Mitigation in Buildings

The World Health Organization (WHO) and Centers for Disease Control and Prevention (CDC) acknowledge the elevated risks of aerosol transmission of SARS-CoV-2 in poorly ventilated and/or crowded indoor settings, where people tend to spend longer periods of time [29], [30]. In response, international health organizations such as WHO, CDC, and the Federal Public Service (FPS) Health, Food Chain Safety and Environment of Belgium; organizations dedicated to advancing the arts and sciences of HVAC systems such as ASHRAE and the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA); and several independent teams of scientists have suggested guidelines and frameworks for infection control strategies using ventilation, air filtration, and air disinfection in indoor environments. These suggestions are not particular to the COVID-19 pandemic, and following them could also reduce exposures to other infectious aerosols, as well as some indoor air pollutants such as PM, allergens, and VOCs.

The current guidelines and frameworks to control the aerosol transmission risk of SARS-CoV-2 can be divided into two main categories: approaches for reducing the infection transmission risk inside buildings without providing a target for control measures, and approaches that are specific about target ventilation, filtration, and/or air disinfection rates based on various indoor environmental and epidemiological factors. Most organizations have adopted a hybrid approach, recommending tighter control measure targets for some critical building types such as healthcare, while only providing guidelines to improve ventilation, filtration, and/or disinfection rates in other building types.

The risk mitigation approaches that introduce a target for a combination of control measures have used different terms for the equivalent delivery rates of air without infectious virus: e.g., "total air changes per hour" for a combination of ventilation and recirculated air through air filters in ASHRAE Standard 170 [22] and "equivalent clean air supply rate" [31]; "non-infectious air delivery equivalent - NIADE" [32] and "clean air" [33] for a combination of ventilation, filtration, and disinfection in several other resources. Here, we use "Non-infectious Air Delivery Rate" (NADR), analogous to "Clean Air Delivery Rate" (CADR), to describe the supply rate of air that has been subject to any engineering control measure, such as ventilation, filtration, or air disinfection, to remove infectious bioaerosols. The removal must be quantifiable beyond laboratory-based tests.

The following sections outline ventilation, filtration, and/or air disinfection recommendations from five internationally recognized organizations for developing health and HVAC guidelines (i.e., WHO, CDC, ASHRAE, REHVA, and FPS) and independent teams of scientists who have suggested NADR targets for indoor environments. Pros and cons of different recommended infection control approaches are listed, with the goal of demonstrating that there are several reasonable approaches for using ventilation, filtration, and/or air disinfection to mitigate the transmission of infectious diseases indoors.

## 2-1. LONG-RANGE INFECTION TRANSMISSION CONTROL STRATEGIES SUGGESTED BY INTERNATIONALLY RECOGNIZED ORGANIZATIONS

### 2-1-1. WHO

Implementation of engineering and environmental controls, with emphasis on ventilation, is one of the WHO's key infection prevention and control (IPC) strategies and measures for management of COVID-19. WHO develops a road map to improve and ensure good indoor ventilation after conducting a scoping review of the available literature and an assessment of the available guidance documents from the major internationally recognized authorities on building ventilation [34]. The WHO road map to improve ventilation is divided into three settings: healthcare, non-residential, and residential spaces such as private houses. Each setting is further categorized into mechanical or natural ventilation systems. Based on the road map, the minimum natural and mechanical ventilation requirements for healthcare settings are 160 L/s/patient (339 cfm/patient) or 12 ACH in spaces where aerosol-generating procedures (AGP) are performed and 60 L/s/patient (127.1 cfm/patient) or 6 ACH in other clinical settings.

### 2-1-1. WHO (CONTINUED)

For other types of indoor spaces including both non-residential and residential buildings, WHO's minimum natural and mechanical ventilation recommendation is 10 L/s/person (21.2 cfm/person). In the WHO road map, the ASHRAE Fundamentals Handbook and the REHVA COVID-19 guidance document are mentioned as references for the minimum natural and mechanical ventilation rate of 10 L/s/person (21.2 cfm/person) for all other buildings except healthcare settings [35], [36], although the ASHRAE Handbook recommendations are not directly related to infection transmission mitigation, and the REHVA guideline does not recommend an NADR target.

WHO has recommended ventilation as their primary strategy to reduce long-range aerosol transmission of SARS-CoV-2 in indoor environments. If no other (short-term) strategy can be adopted to improve ventilation, WHO suggests considering stand-alone air cleaners with HEPA filters or GUV systems to cover the gap between the minimum ventilation requirement and the measured ventilation rate. They suggest stand-alone air cleaners should be operated continuously, and users should compare the clean air delivery rate (CADR) (cfm or $m^3$/hr) of portable air cleaners with the room ventilation rate.

### 2-1-2. CDC

The CDC recommends that ventilation improvements be used as part of a layered approach to mitigate the risk of exposure to SARS-CoV-2 [29]. Specifically, the CDC recommends increasing outdoor air ventilation, using fans in combination with open windows, verifying ventilation system operations, rebalancing ventilation systems, disabling demand control ventilation, improving air filtration, verifying bathroom and kitchen exhaust operations and ensuring exhaust is on during occupancy, and running ventilation systems before and after occupied hours each day.

The CDC has provided more detailed recommendations for ventilation requirements for areas affecting patient care in healthcare facilities [37]. For example, based on their recommendations, the minimum total air changes per hour for patient and airborne infection isolation rooms should be 6 and 12, respectively [38]. Regarding filtration improvements, the CDC recommends deploying portable air cleaners with HEPA filters, increasing central air filtration as high as possible without significantly reducing design airflow, upgrading filtration efficiency of central air systems when enhanced outdoor air delivery options are limited, and making sure air filters are properly sized and within their recommended service life [29]. The CDC also recommends that general airflow patterns be carefully considered so that air generally moves from cleaner spaces to more contaminated areas and then is removed either through filtration or ventilation. The CDC recommends using GUV systems including upper-room GUV in spaces where mechanical and reliable natural ventilation are not present. The CDC further specified that upper-room GUV was appropriate in spaces with ceiling heights of at least 8 feet (8.5 feet is preferred), with some airflow to move air (for example, fans at low speed) [17]. The CDC has provided detailed guidance on how to design and implement upper-room germicidal UV in healthcare facilities, and these recommendations are broadly applicable to other types of occupied public buildings [39].

### 2-1-3. ASHRAE

The ASHRAE Epidemic Task Force provided recommendations on how to achieve a desired equivalent clean air supply rate after selecting the target, but these were never formally released or published by ASHRAE during the pandemic. However, ASHRAE did not specify enhanced ventilation targets. They recommended to maintain at least the required minimum outdoor airflow rates as specified by applicable codes and standards (e.g., Standards 62.1 and 62.2); limit re-entry of contaminated air that may re-enter the building from energy recovery devices, outdoor air, and other sources to acceptable levels; and when necessary flush spaces between occupied periods for the time required to achieve three air changes of equivalent clean air supply [31]. ASHRAE also has more detailed recommendations for ventilation in industrial settings, such as increasing the outdoor air supply to the maximum allowed by the capabilities of the ventilation system, making sure restroom fans operate continuously and are exhausted directly outdoors away from ventilation supply intakes, and maintaining ventilation between 6 and 12 ACH [40]. ASHRAE Standard 170-2021 for ventilation of healthcare facilities recommends at least 4-6 total ACH, including at least 2 ACH of outdoor air plus air recirculated through filters with ratings of MERV14 or better for inpatient hospital rooms and emergency department exam/treatment rooms, and elevated total air change rates of 12 ACH and 20 ACH for high-risk inpatient areas, including airborne infection isolation rooms and operating rooms, respectively, recognizing the use of a combination of ventilation and filtration for healthcare facilities [22]. For filtration systems specifically, ASHRAE recommended filters that achieve MERV 13 or better levels of performance for air recirculated by HVAC systems, deploy air cleaners for which evidence of effectiveness and safety is clear, and select control options, including stand-alone filters and air cleaners that provide desired exposure reduction while minimizing associated energy penalties. For GUV systems, ASHRAE recommended that in-duct air disinfection systems should have a minimum target UV dose of 1,500 μW-s/cm$^2$ and exposure times of 0.25 s, and upper-room air disinfection systems should be mounted in occupied spaces at heights of 7 feet and above [41].

### 2-1-4. REHVA

REHVA COVID-19 guidance provided practical recommendations for building operations during an epidemic, without providing any target ventilation rates for mitigation of infectious disease risk [36]. The guidance on building services operation covers 15 main items. For ventilation, it suggested starting ventilation at the nominal speed at least 2 hours before the building opening time and switching off or to a lower speed 2 hours after the building usage time (or one hour is enough in commercial buildings if the building would be ventilated with 3 volumes of outdoor air in that time). It also recommended that $CO_2$ setpoints in demand-controlled ventilation systems be changed to 550 ppm to maintain operations at nominal speed and that minimally occupied buildings operate ventilation continuously at reduced speed during normal operating hours. For filtration, it recommended not using central recirculation; if recirculation cannot be avoided, REHVA guidance recommended the outdoor air fraction be increased as much as possible and existing low-efficiency air filters be replaced with $ePM_1$ 80% filters (i.e., minimum 80% removal efficiency for particulate matter less than 1 micron in size). REHVA also acknowledged that room air cleaners and GUV systems can be useful in specific situations. To select the right size air cleaner, REHVA recommended that the airflow capacity of the unit (at an acceptable noise level) be at least 2 ACHe and indicated that additional airflow will be beneficial up to 5 ACHe (equivalent air changes per hour can be calculated by dividing air cleaner CADR by the volume of the room). If ventilation control relies on occupant behavior (hybrid or natural ventilation systems) or there is no dedicated ventilation system in the building, REHVA recommended installation of $CO_2$ sensors and with warning and alarm notices for $CO_2$ concentrations above 800 ppm and 1000 ppm, respectively.

### 2-1-5. FPS Public Health

The Federal Public Service (FPS) Health, Food Chain Safety and Environment of Belgium has defined a series of measures for indoor environments to fight the pandemic and to ensure healthy indoor air [42]. Their suggested measures are developed to ensure effective ventilation and air cleaning in closed spaces to reduce the transmission of COVID-19 and other airborne infectious diseases. Based on the expertise acquired during the pandemic and on the existing legal foundations, the FPS Public Health has found agreement for a legal framework that will require monitoring of air quality in all publicly accessible spaces. Their Code of Wellbeing at Work (Codex) applies to all companies and organizations that employ staff and sets generic, cross-cutting air quality standards on two levels:

#### Standard A level

- $CO_2$ concentration within premises should be generally below 900 ppm, or
- A minimum ventilation or filtration flow rate of 40 m$^3$/h (11.1 L/s or 23.5 cfm) per occupant, of which at least 25 m$^3$/h (6.9 L/s or 14.7 cfm) per occupant, should be outdoor air ventilation.

#### Standard B level

- $CO_2$ concentration within rooms should be generally below 1,200 ppm, or
- A minimum ventilation rate of 25 m$^3$/h (6.9 L/s or 14.7 cfm) per occupant.

Moreover, the FPS Public Health of Belgium requires all publicly accessible spaces to have a $CO_2$ monitor that will have to be clearly visible to the public and may not be placed in the immediate vicinity of a door or window.

## 2-2. RECOMMENDED NADR TARGETS FROM INTERNATIONALLY RECOGNIZED INDEPENDENT RESEARCH TEAMS

### 2-2-1. Based on Number of Occupants

NADR recommendations based on the number of occupants are appropriate for well-mixed large volume spaces, crowded indoor environments, and rooms where the numbers of occupants are known. Modeling by Li et al. suggests that a ventilation rate of 10 L/s per person (21.2 cfm/person) provides a similar concentration vs distance decay profile to that in outdoor settings, which provides some justification for adopting a ventilation standard of 10 L/s per person [5].

### 2-2-1. Based on Number of Occupants (Continued)

Allen and Macomber recommended 30 cfm per person of outdoor air as the optimal target for an office building to reduce absenteeism from illness and capture multiple benefits of higher ventilation (e.g. better cognitive function). [43].

### 2-2-2. Based on Equivalent Air Change Rate (NADR Divided by Room Volume)

NADR targets based on room equivalent air changes per hour (ACHe) have also been proposed. An air change rate is the number of times the equivalent volume of room air is replaced by outdoor air over a period of time, such as an hour. The total, equivalent, or effective air change rate is similar except that room air is replaced by any NADR instead of just outdoor air. A common unit for air change rate is air changes per hour (ACH, 1/h).

An effective air change rate of 4-6 ACH has been proposed to reduce long-range airborne transmission of SARS-CoV-2 in small volume spaces with typical or low occupancy [33]. This guideline is in line with ASHRAE recommendations for specific hospital spaces, but it is not designed to replace current standards for ventilation in healthcare facilities such as ASHRAE Standard 170-2021, where the design parameters for inpatient spaces are provided [22].

### 2-2-3. Based on Floor Area Plus Minimum ASHRAE Ventilation Requirement

The Science Applications Team for ASHRAE Epidemic Task Force developed an approach for recommending NADR in buildings based on building floor area. This guidance was developed during the pandemic but was never formally published or released by ASHRAE. They recommended that in addition to the minimum ASHRAE ventilation requirements, building owners or managers provide an extra 0.75 cfm per square foot (3.81 L/s/$m^2$) of NADR by any combination of increased ventilation, filtration, GUV, or other engineering control measures to reduce the long-range transmission of infectious aerosols [44]. They also demonstrated that providing an additional 0.75 cfm/$ft^2$ NADR to selected hypothetical indoor environments could reduce the long-range transmission risk of COVID-19 by up to 72% compared to similar indoor spaces using the minimum ASHRAE ventilation rates.

Suggesting NADR based on floor area plus minimum ASHRAE ventilation requirement has the advantages of ignoring occupancy considerations, ensuring minimum required ventilation to reduce exposures to other air pollutants, and being appropriate for large buildings with high ceilings. This approach should also be achievable by existing central air filtration systems in commercial buildings after filter upgrades to MERV 13 or higher. However, the approach is hard to implement in spaces with complex or unknown floor plans, and the suggested NADR might not be sufficient for overcrowded spaces.

### 2-2-4. Based on Secondary Attack Rate

NADR based on the secondary attack rate is an approach that is designed to reduce the secondary attack rates below 1.0 during the "subclinical infectious period" such that the infection transmission would eventually cease. This approach was suggested by Federspiel [45] and then developed further by Federspiel et al. [32].

Federspiel et al. provided a "Criterion" for integrating the effects of engineering and administrative controls with personal protective equipment (PPE) for indoor environments. Their guideline accounts for ventilation, filtration, temperature control, humidity control, masks, occupant density, occupancy category, and activity. Their recommended Criterion for each indoor environment is independent of the time that individuals spend there. In their approach, recommended NADRs are described by the Equation 1:

**Equation 1:**

$$NADR = ( S \times E_{SS} \times B \times T \times p_i \times p_s ) / R_t$$

where:

$NADR$: Minimum required non-infectious air delivery rate (L/s or cfm)

$S$: Number of susceptible occupants (person)

$E_{ss}$: Steady-state quanta emission rate (per hour)

$B$: Breathing rate of a susceptible occupant (L/s/person or cfm/person)

$T$: Average interaction time between infector and susceptible occupant during the infectious period (hour)

$p_i$: Penetration ratio of masks worn by an infector and equals 1 if mask is not required (-)

$p_s$: Penetration ratio of masks worn by a susceptible occupant and equals 1 if mask is not required (-)

$R_t$: Target reproduction number - usually set to 1 (-)

**2-2-4. Based on Secondary Attack Rate (Continued)**

It is important to note that in this approach, the assumptions for steady-state quanta emission and breathing rates can drastically change the recommended NADRs. Therefore, Federspiel et al. created a calculator that shows the acceptable quanta generation rates and breathing rates for ASHRAE 62.1 typical indoor environments and computes the Criterion threshold as a loss rate, as an equivalent flow rate, and as a carbon dioxide concentration target.

Suggesting NADR based on the secondary attack rate has the advantage of adjusting the recommended rates for different types of infectious disease and control measures. However, this approach is more complex than the other approaches discussed here; relies on epidemiological parameters that may not be certain or available, particularly for new infectious diseases; and is more conservative than the other approaches such that it is hard to be achieved in crowded spaces and for diseases with long subclinical infectious periods.

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## 2-3 SUMMARIZING DIFFERENT APPROACHES FOR RECOMMENDING A TARGET NADR

The varying NADR recommendations for reducing the long-range aerosol transmission of infectious diseases are presented in Table 2, divided into seven categories, with a brief list of pros and cons.

Table 2.
**Summary of Different Approaches for Target Non-infectious Air Delivery Rates (NADR)**

| Approach | Recommended NADR [Delivery Approach] | Pros | Cons |
|---|---|---|---|
| **Minimum OA ventilation requirement [a]** | **ASHRAE [b]**<br>• Non-residential buildings: Standard 62.1-2022<br>• Residential buildings: Standard 62.2-2022<br>**[Ventilation only]** | • Has been used for many years in buildings<br>• Ensures providing ventilation rate to reduce exposures to various pollutants | • Minimally "acceptable" targets<br>• Not designed specifically for infectious disease transmission control<br>• Not appropriate for crowded or overcrowded spaces<br>• Does not account for other infection control measures such as filtration and disinfection |
| **Maximum $CO_2$ concentration** | **REHVA [c]**<br>• Set warning for $CO_2$ concentrations > 800 ppm<br>• Set alarm for $CO_2$ concentrations > 1000 ppm<br>**FPS Public Health [d]**<br>• Standard A Level for $CO_2$ concentrations < 900 ppm<br>• Standard B Level for $CO_2$ concentrations < 1200 ppm<br>**[Ventilation only]** | • Easy to be measured and validated after implementation<br>• Appropriate for small volume spaces with high occupancy | • Does not account for other infection control measures such as filtration and disinfection<br>• Provides minimal ventilation in sparsely occupied spaces<br>• Requires real-time $CO_2$ measurements |

Table 2.

**Summary of Different Approaches for Target Non-infectious Air Delivery Rates (NADR) Continued**

| Approach | Recommended NADR [Delivery Approach] | Pros | Cons |
|---|---|---|---|
| **NADR recommendation based on occupancy** | **WHO [e]**<br>• 160 L/s/patient (339 cfm/patient) where AGP are performed in healthcare settings<br>• 60 L/s/patient (127 cfm/patient) in other rooms in healthcare settings<br>• 10 L/s/person (21.2 cfm/person) in other indoor environments<br>**Li et al. (2022)**<br>• 10 L/s/person (21.2 cfm/person)<br>**Allen and Macomber (2022)**<br>• 30 L/s/person (63.3 cfm/person)<br>**FPS Public Health [d]**<br>• Standard A Level for min NADR of 11.1 L/s/person (23.5 cfm/person), of which 6.9 L/s/person (14.7 cfm/person) should be ventilation<br>• Standard B Level for min 6.9 L/s/person (14.7 cfm/person) ventilation<br>**[Emphasis on ventilation, HEPA filtration when ventilation cannot be improved]** | • Appropriate in large volume spaces<br>• Appropriate for crowded spaces<br>• Appropriate for indoor spaces with known number of occupants<br>• Ensures providing ventilation rate to reduce exposures to other pollutants | • Provides minimal ventilation in sparsely occupied spaces<br>• Complex to calculate the required NADR in buildings with dynamic occupancy |
| **NADR recommendation based on equivalent air change rate for healthcare settings** | **WHO [e]**<br>• 6-12 ACH<br>• Patient rooms where AGP are performed or airborne infection isolation rooms (12 ACH)<br>• Regular patient rooms in healthcare settings (6 ACH)<br>**[Emphasis on ventilation, HEPA filtration only if ventilation cannot be improved]** | • Has been used in healthcare settings for many years and the effectiveness has been tested<br>• Appropriate for high risk indoor environments | • Standard applies to healthcare settings<br>• Not appropriate for large spaces (i.e., high ceilinged) with low occupancy |

Table 2.

**Summary of Different Approaches for Target Non-infectious Air Delivery Rates (NADR) Continued**

| Approach | Recommended NADR [Delivery Approach] | Pros | Cons |
|---|---|---|---|
| **NADR recommendation based on equivalent air change rate for healthcare settings (Continued)** | **ASHRAE, CDC [f]**<br>• 2-20 ACH<br>• Patient room (2 outdoor ACH and 4 or 6 total ACH with min MERV14 air filters)<br>• Patient care area corridor (2 total ACH with min MERV14 air filters)<br>• Operation room (4 outdoor ACH and 20 total ACH with min MERV16 air filters)<br>**[recommended a minimum outdoor air ACH plus air recirculated through various MERV rating filters]** | • Has been used in healthcare settings for many years and the effectiveness has been tested<br>• Appropriate for high risk indoor environments | • Standard applies to healthcare settings<br>• Not appropriate for large spaces (i.e., high ceilinged) with low occupancy |
| **NADR recommendation based on equivalent air change rate for buildings other than healthcare settings** | **Allen and Ibrahim (2021)**<br>• 4-6 ACHe<br>• Ideal (6 ACHe)<br>• Excellent (5-6 ACHe)<br>• Good (4-5 ACHe)<br>**[A combination of ventilation, filtration, and disinfection]** | • NADR is maintained in sparsely occupied spaces<br>• Simple to calculate and implement in buildings with dynamic occupancy and/or complex floor plan<br>• Appropriate for small volume spaces with typical or low occupancy | • Not appropriate for large volume (i.e., high ceilinged) spaces<br>• Not appropriate for overcrowded spaces<br>• Does not provide recommendation for minimum ventilation |
| **NADR recommendation based on floor area + min ASHRAE OA ventilation** | **Azimi et al. (2021)**<br>• 0.75 cfm/ft$^2$ (3.81 L/s/m$^2$) + ASHRAE minimum ventilation requirement<br>**[A combination of ventilation, filtration, and disinfection]** | • Ensures NADR is maintained in sparsely occupied spaces<br>• Appropriate for large buildings with high ceilings<br>• Appropriate for spaces with typical or low occupancy<br>• Ensures providing ventilation rate to reduce exposures to other pollutants | • Hard to implement in spaces with complex or unknown floor plans<br>• Suggested NADR might not be sufficient for overcrowded spaces |

Table 2.
**Summary of Different Approaches for Target Non-infectious Air Delivery Rates (NADR) Continued**

| Approach | Recommended NADR [Delivery Approach] | Pros | Cons |
|---|---|---|---|
| **Based on secondary attack rate** | **Federspiel et al. (2021)**<br>• $NADR > \frac{SE_{ss}BTp_ip_s}{R_t}$ **[g]**<br>**[A combination of ventilation, filtration, disinfection, masks, occupant density, and occupancy category and activity]** | • Designed to reduce secondary attack rates below 1.0<br>• Adjustable for different infectious diseases<br>• Provides credits for wearing masks<br>• Considers activity type | • More complex than other approaches<br>• Relies on epidemiological parameters that may not be available for new infectious diseases<br>• Hard to be achieved in crowded spaces and for diseases with long subclinical infectious periods<br>• Does not provide recommendation for minimum ventilation |

[a] Minimum ASHRAE ventilation requirements were not suggested as a response to the COVID-19 pandemic

[b] Other organizations such as REHVA also provide ventilation recommendations close to ASHRAE that are not summarized here

[c] For buildings where the ventilation control needs actions by occupants (hybrid or natural ventilation systems) or there is no dedicated ventilation system in the building

[d] FPS Health, Food Chain Safety and Environment of Belgium adopted a framework based on maximum $CO_2$ concentration OR minimum NADR per occupant

[e] WHO, (2021) Roadmap to improve and ensure good indoor ventilation in the context of COVID-19, 2021

[f] ASHRAE, (2021) Standard 170-2021, Ventilation of Health Care Facilities, Table 7.1,
CDC, (2003) Guidelines for Environmental Infection Control in Health-Care Facilities, Last update: July 2019, Table B.2.

[g] Parameters are defined in Section 2-2-4.

# 3. Comparing Alignment Across Different NADR Approaches

The focus of this report was on the use of engineering control strategies for reducing the long-range aerosol transmission risk of airborne infectious diseases. More precisely, we discussed air ventilation, filtration, and disinfection as the most common infection control strategies inside buildings and briefly described the current ASHRAE standards for their minimum recommended rates. Next, we outlined different approaches for SARS-CoV-2 long-range airborne risk mitigation in buildings suggested by five internationally recognized organizations (i.e., WHO, CDC, ASHRAE, FPS, REHVA) and independent teams of scientists and compared the advantages and disadvantages of their proposed approaches. Then, we summarized key studies supporting the benefits of ventilation, filtration, and air disinfection against COVID-19 and other airborne infectious diseases. We also summarized key studies demonstrating the ability of ventilation and filtration in reducing exposures to indoor air pollutants and improving health factors among building occupants.

In the last section of this report, we compare the recommended approaches for calculating desired NADRs in buildings based on the recommendations of various organizations and teams of scientists after normalizing their suggestions for five typical occupied indoor environments (non-health care settings): (i) a medium-size office space, (ii) a restaurant dining room, (iii) a medium-size elementary classroom, (iv) a small hotel lobby, and (v) a supermarket. Additional information on the calculations for the recommended NADRs are provided in Appendix B.

Table 3.

**Comparison of NADR Across Five Different Space Types**

| | Space Type | Medium-size office space | Fully-occupied restaurant dining room | Medium-size elementary classroom | Small hotel lobby | Supermarket |
|---|---|---|---|---|---|---|
| Space characteristics | Floor area ($ft^2$) | 1,000 | 2000 | 1,000 | 1,000 | 10,000 |
| | Ceiling height (ft) | 10 | 15 | 10 | 10 | 30 |
| | Number of occupants (person) | 5 | 140 | 25 | 3 | 80 |
| | Occupants' age | 35 | 35 | 5-8 | 35 | 35 |
| | Activity Level | Standing tasks, light effort | Standing tasks, light effort | Standing tasks, light effort | Standing tasks, light effort | Walking, 2.8-3.2 mph, level surface, moderate pace |
| NADR (cfm) requirements based on: | ASHRAE:<br>Minimum outdoor ventilation rate [a] | 85 | 1,410 | 370 | 285 | 1,200 |
| | REHVA:<br>Warning $CO_2$ conc. of 800 ppm [a]<br>Alarm $CO_2$ conc. of 1000 ppm [a] | 133<br>107 | 3,740<br>2,980 | 513<br>410 | 1,598<br>1,278 | 5,000<br>4,000 |
| | WHO and Li et al. (2022):<br>Minimum NADR of 10 L/s/person | 106 | 2,968 | 530 | 636 | 1,696 |
| | Belgium FPS:<br>Std. Level A for $CO_2$ conc. of 900 ppm [a]<br>Std. Level A of 40 $m^3$/h/person NADR<br>Std. Level B for $CO_2$ conc. of 1200 ppm [a]<br>Std. Level B of 25 $m^3$/h/person NADR [a] | 90<br>118<br>67<br>74 | 2,485<br>3,296<br>1,865<br>2,059 | 342<br>589<br>257<br>368 | 1,065<br>706<br>799<br>441 | 3,300<br>1,883<br>2,500<br>1,177 |

Table 3.

**Comparison of NADR Across Five Different Space Types**

| | Space Type | Medium-size office space | Fully-occupied restaurant dining room | Medium-size elementary classroom | Small hotel lobby | Supermarket |
|---|---|---|---|---|---|---|
| NADR (cfm) requirements based on (cont'd): | Allen and Macomber (2022):<br>30 cfm/person of outdoor air | 150 | 4,200 | 750 | 900 | 2,400 |
| | Allen and Ibrahim (2021):<br>Ideal ACHe of 6<br>Excellent ACHe of 5<br>Good ACHe of 4<br>Minimum ACHe of 3 | 1,000<br>833<br>667<br>500 | 3,000<br>2,500<br>2,000<br>1,500 | 1000<br>822<br>667<br>500 | 1,500<br>1,250<br>1,000<br>750 | 30000<br>25,000<br>20,000<br>15,000 |
| | Azimi et al. (2021):<br>0.75 cfm/sq.ft. + min ASHRAE ventilation | 835 | 2,910 | 1,120 | 1,035 | 8,700 |
| | Federspiel et al. (2021):<br>Secondary infection rate < 1 | 283 | 21,825 | 311 | 876 | 13,368 |
| ACHe (1/hr) requirements based on: | ASHRAE:<br>Minimum outdoor ventilation rate [a] | 0.51 | 2.82 | 2.22 | 1.14 | 0.24 |
| | REHVA:<br>Warning $CO_2$ conc. of 800 ppm [a]<br>Alarm $CO_2$ conc. of 1000 ppm [a] | 0.80<br>0.64 | 7.48<br>5.96 | 3.08<br>2.46 | 6.39<br>5.11 | 1.00<br>0.80 |
| | WHO and Li et al.(2022):<br>Minimum NADR of 10 L/s/person | 0.64 | 5.94 | 3.18 | 2.54 | 0.34 |
| | Belgium FPS:<br>Std. Level A for $CO_2$ conc. of 900 ppm [a] Std.<br>Level A of 40 $m^3/h$/person NADR<br>Std. Level B for $CO_2$ conc. of 1200 ppm [a] Std.<br>Level B of 25 $m^3/h$/person NADR [a] | 0.54<br>0.71<br>0.40<br>0.44 | 4.97<br>6.59<br>3.73<br>4.12 | 2.05<br>3.53<br>1.54<br>2.21 | 4.26<br>2.82<br>3.20<br>1.77 | 0.66<br>0.38<br>0.50<br>0.24 |
| | Allen and Macomber (2022):<br>30 cfm/person of outdoor air | 0.90 | 8.40 | 4.50 | 3.60 | 0.48 |
| | Allen and Ibrahim (2021):<br>Ideal ACHe of 6<br>Excellent ACHe of 5<br>Good ACHe of 4<br>Minimum ACHe of 3 | 6.00<br>5.00<br>4.00<br>3.00 | 6.00<br>5.00<br>4.00<br>3.00 | 6.00<br>5.00<br>4.00<br>3.00 | 6.00<br>5.00<br>4.00<br>3.00 | N/A<br>N/A<br>N/A<br>N/A |
| | Azimi et al. (2021):<br>0.75 cfm/sq.ft. + min ASHRAE ventilation | 5.01 | 5.82 | 6.72 | 4.14 | 1.74 |
| | Federspiel et al. (2021):<br>Secondary infection rate < 1 | 1.70 | 43.65 | 1.87 | 3.50 | 2.67 |

[a] The required NADR values should be provided using ventilation

N/A Not applicable due to atypical ceiling height.

**The analysis using these five indoor spaces yielded several important findings:**

## 1. The current ASHRAE ventilation rates are too low

- In four out of five case studies (i.e., office, restaurant, residential, and supermarket) the recommended ACHe values based on minimum ASHRAE requirements were lower than the other approaches, which was predictable as the ASHRAE minimum ventilation recommendations were not developed as infection control strategies and only account for outdoor air supply

## 2. There is strong agreement between the ACHe approach and the volumetric flow rate per floor area approach

- The ACHe approach suggested by Allen and Ibrahim and the "volumetric flow per floor area + min ASHRAE ventilation" approach suggested by Azimi et al. recommend similar NADRs for indoor environments with typical ceiling heights.

## 3. There is good agreement between the volumetric flow rate per person and the ACHe and volumetric flow rate per floor area approaches

- The volumetric flow per person approach yielded similar results to the ACHe and volumetric flow rate per floor area approaches, except in places with lower occupant densities, as expected. In all explored scenarios except the fully occupied restaurant dining room, where the occupant density was higher than the other explored environments, the recommended NADR/ACHe values using the volumetric flow rate per person approach were significantly lower than other summarized recommendations

## 4. Volumetric flow rate per person and $CO_2$-based approaches were similar

- The calculated NADRs based on maximum $CO_2$ concentration and occupancy were closer to each other than to other approaches. These similarities were expected because both strategies' focus on the presence of human individuals in indoor spaces.

## 5. Secondary attack rate approaches were in between the occupancy based and ACHe approaches

- The recommended ACHe values based on the secondary attack rates were achievable and fell between occupancy-based suggestions and excellent ACHe-based recommendations in most studied cases; however, in the restaurant dining room case study, because so many people were assumed in a medium-size space, the infection control approach suggested a significantly higher and largely unachievable NADR to keep the secondary attack rates below 1.

# 4. Conclusion

The scientific evidence is clear that enhanced ventilation, filtration, and air disinfection are effective at reducing the exposure risk from SARS-CoV-2 and other respiratory infectious diseases, and also provide multiple co-benefits beyond reduced infection risk, including better cognitive function; reduced risk of allergic manifestations and number of unscheduled asthma visits among children; and improvements in subclinical cardiopulmonary health, prevalence of sick building syndrome (SBS) symptoms, and asthma control and quality of life scores. However, current standards for ventilation are based on bare minimums targets, do not reflect the latest scientific evidence on the multiple benefits of enhanced ventilation and filtration, and are not designed for health or infection control. In this report, we reviewed three of the most common ventilation metrics – air changes per hour, volumetric flow rate per person, and volumetric rate flow per floor area – and proposed new non-infectious air delivery rate (NADR) targets that exceed the current minimum standards. We found that, despite differences across metrics and publications, in all cases the new targets exceed current minimums and are largely in agreement. We note that there are important differences by location, space type, building operation, and risk level, and care is required in the application of these new proposed NADRs. Overall, these new NADRs collectively represent what should be considered new minimum standards for ventilation and filtration in buildings to help mitigate infection risk and promote health.

# APPENDIX A

## A-1: KEY STUDIES SUPPORTING VENTILATION/FILTRATION/DISINFECTION BENEFITS AGAINST SARS-COV-2

This section summarizes some of the key studies evaluating the performance of ventilation, filtration, and disinfection for reducing the transmission risk of SARS-CoV-2 in indoor environments. This is not intended to be a complete review of the literature; rather, we highlight key studies that give insight on ventilation effects and point toward useful metrics. The studies in this section are grouped into two categories of (i) epidemiological, experimental, and intervention studies and (ii) modeling-based and literature review (non-experimental) studies. Briefly, all of the summarized studies support the use of the intervention control measures and their effectiveness in reducing the transmission of SARS-CoV-2.

### A-1-1. Epidemiological, Experimental, and Intervention Studies

De Man et al. reported an outbreak in a Dutch nursing home that was likely to be the result of aerosol transmission in a setting of inadequate ventilation. In the outbreak, 81% of residents and 50% of healthcare workers (HCWs) in one of the seven wards in a nursing home with psychogeriatric residents were diagnosed with COVID-19, while all tests of the 106 HCWs and 95 residents in the six other wards were negative. The authors noticed that a $CO_2$-controlled energy-efficient ventilation system and two air conditioning units, which recirculated air through a 1-mm mesh dust filter, were used in the ward in which the cases were reported. In contrast, the other six wards were ventilated with outside air [46].

Li et al. analyzed a COVID-19 outbreak involving 10 infected people in three families in a restaurant in Guangzhou, China. They collected epidemiological data, obtained a full video recording and seating records, and measured the ventilation rate and dispersion of a warm tracer gas as a surrogate for exhaled droplets from the index case. The authors did not identify any close contact or fomite contact between the index case and other cases. Their analysis of the airflow dynamics indicated that the infection distribution was consistent with a spread pattern indicative of long-range transmission of exhaled virus-laden aerosols. As the measured ventilation rate was 0.9 L/s per person, the authors concluded that the airborne transmission of the SARS-CoV-2 is possible in crowded indoor environments with ventilation rates lower than 1 L/s per person [47].

### A-1-1. Epidemiological, Experimental, and Intervention Studies (continued)

Morris et al. conducted a study in two repurposed COVID-19 units (i.e., a ward and an intensive care unit - ICU) in Addenbrooke's Hospital, Cambridge, United Kingdom, to detect SARS-CoV-2 RNA in the various size fractions of air samples. During their study, airborne SARS-CoV-2 was detected in the ward before activation of HEPA-air filtration but not during filter operation. SARS-CoV-2 was again detected following filter deactivation. Airborne SARS-CoV-2 was infrequently detected in the ICU. Their results also showed SARS-CoV-2 bioaerosols were effectively filtered by the HEPA filters [48].

Gettings et al. investigated the role of mask use and ventilation improvements to reduce COVID-19 incidence in elementary schools in Georgia between November 16 and December 11, 2020. Their study showed COVID-19 incidence was 37% lower in schools that required teachers and staff members to use masks and 39% lower in schools that improved ventilation. Ventilation strategies associated with lower school incidence included dilution methods alone (35% lower incidence) or in combination with filtration methods (48% lower incidence) [49].

Myers et al. performed an intervention study on reducing the transmission risk of SARS-CoV-2 using portable air cleaners with HEPA filters. They recruited 17 individuals with newly diagnosed COVID-19 infection for their single-blind, crossover, randomized study and collected aerosol samples from the patient rooms with portable air cleaners (primary) and another room (secondary) for two consecutive 24-hour periods, one period with HEPA filtration and the other with the filter removed (sham). In their study, the number of positive SARS-CoV-2 RNA air samples dropped from seven out of 16 samples in primary rooms during the sham period to four out of 16 samples when HEPA filters were used in the portable air cleaners [50].

Ricolfi et al. investigated the strength of association between ventilation and SARS-CoV-2 transmission reported among the students of Italy's Marche region in more than 10,000 classrooms, of which 316 were equipped with mechanical ventilation. They used ordinary and logistic regression models to explore the relative risk associated with the exposure of students in classrooms. Their results showed in classrooms equipped with mechanical ventilation systems, the relative risk of infection decreased with an increase in ventilation. They also demonstrated that ventilation rates from 10 to 14 L/s per student reduced the likelihood of infection for students by 80% compared with a classroom relying only on natural ventilation. They obtained relative risk reductions in the range of 12%-15% for each additional unit of ventilation rate per person [51].

Parhizkar et al. studied the environmental characterization of SARS-CoV-2 viral load with respect to human activity, building parameters, and environmental mitigation strategies. They recruited 11 participants diagnosed with COVID-19 to individually occupy a controlled chamber and conduct specified physical activities under a range of environmental conditions and collected human and environmental samples over a period of three days for each participant. The authors found that increased viral load in nasal samples is associated with higher viral loads in environmental aerosols and on surfaces, and aerosol viral load in the far field (3.5 m) is correlated with the number of exhaled particles in the size range of 1–2.5 µm. More importantly, they demonstrated that increased ventilation (from below 4.5 per hour to above 9 per hour) and filtration (1000 $m^3$/hour or 588 cfm) significantly reduced aerosol and surface viral loads, while higher relative humidity resulted in lower aerosol and higher surface viral load [52].

Horve et al. tracked a cohort of subjects as they occupied a COVID-19 isolation dormitory to better understand the impact of subject and environmental viral load over time, symptoms, and room ventilation on the detectable viral load within a single room. They found that subject samples demonstrated a decrease in overall viral load over time, symptoms significantly impacted environmental viral load, and increasing both mechanical (i.e., from 0.16 ACH to 0.93 ACH) and natural ventilation rates (i.e., closed versus open windows) decreased aerosol SARS-CoV-2 load in studied spaces [53].

### A-1-2. Modeling-Based and Literature Review (Non-Experimental) Studies

Luongo et al. focused on summarizing the strengths and limitations of epidemiologic studies that specifically addressed the association of at least one HVAC system-related parameter with airborne disease transmission in buildings. They assessed the quality and quantity of available data and identified research needs. Luongo et al. suggested that there is a need for well-designed observational and intervention studies in buildings with better HVAC system characterization and measurements of both airborne exposures and disease outcomes [54]

Mikszewski et al. used a predictive estimation approach to compare the quanta generation rates of respiratory pathogens. They applied the approach to SARS-CoV-2 and several other airborne infectious disease vectors including measles virus, influenza virus, and mycobacterium tuberculosis (TB) and assessed the relative ability of ventilation to mitigate airborne transmission. Their results demonstrated that SARS-CoV-2 is nearly as contagious as TB and more transmissible through indoor air than seasonal influenza. They also concluded that although ventilation reduces the transmission risk of infectious diseases, the current ventilation standards in public buildings are unlikely to be able to keep the COVID-19 reproduction numbers below 1 [55].

Azimi et al. developed a modeling framework and leveraged detailed information available from the Diamond Princess cruise ship outbreak that occurred in early 2020 to evaluate the relative importance of multiple transmission routes for SARS-CoV-2. Their results demonstrate that aerosol inhalation was likely the dominant contributor to COVID-19 transmission among the passengers, even considering a conservative assumption of high ventilation rates and no air recirculation conditions for the cruise ship. Passenger quarantine procedures also affected the importance of each mode, demonstrating the impacts of multiple interventions. Their findings underscore the importance of implementing public health measures such as ventilation and filtration that target the control of inhalation of aerosols in indoor environments [56].

Miller et al. studied a COVID-19 outbreak that occurred among members of the Skagit Valley Chorale, where 53 out of 61 rehearsal attendees were confirmed or strongly suspected to have contracted COVID-19 and two of whom died. They concluded that transmission by the aerosol route was likely as either fomite or ballistic droplet transmission could not explain a substantial fraction of the cases. Based on a conditional assumption that transmission during this outbreak was dominated by the inhalation of respiratory aerosols generated by one index case, the authors used the available evidence to infer the emission rate of aerosol infectious quanta to explore how the risk of infection would vary with several influential factors including ventilation rate, duration of event, and deposition onto surfaces. Their results indicate infection risk would be reduced by a factor of two by increasing the NADR to 5 per hour and shortening the event duration from 2.5 to 1 hour [57].

Parhizkar et al. estimated COVID-19 infections for four outbreak scenarios using a quantitative microbial risk assessment (QMRA) model for far-field (long-range) transmission. The model accounts for particle emission dynamics, particle deposition to indoor surfaces, ventilation rate, and single-zone filtration to estimate inhalation dose in the respiratory system of receptors. The volume of inhaled and deposited doses of particles in the 0.5–4 μm range expressed in picoliters (pL) in a well-documented COVID-19 outbreak in restaurant X in Guangzhou, China, was anchored to a dose–response curve of HCoV-229E. For a reasonable emission scenario, it was estimated that approximately three PFU per pL were deposited in the respiratory system of those who became infected, yielding roughly 10 PFUs deposited. The authors applied the model to four reported COVID-19 outbreaks. Model results reasonably predicted the reported number of confirmed cases given available metadata from the outbreaks [58].

Yan et al. applied a novel approach based on the Wells-Riley model to a multi-zone building to simulate exposure to infectious doses in terms of “quanta.” Their modeling approach quantifies the relative benefits of different risk mitigation strategies. They evaluated the infectious risk transmission throughout an office building and implemented different mitigation strategies including increasing outdoor air ventilation rates and adding air-cleaning devices. Their results showed that, to keep the risk of the infection propagating low, the best strategy without universal masking was the operation of in-room GUV or a large industrial-sized portable air cleaner, whereas with masking all strategies were acceptable [59].

## A-2: KEY STUDIES SUPPORTING VENTILATION/FILTRATION/AIR DISINFECTION BENEFITS AGAINST OTHER RESPIRATORY DISEASE OR RESPIRATORY AEROSOLS IN GENERAL

Similar to the key studies supporting the benefits of control measures in reducing the transmission of SARS-CoV-2 in Section 3, the summarized studies in this section also support the effectiveness of ventilation, filtration, and air disinfection against a wide variety of airborne infectious diseases such as TB, influenza, and measles. The studies in this section are divided into two categories of (i) epidemiological, experimental, and intervention studies and (ii) modeling-based and literature review (non-experimental) studies.

### A-2-1. Epidemiological, Experimental, and Intervention Studies

Xu et al. evaluated the efficacy of upper-room GUV systems for inactivating airborne bacterial spores and vegetative mycobacteria cells under full-scale conditions in two studies. They conducted airborne bacteria inactivation experiments in a test room with a GUV system under various ventilation rate, temperature, and relative humidity conditions. They aerosolized the tested bacteria continuously into the room such that their numbers and physiologic state were comparable both with and without the UVGI and ventilation system operating. Their results demonstrated that the GUV system reduced the room-average concentration of airborne bacteria up to 98% depending on the type of bacteria and ventilation rate, and the performance of the GUV system degraded significantly when the relative humidity was increased from 50% to 75–90%. Xu et al. also performed an additional set of experiments, in which they aerosolized particles containing bacteria into the test room and then allowed them to decay under varying GUV and ventilation rates, yielding a maximum inactivation rate of 16±1.2 per hour for the GUV system [60], [61].

Kunkel et al. designed and performed a series of experiments to quantify the size-resolved dynamics of indoor bioaerosol transport and control in an unoccupied apartment unit operating under four different HVAC particle filtration conditions. Two model organisms (Escherichia coli K12 and bacteriophage T4) were aerosolized under alternating low and high flow rates to roughly represent constant breathing and periodic coughing. They conducted size-resolved aerosol sampling (at four locations between 0.5 and 7 m from the source) and settle plate swabbing (at three locations between 0.5 and 6 m from the source with different heights from floor), and analyzed the samples by DNA extraction and quantitative polymerase chain reaction (qPCR). Their results demonstrated that tested bioaerosols were recovered and amplified in air samples up to 7 m away under all filtration conditions, albeit in much smaller amounts than in near-source samples. They also showed higher efficiency HVAC particle filtration (e.g., MERV 11 and MERV 16 filters) clearly reduced the recoverable amount of DNA from both organisms in air samples and on settle plates located ~3 to ~7 m away from the source [62].

Zhu et al. designed a study to show the association between acute respiratory infection (ARI) transmission and low ventilation by combining characterization of ventilation with assessment of laboratory-confirmed infections. They followed laboratory-confirmed ARI rates and measured $CO_2$ concentrations for four months during the winter-spring of 2018 in two campus residence halls with high and low ventilation rates. They observed an ARI rate of 0.70 and 2.83 per person-year and average $CO_2$ concentrations of 1230 and 1492 ppm in high and low ventilation buildings, respectively. Their models also show that the residents in the high and low ventilation buildings had on average 6.6 and 2.3 L/s-person of outside air, respectively, when the doors and windows were closed. They concluded high ARI rates in the low ventilation building implicate transmission by infectious bioaerosols [63].

Du et al. measured the effect of improving ventilation rate on the transmission of TB during an outbreak in under-ventilated university buildings. The outbreak involved 27 TB cases and 1665 contacts. During their study, the mechanical ventilation rates of the university buildings were improved, reducing the average $CO_2$ concentrations from 3204 ± 50 ppm to 591 ± 603 ppm. After the increase in mechanical ventilation, the secondary attack rate of new contacts in the university dropped to zero (mean follow-up duration: 5.9 years). Therefore, the authors suggested that the exposure to source TB cases in indoor environments, where the $CO_2$ levels were above 1000 ppm (i.e., crowded space with low ventilation), was a significant infection transmission risk factor. After adjusting for effects of contact investigation and latent TB infection treatment, the authors also demonstrated that improving ventilation rates to levels with $CO_2$ <1000 ppm was independently associated with a 97% decrease in the incidence of TB among contacts [64].

### A-2-1. Epidemiological, Experimental, and Intervention Studies (continued)

A group of scientists from the University of Melbourne traced the airflow, transmission, and clearance of aerosols in the clinical spaces of a hospital ward that had been used to care for patients with COVID-19 and examined the effectiveness of commercially available air cleaners in reducing airborne particle concentrations. The authors used glycerin-based aerosol as a surrogate for respiratory aerosols. Their results demonstrate that aerosols rapidly traveled from the patient room into other parts of the ward, and air cleaners were effective in increasing the clearance of aerosols from the air in clinical spaces and reducing their spread to other areas. With two small domestic air cleaners in a single patient room of a hospital ward, 99% of aerosols could be cleared within 5.5 minutes (providing approximately 50 ACHe) [65].

### A-2-2. Modeling-Based and Literature Review (Non-Experimental) Studies

Kujundzic et al. studied six different types of air cleaners and quantified their ability to remove and/or inactivate airborne bacteria and fungal spores. Four of the air cleaners incorporated UV lamp(s) into their flow path. The authors also evaluated the efficacy of combining air cleaners with upper-room GUV systems. The experiments were performed in an 87- $m^3$ test room with a ventilation system providing zero or six air changes per hour. The authors aerosolized active bacteria cells and fungal spores into the room such that their numbers and physiologic states were comparable both with and without air cleaning and upper room GUV. The disinfection performances of the GUV system were also evaluated. The average reported airborne microbial NADR varied between 26 and 981 $m^3hr{-1}$ depending on the AC. The provided NADRs were significantly higher, 1480–2370 $m^3hr{-1}$, when using air cleaners in combination with upper-room air GUV. Their results demonstrated that no additional air cleaning was provided with the operation of a UV-C lamp inside the air cleaners; the internal UV-C lamps, however, inactivated 75% of fungal spores and 97% of bacterial cells captured in the air filter medium within 60 minutes [66].

Li et al. performed a literature review on the association between the transmission of airborne infectious diseases and ventilation in indoor environments. The authors selected 40 original studies published between 1960 and 2005 based on a set of criteria, systematically assessed them, and concluded that there is strong and sufficient evidence to demonstrate the association between ventilation, air movement in buildings, and the transmission of infectious diseases such as measles, tuberculosis, chickenpox, influenza, smallpox, and SARS. However, they suggested that there is a knowledge gap on the specification and quantification of the minimum ventilation requirements in hospitals, schools, and offices associated with the spread of airborne infectious diseases [67].

Azimi and Stephens used a modified version of the Wells-Riley model to estimate the transmission risk of influenza in a hypothetical office space and compared associated operational costs of HVAC filtration and equivalent outdoor air ventilation assuming the hypothetical office is located in four different cities in the U.S. They predicted HVAC filtration can achieve risk reductions at lower costs of operation compared to equivalent levels of outdoor air ventilation, particularly for MERV 13–16 filters. Moreover, their results showed medium efficiency filtration products (MERV 7–11) were also inexpensive to operate but appear less effective in reducing infectious disease risks [68]

Nardell reviewed available studies on environmental interventions to control TB, which also can be applied to influenza and other infections with airborne potential. He mentioned that the best means of TB transmission control is source control – to identify unsuspected infectious cases and to promptly begin effective therapy. However, even with active case finding and rapid diagnostics, not every unsuspected case will be identified, and environmental control measures remain the next intervention of choice. He added natural ventilation is the main means of air disinfection and has the advantage of wide availability, low cost, and high efficacy under optimal conditions, but it is usually not desirable year-round. Nardell indicated that mechanical ventilation, when properly installed and maintained, can provide adequate air disinfection, though it is expensive to install, maintain, and operate. He concluded upper room germicidal irradiation is the most cost-effective way to achieve high levels of air disinfection [69].

### A-2-2. Modeling-Based and Literature Review (Non-Experimental) Studies (continued)

Escombe et al. suggested natural ventilation is a low-cost environmental control measure for TB infection control, where climate permits, that is suited to many different areas in healthcare facilities. They measured the effect of simple architectural modifications to existing hospital waiting and consulting rooms in a low-resource setting to enhance natural ventilation and reduce modeled TB transmission risk. In their model, the room ventilation in the four waiting rooms was increased from a mean of 5.5 to 15, 11 to 16, 10 to 17, and 9 to 66 ACH, respectively, and in the two consulting rooms from a mean of 3.6 to 17 and 2.7 to 12 ACH, respectively. Due to the modifications, they reported a median 72% reduction in the transmission risk of TB to susceptible individuals [70].

Azimi et al. evaluated the influence of personal (vaccination), social (compartmentalizing), and building systems (ventilation, purification, and filtration) factors on measles transmission in schools. They used a combination of a newly developed multi-zone transient Wells-Riley approach, a nationwide representative School Building Archetype model, and a Monte-Carlo simulation to estimate measles risk among U.S. students. Their simulation results showed that infection control strategies could cut the average number of infected cases in schools about 55% when a combination of advanced HVAC system filtration, ventilation, and air cleaning was adopted in the modeled schools providing 11.7 ACHe [71].

Li et al. developed a simple macroscopic aerosol balance model to link short- and long-range airborne transmission. The model considers the involvement of exhaled droplets with an initial diameter ≤50 μm in the short-range airborne route, whereas only a fraction of these droplets with an initial diameter ≤15 μm or equivalently a final diameter ≤5 μm were considered in the long-range airborne route. They demonstrated that room ventilation rate significantly affects the short-range airborne route, in contrast to the traditional belief, and when the ventilation rate in a room is insufficient, the airborne infection risks due to both short- and long-range transmission are elevated. They suggest a ventilation rate of 10 L/s per person provides a similar concentration vs distance decay profile to that in outdoor settings, which provides additional justification for the widely adopted ventilation standard of 10 L/s per person [5].

## A-3. KEY STUDIES SUPPORTING MULTIPLE BENEFITS OF VENTILATION/FILTRATION BEYOND RESPIRATORY DISEASES

This section summarizes key studies evaluating other benefits of infection control measures adopted for indoor environments. The benefits of air disinfection using GUV systems are limited to infection control; therefore, the focus of this section is only on ventilation and filtration systems. Moreover, as a large number of strong experimental and intervention studies were available to support the multiple benefits of filtration and ventilation systems, this section excludes modeling-based studies. This section includes some studies that directly investigated the health benefits of ventilation and filtration in buildings, as well as other studies that illustrated the effectiveness of ventilation and filtration systems in reducing exposures to indoor air pollutants which have harmful effects on health. The summarized studies are divided into two categories of (i) experimental and intervention studies and (ii) literature reviews. This review demonstrates that ventilation and filtration systems can reduce exposures to indoor air pollutants such as PM, $CO_2$, and NOx and improve health factors such as activity limitation, allergy symptoms, cognitive function, and cardiopulmonary health.

### A-3-1. Experimental and Intervention Studies

Du et al. performed a study on the effectiveness of filters in reducing pollutant exposures of children with asthma. They recruited 126 households with an asthmatic child in Detroit, Michigan, and randomized them into a control group or a treatment group that received a high-efficiency air filter placed in the child's bedroom. They measured PM, $CO_2$, environmental tobacco smoke tracers, and air change rates over a one-week period and demonstrated that installing filters could reduce PM concentrations by an average of 69-80% in homes with asthmatic children [72].

### A-3-1. Experimental and Intervention Studies (continued)

Lanphear et al. conducted a double-blind, randomized trial to test the impacts of HEPA air cleaners on unscheduled asthma visits and symptoms among 225 eligible asthmatic children between 6 to 12 years of age who were exposed to secondhand smoke from more than five cigarettes per day. The authors found that unscheduled asthma visits among children in the intervention group were 18.5% (95% confidence interval: 1.25%–82.75%) lower compared with those in the control group, after adjustment for baseline differences. They also reported a 25% reduction in particle levels in the intervention group, compared with a 5% reduction in the control group, while there were no significant differences in parent-reported asthma symptoms, exhaled nitric-oxide levels, air nicotine levels, or cotinine levels according to group assignment [73].

Bakó-Bíró et al. investigated the effects of classroom ventilation on students' performance in eight primary schools in England by increasing the outdoor air ventilation from about 1 l/s per person to about 8 l/s per person. They monitored the concentrations of $CO_2$ and other parameters in each school for three weeks in two selected classrooms. They analyzed the performance of more than 200 students and demonstrated that higher ventilation rates increase the cognitive performance of students. They also provided strong evidence that low ventilation rates in classrooms significantly reduce pupils' attention and vigilance, and negatively affect memory and concentration [74].

Spilak et al. assessed the association between the concentration levels of particulate matter and building characteristics, and the use of air cleaners as a way to effectively reduce the levels of $PM_{2.5}$ indoors. In their study, the custom-built air cleaners ran for two weeks with HEPA filters and another two weeks without them. The authors also assessed the particle-removal efficiency of the air cleaners by considering the amount of infiltrated air, the size of the controlled room, and filtration effectiveness. The results demonstrated that the use of air cleaners led to a decrease in the concentrations of $PM_{2.5}$ by a median value of 54.5% [75].

Allen et al. evaluated the associations of cognitive function scores with $CO_2$ and VOC exposures and ventilation rates in different types of simulated office buildings. They asked 24 participants to spend six full work days in an environmentally controlled office space, blinded to test conditions, and exposed the participants to various levels of VOC and $CO_2$ concentrations as well as ventilation rates on different days. Their results demonstrated that, on average, the cognitive scores were about 60% and 100% higher on the days that the participant experienced lower VOC concentrations and high ventilation rates, respectively. The author concluded that cognitive function scores were significantly better in a building with low $CO_2$ and VOC concentrations and high ventilation rates for all tested functional domains [76].

Cox et al. conducted a placebo-controlled cross-over study, in which a HEPA cleaner and a placebo dummy were placed in 43 homes for four weeks each, with 48-hour air sampling prior to and during the end of each treatment period, to investigate the effectiveness of portable HEPA air cleaners in reducing indoor concentrations of traffic-related and other aerosols, including black carbon, $PM_{2.5}$, ultraviolet absorbing particulate matter (a marker of tobacco smoke), and fungal spores. The concentrations of all measured air pollutants were significantly reduced following HEPA filtration, but not following the dummy period. Their results demonstrate that HEPA air purification can result in a significant reduction of traffic-related and other aerosols in residential buildings [77].

Luo Jia-Ying et al. conducted an intervention study on 32 subjects (25 +/- 13.5 years old) diagnosed with allergic rhinitis to evaluate the ability of air cleaners to reduce allergic rhinitis. They deployed HEPA air cleaners in volunteers' bedrooms for four months. The authors collected dust samples before the intervention and each month and assessed the samples for allergen content. Additionally, they placed static dust collectors in the sampling sites to collect dust by sedimentation. The authors assessed aerosols using PM indoor/outdoor ratios and allergic symptoms using the Rhinitis Quality of Life Questionnaire (RQLQ). Their results demonstrate that allergen levels (i.e., Der f1) in both air and bed sampling and indoor/outdoor ratios of $PM_1$, $PM_{2.5}$, and $PM_{10}$ all significantly decreased after the initiation of HEPA air cleaners. Moreover, according to RQLQ data, HEPA filtration was associated with improvements in activity limitation, non-nasal-eye symptoms, practical problems, and nasal symptoms [78].

### A-3-1. Experimental and Intervention Studies (continued)

James et al. designed a double-blind, placebo-controlled study to assess the impact of HEPA filtration on the concentrations of in-home traffic particles and the consequent health effects on 43 children with asthma. They placed either a HEPA air cleaner or a placebo "dummy" in children's homes for four weeks, then they switched to the other treatment arm for four weeks, leaving the home untreated for one month between these two periods. The authors performed air sampling and collected information on the health outcomes of the interventions (i.e., asthma control and quality of life measures) at the end of each treatment period. Their results showed indoor concentrations of traffic particles were significantly reduced with the HEPA treatment but not with the "dummy" treatment, and in participants with poorly controlled asthma and lower quality of life at baseline, asthma control and quality of life scores were significantly improved following the HEPA treatment [79].

Barkjohn et al. used real-time sensors to assess the exposures of 39 children with asthma in Shanghai, China, and quantified micro environmental exposure to $PM_{2.5}$ and ozone. They deployed air cleaners in participants' bedrooms for two 48-hour periods (i.e., one with portable HEPA air cleaner and activated carbon filters and the other without), where they hypothesized exposure could be most efficiently reduced. Their results demonstrated that the HEPA filtration in bedrooms reduced the exposure to $PM_{2.5}$ in the bedrooms by 75% and the total exposure by 45%. They concluded that actions taken to reduce bedroom $PM_{2.5}$ concentrations could most efficiently reduce total exposure [80].

Riederer et al. conducted a randomized trial of portable HEPA air cleaners with NH3 pre-filters in non-smoking homes of asthmatic children aged 6-12 years. They deployed two HEPA air cleaners in each child's sleeping area and main living area and measured 14-day integrated samples of endotoxin in settled dust and $PM_{2.5}$, $NH_3$, $PM_{10}$, and $PM_{10\text{-}2.5}$ in the air at baseline and after one year. Seventy-one households (36 HEPA, 35 control) completed the study. Their results, which are published in two articles, demonstrated that in homes with HEPA filtration, the concentrations of $PM_{2.5}$ were reduced 60% (95% CI, 41%-72%) and 42% (19%-58%) in sleeping and living areas, respectively; $PM_{10}$ concentration reduced 46% (95% CI, 31%-57%) on average; and $PM_{10\text{-}2.5}$ concentration at 50th and 75th percentile baseline concentrations were 49% (95% CI, 6%-110%) and 89% (95% CI, 28%-177%) lower. However, NH3 and endotoxin loadings reductions were not observed [81], [82].

Kang et al. conducted a more than two-year longitudinal, pseudo-randomized, crossover study designed to assess indoor air quality and adult asthma outcomes before and after installing residential mechanical ventilation systems in 40 existing homes in Chicago, IL. They deployed one of three types of ventilation systems in volunteers' homes. Residential buildings with central heating and/or cooling systems also received MERV 10 filter replacements. They monitored environmental conditions, ventilation operation, and indoor and outdoor pollutants, including size-resolved particles (0.3–10 µm), ozone (O3), nitrogen dioxide ($NO_2$), $CO_2$, carbon monoxide (CO), and indoor formaldehyde (HCHO) in approximately week-long measurements every three months during the study (four times before intervention and four times after). Their results demonstrated the indoor/outdoor ratios of $CO_2$, $NO_2$, $PM_1$, $PM_{2.5}$, and $PM_{10}$ across all systems after the intervention were approximately reduced 12%, 10%, 42%, 39%, and 33%, respectively. The authors also mentioned that there was a reduction in I/O ratios for all measured constituents with each type of system, on average, but with varying magnitude and levels of statistical significance [11].

### A-3-2. Literature Reviews

Seppänen et al. reviewed the literature on the associations of ventilation rates and $CO_2$ concentrations in non-residential and non-industrial buildings (primarily offices) with health and other human outcomes. They reported that almost all reviewed studies found that ventilation rates below 10 Ls-1 per person in all building types were associated with statistically significant worsening in one or more health or perceived air quality outcomes. The authors also highlighted that increases in ventilation rates are associated with significant decreases in the prevalence of SBS symptoms, and the risk of SBS symptoms significantly decreases with decreasing in $CO_2$ concentrations below 800 ppm. Their analysis demonstrated that the ventilation studies reported relative risks of 1.5–2 for respiratory illnesses and 1.1–6 for sick building syndrome symptoms for high compared to low ventilation rates [83].

### A-3-2. Literature Reviews (continued)

Sundell et al. reviewed the effects of ventilation rates on health in indoor environments. The authors highlighted a biological plausibility for an association of health outcomes with ventilation rates, although they mentioned that the literature does not provide clear evidence on particular agent(s) for the effects. The reviewed papers suggested that higher ventilation rates in offices, up to about 25 l/s per person, are associated with reduced prevalence of SBS symptoms and lower ventilation rates are associated with increased inflammation, respiratory infections, asthma symptoms, and short-term sick leave. They also noticed that home ventilation rates above 0.5 air changes per hour have been associated with a reduced risk of allergic manifestations among children. The authors concluded that increasing ventilation rates above currently adopted standards and guidelines should result in a reduced prevalence of negative health outcomes [84].

Sublett reviewed recent studies of various types of filtration, used alone or as part of more comprehensive environmental control measures. His summary showed that residential air filtration can be provided by whole-house filtration via the home's HVAC system, portable air cleaners, or a combination of both. He suggested that inexpensive, low-efficiency HVAC filters offer no better particle removal than HVAC systems with no filter. Sublett also suggested that whole-house filtration with high-efficiency HVAC filtration was more effective in particulate reduction than individual HEPA portable air cleaners, and ionic electrostatic room air cleaners produce ozone and provide little or no benefit compared with whole house filtration or HEPA portable air cleaners. The author concluded that the best and most cost-effective approach may be to consider "combination filtration" using high-efficiency whole house filtration with portable air cleaners or breathing zone filtration in the bedroom [85].

Fisk reviewed and summarized the evidence of the health benefits of particle filtration in homes and commercial buildings. His literature review included a summary of intervention studies as well as four studies that modeled the health benefits of using filtration to reduce indoor exposures to particles from outdoors. He suggested that the percentage improvement in health outcomes is typically modest (i.e., between 7% to 25%), and delivery of filtered air to the breathing zone of allergic or asthmatic individuals during sleeping may be more consistently effective in improving health than room air filtration [86].

Carrer et al. reviewed epidemiological articles providing information on the link between outdoor air ventilation rates and health. They reported effects on health were seen for a wide range of outdoor ventilation rates from 6 to 7 L/s per person, which were the lowest ventilation rates at which no effects on any health outcomes were observed in field studies, up to 25-40 L/s per person, which were in some studies the highest outdoor ventilation rates at which no effects on health outcomes were seen. They concluded that these data show that, in general, higher ventilation rates in many cases will reduce health outcomes, and that there are the minimum rates, at which some health outcomes can be avoided [87].

Allen and Barn reviewed recent peer-reviewed literature on three categories of individual- and household-level interventions against air pollution, including air cleaners, face masks, and behavior change. Recent findings of the articles summarized in their literature review suggested that HEPA air cleaners used over days to weeks can substantially reduce $PM_{2.5}$ concentrations indoors and improve subclinical cardiopulmonary health. They mentioned that several studies have also reported subclinical cardiovascular health benefits from well-fitting respirators, while evidence of health benefits from other types of face masks and behavior changes remains very limited. They concluded that in situations when emissions cannot be controlled at the source, such as during forest fires, individual- or household-level interventions may be the primary option [88].

# APPENDIX B

To calculate the recommended NADRs and ACHes in Table 2, we selected typical values for the floor area, ceiling height, and occupants' ages in the selected indoor environments. The number of occupants was calculated based on ASHRAE Standard 62.1 default occupant densities, and occupant activity levels were based on published values [89]. The minimum ASHRAE outdoor ventilation rates for selected spaces were calculated based on Standards 62.1 and 62.2-2019. The required ventilation rates for keeping the indoor concentration of $CO_2$ below 800 ppm were estimated using the Maximum $CO_2$ Calculator designed by the For-Health research team using the assumed floor area, ceiling height, number of occupants, and occupant's average age and activity levels [90]. We also calculated the recommended NADR values based on the number of occupants (i.e., 10 L/s/person or 21.2 cfm/person) and the floor area (i.e., 0.75 cfm/ft$^2$) plus the minimum ASHRAE ventilation requirements. Equation 1 in Section 2-2-4 was adopted to estimate the NADR based on the secondary attack rate in the selected indoor environments.

In Equation 1, the model-acceptable breathing rate (B) and steady state quanta emission rates (Ess) of SARS-CoV-2 were culled from the Guideline Calculator developed by Federspiel et al. for each selected environment [32], the total average interaction time between infector and susceptible occupants during the infectious period (T = 48) was assumed to be 48 hours over the span of a four-day subclinical infectious period for COVID-19 [56], no mask mandates were considered (i.e., pi and ps = 1), the desired secondary reproduction number was set equal to one (Rt = 1), and the number of susceptible occupants (S) were estimated from Equation B-1:

**Equation B-1:**

$$S = ( N_{occupants} - 1 ) X i$$

where:

$N_{occupants}$: Number of occupants for selected indoor environments

$i$ : Immunity proportion of the community (assumed to be 80% in the U.S.)

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