Shaping Tomorrow's Built Environment Today

ASHRAE Positions on

Infectious Aerosols

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ASHRAE is a global professional society of over 55,000 members, committed to serve humanity by advancing the arts and sciences of heating, ventilation, air conditioning, refrigeration and their allied fields (HVAC&R). ASHRAE position documents are approved by the Board of Directors and express the views of the Society on specific issues. These documents provide objective, authoritative background information to persons interested in issues within ASHRAE's expertise, particularly in areas where such information will be helpful in drafting sound public policy. The documents also clarify ASHRAE's position for its members and building professionals.

Infectious Aerosols is a Public Interest Issue

The magnitude of risk from aerosolized pathogens has become increasingly obvious, especially during the COVID crisis. These risks are particularly elevated in enclosed buildings.

Public-health officials, policymakers, building owners, designers, and members of the public all need accurate, reliable guidance for appropriate ways to mitigate the risk from these pathogens. Available risk mitigation strategies include pharmaceutical interventions, nonengineering controls, and engineering controls. Given the concurrent climate crisis, the optimal mitigation bundle of interventions must achieve the highest possible risk reduction with the lowest possible resultant emissions.

Why ASHRAE Takes Positions on Infectious Aerosols

ASHRAE consensus standards and other guidance provide the technical foundation for international building practices and energy codes that balance the need for energy efficiency with the need to keep the indoor environment healthy and comfortable for occupants. The design, installation, and operation of buildings' mechanical systems can improve—or impede—the buildings' ability to mitigate risk from infectious aerosols.

Consequently, ASHRAE's positions, standards, and design guidance can help avoid health risks associated with infectious aerosols.

ASHRAE Takes the Positions That:

- Exposure to infectious aerosols is an important factor in the transmission of infections in indoor environments between a source and a susceptible individual.
- Engineering controls demonstrated to reduce the risk of exposure to infectious aerosols include dilution with outdoor air provided by mechanical or natural ventilation, filtration of

indoor air, indoor airflow patterns, and disinfection by germicidal ultraviolet light and other technologies proven to be effective and safe.

- Strategies using engineering controls for managing the risk from infectious aerosols should focus on reducing exposure to infectious aerosols in the breathing zone.
- Effective design, installation, maintenance, and operation of ventilation controls are critical to achieving needed risk mitigation.
- Existing evidence for the effects of temperature and humidity on infection risk does not justify changes to ventilation and IAQ standards, regulations, and guidelines at this time.
- The effectiveness of any one risk mitigation strategy depends on many factors. Using multiple risk mitigation strategies will usually be more effective than reliance on any single strategy.
- Risk mitigation measures should be adaptable to levels of risk in a particular space.
- Combinations of engineering controls and non-engineering controls can be optimized for effectiveness, cost, and energy use.

ASHRAE Recommends that:

A multidisciplinary research and development (R&D) working group be established, aiming to improve coordination between engineers, scientists, and health professionals and prioritize and accelerate the research agenda, development process, and dissemination. As a minimum, this research should include the following topics:

- Controlled intervention studies to quantify the impact on infection transmission resulting from various engineering controls considered singly and in combination with other nonengineering controls with respect to infectious aerosols of varying characteristics.
- Real-time detection methodologies for the purpose of improved variable control of HVAC controls responsive to different levels of risk.
- Methods to reduce the life-cycle cost and carbon emissions of engineering controls in all conditions.
- Studies to characterize the size-resolved emission rate of infectious aerosols for different pathogens and different respiratory activities and metabolic intensities, determine the relationship between size and risk of transmission, and predict the fate and transport of these aerosol particles in indoor environments.
- Quantitative infection risk evaluation tools for infectious aerosols (quantitative microbial risk assessment is widely used for water and food, but much less for aerosols).
- Impact of indoor airflow patterns on the transmission of infectious aerosols and the resulting risk of infection.

ASHRAE Commits to:

- Support model codes and standards that address exposure to infectious aerosols, balancing quality of evidence, risk mitigation, cost of installation and operation, and energy use and carbon emissions.
- Support model codes and standards using variable amounts of outdoor/clean air delivery in response to the measurement of air quality to optimize indoor air quality in an efficient way.
- Promote research to enhance HVAC technologies and knowledge to mitigate the risk of infection due to airborne transmission.

- Develop protocols for better testing and certification of control technologies.
- Encourage publication of filter test data indicating removal efficiency by particle size for each filter as part of the certification process. This data should include information on performance effects associated with filter loading and electrostatic charge (if applicable).

Appendix A: Background Information

This document is not a design guide. Its purpose is to advise policymakers on appropriate engineering control strategies for various settings, various normal/epidemic disease states, and in combination with nonengineering strategies, based on the best available science, the number of benefits and costs resulting from various strategies including their carbon implications, using principles of evidence-based medicine (EBM).

Infectious Aerosols Risk

Respiratory diseases are among the most common causes of severe illness and death worldwide (Forum of International Respiratory Societies 2017). Acute respiratory infections (ARIs) are the leading cause of morbidity and mortality from infectious diseases worldwide. Almost four million people die from ARIs each year, with 98% of these deaths due to lower respiratory tract infections (WHO 2014). The current COVID-19 pandemic, caused by the SARS-CoV-2 virus, and the increasing rate of emergent respiratory viral infections in recent years are of great concern, as some of the ARI pathogens may be capable of global public-health emergencies.

Pathogens are classified into different risk groups describing the relative hazard posed by infectious agents or toxins. Considerations used in a biological risk assessment include the pathogenicity of the agent and infectious dose, potential outcome of exposure, natural route of infection, other routes of infection resulting from manipulations, stability of the agent in the environment, information available from animal studies, and the availability of effective prophylaxis or therapeutic interventions (WHO 2004).

While multiple factors must be considered for risk assessment, the design of engineering and environmental mitigation measures should be guided by the specific route of transmission or contaminant dissemination. Transmission of infection is a complex process; the risk of disease is determined by numerous factors that have considerable and uncertain variability including the characteristics of the pathogen concerned, the infectiousness of the host, the media through which the infectious agent passes from source to new host, and the immune response of the new host (Noakes and Sleigh 2009). Transmission or dissemination through the air complicates this further by adding other influencing factors (Sze To and Chao 2010).

Mechanisms of Transmission of Infectious Aerosols

An infectious aerosol is a collection of pathogen-laden particles in the air. Typically, infectious aerosols are released by an infected person as part of respiratory activities such as breathing, talking, singing, coughing, and sneezing. All people, whether infected or not, release droplets of respiratory fluid (mucus, sputum, or saliva) spanning a wide range of sizes during such respiratory activities. Some droplets are so large that they cannot remain suspended for more than a few seconds in the expired jet. Some droplets are small enough to be considered aerosol particles (aerosols) that can remain suspended in the air for an extended period. Under all but the most humid conditions, the smallest droplets rapidly evaporate, leaving behind solid or semisolid residue consisting of nonvolatile components of the respiratory fluid. If a person is infected, their respiratory droplets and aerosols may carry pathogens and may be infectious.

Traditional definitions of “airborne” and “droplet” transmission have been shown to be misleading, and revised definitions of transmission routes are more closely aligned with the actual mechanisms by which pathogens are transferred from one person to another (Marr and Tang 2021). These revised routes are (1) inhalation of aerosols, (2) spray of large droplets, and (3) touching a contaminated surface. The first supplants the traditional airborne route, which was assumed to apply only at long distance, while the second and third correspond to the traditional droplet and fomite (or contact) routes. To facilitate readability and understanding, this committee agreed to leverage recently proposed terminology.

Inhalation of infectious aerosols can cause infection, though the risk of infection of any individual is a function of the infectivity of the particular organism, its ability to remain infectious in air, the exposed person’s susceptibility to infection, the number of particles inhaled, the amount of infectious virus in the inhaled particles, where the particles are deposited along the respiratory tract, and other factors.

In the past, the transmission of most respiratory pathogens was thought to be associated primarily with larger droplets, of concern only to people at close range to an infected person. It is now clear that transmission of COVID-19 and other respiratory infections is likely dominated by inhalation of infectious aerosols both at close range and long range (Wang et al. 2021)

Pathogen-carrying droplets and aerosolized particles that fall to a surface can be a source of infection through touch and subsequent touching of the eyes or nose or through reaerosolization (or resuspension) followed by inhalation.

Factors Affecting Respiratory Infection Risk

Both duration of exposure and proximity to the source—a person who exhales infectious aerosols—are risk factors. Proximity to others influences the risk because airborne pathogens are most concentrated in the expiratory jets close to the point of release (Cortellessa et al. 2021). The concentration of aerosols decreases with distance. As infectious aerosols move through a space, they may lose infectivity over time. The risk of transmission also increases with the duration of exposure (Buonanno et al. 2020).

From the perspective of potential risk mitigation interventions, four primary factors influence the chain of infection for aerosolized pathogens: source, pathway, exposure and vulnerability.

The *source* is a function of the number of emitters of the pathogen, the quantity of pathogen emitted by each infected host, and the infectiousness of the pathogen. In the case of aerosolized pathogens, the source will normally be an infected person. In some cases, the source may consist of a surface on which particles have fallen and may be resuspended due to disturbance. In some cases, fecal material and waterborne pathogens may aerosolize to create yet a third kind of source. Many factors influence the risk from a particular source, but the most important is a particular pathogen’s infectiousness (e.g., transmissibility).

Exhalations release droplets spanning a wide range of sizes, including those small enough to be considered aerosols. The number, size, and velocity of these droplets and aerosols vary widely by individual, type of respiratory activity and/or metabolic intensity, the volume of vocalization, and stage of disease if the person is infected. Speaking loudly, singing, and deeper breathing associated

with physical activity and the like increase the number and speed of droplets and aerosols discharged into the air (Coleman et al. 2021; Pöhlker et al. 2021; Tomisa et al. 2021; Wang et al. 2021).

The *pathway* refers to the physical movement of the pathogen between the source and the new host, the duration of time the source and new host are proximate, the medium of transfer from the source to the new host, and the characteristics of the medium (in the case of air, humidity, temperature, indoor airflow patterns, etc.).

Exposure depends on the inhalation rate (volume per unit time), which varies with physical activity (Wang et al. 2021) and concentration of pathogens in inhaled air.

Vulnerability refers to the defenses the new susceptible host has to the particular pathogen being transmitted. This refers to both their immune response and behavior. Vulnerability at a population level is affected by the number of potential new hosts in proximity to a source. Therefore, risk is higher in "hubs for community transmission." Vulnerability at a population level is similarly high in locations with large numbers of persons who are more than normally susceptible to infection and with a higher risk of severe disease when infected (Bueno de Mesquita et al. 2021).

Managing Risk

Risk from pathogen spread can be reduced by nonengineering interventions (i.e., pharmaceutical interventions, administrative controls, etc.) and engineering controls. The risk of exposure to infection from various aerosolized pathogens is unlikely to be reduced to zero. The goal, therefore, must be to select a bundle of strategies, both engineering and nonengineering, that most practically minimizes risk and waste.

Given the variability of factors affecting the risk of infection in any given circumstance, no single set of mitigation strategies can balance the evidence, effectiveness, timeliness, and cost against all possible combinations of risk factors.

In general, policymakers should consider two broad sets of operating conditions: "normal" circumstances, where there is a somewhat regular level of risks, and epidemic states, where there are temporarily higher levels of risks.

In a normal state, largely because of the public-health measures implemented over time, we experience a relatively similar, low risk of transmission of all disease from infectious aerosols in most buildings. Some buildings and spaces, such as health care buildings, normally contain larger numbers of infectious and immunocompromised persons or otherwise vulnerable persons. Therefore, those spaces warrant higher levels of risk mitigation under normal circumstances.

In an epidemic state, risks step upwards, generally because of the presence of a particular pathogen with a particularly high reproduction rate and few or no medical controls widely available. The risks will vary with public adherence to various behavior protocols (i.e., closing bars and shopping malls, social distancing, mask-wearing, etc.).

To mitigate the risks of infection, policymakers have different public-health measures at their disposal. These measures include source controls, pathway controls, and controls to protect vulnerable persons. Source controls include administrative controls (limiting access to a space,

requiring screening, etc.), pharmaceutical controls (vaccination), personal protective equipment (PPE), isolation/separation, contact tracing to facilitate isolation/separation, and sometimes cleaning or water management. Pathway controls include both engineering controls (mechanical or natural ventilation, filtration, air cleaning, indoor airflow patterns, and temperature and humidity controls) and nonengineering controls (daylight, surface disinfection, and barriers). Controls to protect vulnerable persons include administrative controls, pharmaceutical controls, PPE, and isolation/separation. Usually, the right response to a particular situation will be a bundle of strategies from within each of these categories, which are likely to vary over time in response to evolving levels of risk.

A complicating factor is the *velocity* of risk variation combined with *uncertainty* about the characteristics of a novel disease. The shift from a normal to an epidemic state can occur so rapidly that significant harm may ensue before controls are implemented. However, definitive evidence of transmission modes may not be available for a long time, and insistence on incontrovertible evidence can cause long delays in response. Consequently, there is a strong argument for invoking the "precautionary principle" in such cases, i.e., "(o)ne should take reasonable measures to avoid threats that are serious and plausible" (Resnik 2004). Applying the precautionary principle would require that engineering controls capable of coping with the worst likely event are already present and ready for use when needed or that plans exist to deploy effective controls rapidly. The importance of the precautionary principle also extends to public-health guidance that is essential to initiate a timely response to a serious threat.

One important consideration for all policymakers is the need to prescribe controls for the varying states of risk that every building will face. In general, operating at an epidemic-appropriate state all the time will waste resources. The optimal policy will be one that defines appropriate controls for a normal state (including those spaces with higher-than-normal levels of risk) with the flexibility to ramp up at appropriate velocity to match a developing epidemic.

An important difficulty that policymakers face in prescribing the optimal bundle of risk mitigation measures is the varying response of the public to administrative controls and PPE measures and the difficulty of balancing "freedoms." That is, in some cases, people may refuse to socially distance themselves, vaccinate, and/or wear masks. The need for engineering controls in such instances is much greater as a backstop but forcing all building owners to spend capital for extensive engineering controls to enable the freedom of others not to wear masks is a fundamental collision of rights.

This position document assumes a reasonable implementation of nonengineering controls to mitigate risks by the population at large, and policymakers will be well-advised to use their influence to encourage such implementation.

Policymakers will need to define acceptable levels of risk and propose optimal risk mitigation responses. The optimal response to risk management will begin with an assumption of a reasonable level of public adoption of recommended public-health behaviors. Based on anticipated levels of risk and available resources (including time of response), the response will be a layered set of engineering and nonengineering interventions, tiered from least cost and highest benefit/evidence until the appropriate level of mitigation has been achieved.

ENGINEERING CONTROLS FOR MITIGATING AEROSOL TRANSMISSION

This position document uses the term engineering controls to refer to a group of measures typically associated with "ventilation." These include introducing outdoor air and/or removing contaminated air through mechanical or natural means, controlling the flow of air within a space or between spaces, air cleaning (inactivation of infectious aerosols), temperature control, and humidity control. Engineering controls interrupt the pathway for aerosol transmission.

Effective application of most engineering controls requires technical and professional expertise in the design, installation, validation, operation, and maintenance of those controls, implying the need for an ecosystem and financial resources for cost-effective applications (Shen et al. 2021). Systems that do not operate correctly may create a false sense of security, similar to the Peltzman Effect (Iyengar et al. 2021), leading occupants to take avoidable risks assuming that the engineering controls will protect them.

Engineering controls for which there is a strong evidence basis for both effectiveness and safety as well as established quantitative design methods include ventilation, filtration, certain air cleaning and aerosol inactivation technologies, and effective indoor airflow patterns. Other technologies that are not supported by the same level of independent evidence may also be applicable.

Ventilation

Ventilation is *the process of supplying air to or removing it from a space by natural or mechanical means for purposes that include control of air contaminant levels*. Ventilation may involve supply of outdoor air, recirculated air that has been filtered or otherwise treated, or a combination. Its primary function is to dilute and displace contaminated air in a space by replacing/mixing it with less contaminated or uncontaminated air. Ventilation is closely connected with space air distribution because airflow patterns impact the effectiveness of the delivery of ventilation air and can affect occupant exposure.

In many studies, treated outdoor air ventilation rates have shown a positive correlation with indoor air quality, including reduced sick building syndrome symptom incidence and absenteeism and better task performance and learning performance (Sundell et al. 2011). Likewise, higher ventilation rates are associated with lower incidence of airborne diseases. However, systematic reviews of research on the quantitative relationship between risk of infection and ventilation rate have concluded that sufficient data to specify minimum ventilation rates for infection control does not exist (Li et al. 2007).

ANSI/ASHRAE Standard 62.1 affirms that the rates in the Ventilation Rate Procedure Table (Table 6-1 in the Standard) are not meant for infection control: "The requirements of this table provide for acceptable IAQ. The requirements of this table do not address the airborne transmission of airborne viruses, bacteria, and other infectious contagions" (ASHRAE 2019b).

Nevertheless, empirically based ventilation rates for the purpose of infection control have been proposed and even implemented in standards and codes in the past. In the early years of the 20th century, Billings proposed, and ASHRAE's predecessor society ASHVE recommended, outdoor airflow rates of 30 cfm/person (14.2 L/s-person) based on considerations of infection prevention (Janssen 1999). Current minimum outdoor airflow rates found in standards are typically about 15 cfm/person (ASHRAE 2019b). During the COVID-19 pandemic, the World Health Organization (WHO)

recommended minimum outdoor airflow rates of 10 L/s-person (21.2 cfm/person) for nonhealthcare facilities and 60 L/s-person (127 cfm/person) for most spaces in health care facilities (WHO 2021). What seems indisputable is that existing minimum outdoor air ventilation rates are significantly lower than levels recommended for infection control. This is due to the use of a definition of indoor air quality that does not address infection risk mitigation.

Naturally ventilated buildings without mechanical ventilation are common in much of the world. Using a "push-pull" strategy (with features designed both to introduce outdoor air and encourage the removal of contaminated air) in these buildings will help deliver a continuous supply of outdoor air with minimal stagnant indoor zones (Gilkeson et al. 2013). This strategy will also help to provide positive or negative pressurization with respect to the external environment for different modes of operation.

Natural ventilation systems are relatively low in both first and operating costs if appropriately integrated into a building during design. These systems also have a low carbon footprint. However, they are difficult to control with precision, do not permit temperature or humidity control, and do not filter the incoming air. Mechanical ventilation systems have significantly higher costs, both for initial installation and ongoing maintenance and operation. Depending on the local fuel mix, these systems also have a relatively high carbon footprint in the aggregate. However, given the evidence and effectiveness of mechanical ventilation systems, the key to successful deployment is ensuring the maximum effectiveness without incurring excess costs and increasing carbon emissions by ventilating more than needed to reduce transmission risk.

Filtration

Filtration removes particles from the air within a space or from air that is recirculated by centralized or distributed HVAC system components. Filters used in HVAC applications are typically mechanical filters made from fibers that capture larger particles mainly by interception and impaction and finer particles mainly by diffusion. Filters are classified by various schemes, such as the Minimum Efficiency Reporting Value (MERV) scale defined in ANSI/ASHRAE Standard 52.2 (2017). The MERV scale runs from 1 to 16, with larger numbers indicating higher efficiency. Filter performance is assessed in three size ranges: 0.3 to 1 µm (E1), 1 to 3 µm (E2), and 3 to 10 µm (E3). ASHRAE Standard 62.1 generally requires filters in HVAC systems of at least MERV 8, which has no specified minimum efficiency in range E1, 20% in range E2, and 70% in range 3. Given the size distribution of respiratory aerosols, MERV 8 filters have low effectiveness in reducing exposure to infectious aerosols. ASHRAE's COVID-19 guidance recommends upgrading filters to MERV 13 if possible. MERV 13 filters have minimum efficiency requirements of 50%, 85%, and 90% in ranges 1, 2, and 3, respectively. In healthcare and other critical applications, higher MERV filters and even high-efficiency particulate air (HEPA) filters tested to be 99.97% or higher efficiency for 0.3 µm particles may be used. It is important to understand that even though filter ratings are generally based on particles 0.3 µm and larger, they can, in fact, capture much smaller particles.

Since filtration is a mechanism designed to permit the recirculation of already heated/cooled air, it can be deployed to mitigate risk from infectious aerosols while avoiding a large increase in the amount of heating/cooling energy. A filter provides resistance to air movement, so moving air through a filter requires higher amounts of fan energy compared to unfiltered air. Since filtration and recirculation of air avoids the need to heat/cool air, it provides a way to mitigate risk with a smaller

operating cost relative to simply taking air from outdoors and treating it before use. The relative benefit of filtration varies with both climate and seasonal weather, as the energy for heating and cooling varies.

Filtration has been demonstrated to effectively remove particles that could be infectious (Bueno de Mesquita et al. 2021). In addition, as the electrical grid becomes increasingly renewable, the carbon footprint of this measure will reduce, as well as reducing the need for initial heating or cooling energy, which generally derives from on-site combustion with its higher carbon footprint.

Filtration can be performed within the ducts for a system or in a room with a recirculating system. The strength of evidence for the effectiveness of filtration for recirculated air is relatively high (Bueno de Mesquita et al. 2021). As with other ventilation interventions, the question for filtration is not whether it works but rather how much is needed for how much impact. Liu et al. (2022) performed a systematic scientific review and reported that there is sufficient scientific evidence that in-room air cleaners (IACs) can eliminate airborne SARS-CoV-2. Beyond the effectiveness of an IAC in removing virus-laden aerosols, the size and number of units need to be chosen in the context of the volume of the space they are cleaning. Similar to other filtration systems, IACs are associated with increased energy consumption.

Other Air Cleaning Technologies

In addition to ventilation and filtration, other technologies that inactivate airborne microorganisms or increase the rate of removal of infectious aerosols from the air by electrostatic effects exist. These include germicidal ultraviolet disinfection (GUV), also referred to as ultraviolet germicidal irradiation (UVGI), and several “electronic air cleaners” that produce various reactive species such as ions, hydroxyl radicals, and peroxides, among others. Except for GUV, which has been extensively studied and applied for nearly a century (Kowalski 2010) and is approved by the US Centers for Disease Control and Prevention (CDC) as a control for tuberculosis in healthcare settings (Jensen et al. 2005; Whalen 2009), most of these technologies are not well characterized due to a combination of quality of evidence, and, for some, concerns regarding byproduct production. The current status of air-cleaning technologies is reviewed in the ASHRAE Position Document on Filtration and Air Cleaning (ASHRAE 2021).

The main byproduct of concern for electronic air cleaners is ozone, which can be produced by corona discharge and certain wavelengths of ultraviolet (UV) light. One of the two positions of the ASHRAE Position Document on Filtration and Air Cleaning addresses ozone production. It states that ozone-based air cleaners should not be used and that extreme caution should be used if air cleaners produce ozone as a byproduct. This concern and position are further reflected in ASHRAE Standard 62.1 (ASHRAE 2019b), which requires that all electronic air cleaners pass the UL 2998 standard, which requires no more than five ppb ozone concentration in the emission of an air cleaner (UL 2020). Both germicidal UV sources and some types of reactive species air cleaners have received this certification. However, ozone is not the only byproduct of concern. Recent research has reported the production of various chemical contaminants and aerosols when reactive species air cleaners are used (Joo et al. 2021; Ye et al. 2021). Reactive species themselves (e.g., ions, hydrogen peroxide, etc.) can also be potentially hazardous (Collins et al. 2021). Whether the amount of such production represents a significant hazard requires further study and is currently one factor that argues for caution in applying

air cleaners known to create byproducts.

Light in the UV-C band inactivates microorganisms by affecting genomic and structural components. The susceptibility of hundreds of microorganisms has been determined experimentally (Kowalski 2010). The most commonly used germicidal wavelength is 254 nm UV-C, produced by mercury vapor or amalgam lamps. Because this wavelength can cause short-term eye and skin irritation and even severe and lasting eye damage, it is applied in ways that prevent or minimize exposure of building occupants. Germicidal ultraviolet systems can be applied in a variety of ways. The oldest implementation of GUV to disinfect air is the "upper room" system, in which wall-mounted or pendant fixtures create a disinfection zone above the occupied zone. Such systems were first used in the 1930s and demonstrated very good effectiveness against measles and other childhood diseases in schools (Wells et al. 1942). Germicidal UV is also effective for airstream disinfection in HVAC systems and closed air cleaners (ASHRAE 2019a). Airstream disinfection systems installed in air-handling units can simultaneously prevent microbial growth on cooling coils with resulting reductions in maintenance cost and energy use (Bahnfleth 2017). GUV also has been used to disinfect surfaces in unoccupied spaces to control healthcare-associated infection (HAI) pathogens in healthcare facilities (Weber et al. 2016; Wong et al. 2016).

Emerging germicidal UV source technologies (LEDs and excimer lamps) have the potential to enable new applications of GUV. In particular, "far UV-C" at shorter wavelengths in the UV-C range (approximately 200 nm to 230 nm) have demonstrated both good germicidal effectiveness and the potential for safe exposure of occupants. This would permit full-volume irradiation of occupied spaces to simultaneously disinfect air and surfaces, providing protection against both airborne and fomite transmission (Buonanno et al. 2020).

Indoor Airflow Patterns

Indoor airflow patterns can affect the flow path of aerosols from the source. The breathing zone of occupants is the most critical space where the concentration and movement of aerosols can directly affect the risk of infection. The effectiveness of ventilation in indoor spaces depends on several factors related to the design and operation of HVAC systems, which can impact the airflow patterns in indoor spaces. Ideally, the clean supply air should sweep the contaminants from the breathing zone without significant recirculation and stagnation that form pockets of high concentration. Clean air should not escape the space without collecting contaminants from the breathing zone. Indoor airflow patterns, the resulting flow path of airborne contaminants, and the risk of infection can depend on several factors, including the number, location, and type of supply diffusers in space; supply airflow rates, air change rates, and associated diffuser throws; supply air temperature; number, size, and locations of return/exhaust grilles; the location and strengths of various heat sources in a room; arrangement of furniture and other obstructions to airflow; location, type, and capacity of in-room air cleaners; and importantly, the relative positions of contaminant sources in space. Strategic selection and layout of air supply diffusers and exhaust grilles can form aerodynamic containment zones of the indoor airflow patterns that can help reduce the risk of contaminant exposure in indoor spaces (Khankari 2021).

Physical testing and real-time measurements of all the parameters that affect the ventilation performance of enclosed spaces are often time and labor-intensive, if not impossible. In such situations, computational fluid dynamics (CFD) analyses provide a feasible alternative to gain

comprehensive insights into ventilation performance. If performed properly with adequate expertise, CFD analyses can help designers understand complex indoor airflow patterns and the flow path of aerosols. Such insights gained during the early stages of the design and retrofit process can help improve ventilation performance and reduce the risk of infection in indoor spaces (Khankari 2016, 2021).

Effective indoor airflow patterns (Bolashikov and Melikov 2009; Khankari 2021) are a primary factor that drives the dilution and not solely the quantity of air supplied to the space. No studies have provided sufficient data to quantify the amount of ventilation needed to achieve effective risk mitigation (Bueno de Mesquita et al. 2021; Li et al. 2007). The key underlying reason is the lack of data related to the infectious source strength and dose response to estimate the necessary level of dilution (Li et al. 2007; Pantelic and Tham 2012).

There has been an increased awareness of IAQ in the microenvironment during the COVID-19 pandemic, which has led to the exploration of innovative ventilation systems and indoor airflow strategies. Personalized ventilation systems that supply 100% outdoor, filtered, or UV-disinfected air directly to the occupant's breathing zone could offer protection against exposure to contaminated air and mitigate the risk of infectious aerosol transmission (Bolashikov et al. 2009; Cermak et al. 2006; Danca et al. 2022; Ghaddar and Ghali 2022; Licina et al. 2015a, 2015b; Pantelic et al. 2009, 2015). When coupled with localized or personalized exhaust devices, personalized ventilation systems further enhance the overall ability to mitigate exposure in breathing zones, as seen from both experimental and CFD studies in healthcare settings (Bivolarova et al. 2016; Bolashikov et al. 2015; Yang et al. 2013, 2014a, 2014b, 2015). There are no known epidemiological studies that clearly demonstrate a reduction in infectious disease transmission from indoor airflow patterns.

Evidence of the effectiveness of indoor airflow control in mitigating risk from infectious aerosols is moderate (Bueno de Mesquita et al. 2021).

Indoor airflow pattern control incurs little additional cost or carbon beyond basic ventilation strategies but may require more extensive design expertise with attendant costs.

Humidity and Temperature Control

Research suggests that the persistence of various infectious pathogens in aerosols may be affected by environmental conditions, including temperature and humidity (Tang 2009). Different pathogens respond differently to varying temperature and humidity conditions. Therefore, attempting to modify risk through these mechanisms is problematic. Bahnfleth and Degraw found that "[a]lthough evidence exists that survival time of SARS-CoV-2 virus is higher at low temperature and humidity, it is not clear that manipulation of either temperature or humidity as risk mitigation measures will have a major impact compared to other controls." (Bahnfleth and Degraw 2021).

Humidification imposes significant costs for both installation and operation and generates a significant energy and carbon footprint. It can also create other microbial issues (e.g., mold growth) within the built environment.

Demand-Controlled Ventilation

Ventilation requirements are usually based on either the maximum number of occupants and floor area of a space or the volume of the space. These are static estimates of the necessary flow and do not always adjust as occupancy changes. The use of carbon dioxide (CO_2) concentration as a proxy for ventilation rate per occupant is commonly used to modulate the flow of ventilation air (Bhagat et al. 2020; Franco and Schito 2020; Zivelonghi and Lai 2021). However, there are challenges with this approach as CO_2 measurements may not always be representative of the actual demand in a given space, especially with multizone recirculation-type VAV systems. Additionally, it is important to note that CO_2 concentration is unaffected by filtration and most other air-cleaning methods, so it should not be used as a direct indicator of infection risk. ASHRAE has developed a separate position document and guidance documents that address the use of CO_2 to control of indoor air quality, including the risk of airborne infection (ASHRAE 2022).

New sensor technologies allow for the direct measurement of fine airborne particulate matter ($PM_{2.5}$), which may include infectious aerosols (Kaliszewski et al. 2020). The increasing availability and falling cost of particulate matter (PM) sensors suggest that their use for ventilation control may be feasible. Low-cost IAQ sensors for continuous monitoring (Zhang et al. 2021) and early warning systems for COVID-19 infections (Peladarinos et al. 2021) have been reported. While the sensors cannot differentiate between infectious aerosols and other types of particulate matter, the concentration of fine particulates is an important measure of air quality that can be used to modulate the flow of ventilation or control of air-cleaning systems. Additional research and application protocols are needed, including the development of protocols to validate performance.

NONENGINEERING CONTROLS FOR AEROSOL TRANSMISSION

Nonengineering controls generally target reduction of the source and protection of vulnerable new hosts.

Pharmaceutical Controls

Pharmaceutical controls include vaccination, other forms of prophylaxis, treatment, and other strategies. In general, these strategies work to reduce the source (e.g., number of infected persons, amount of aerosolized pathogens) and protect the vulnerable new host. These strategies generally do not work to affect the path of transmission.

Two features of pharmaceutical controls make them problematic in some ways. First, to be successful, pharmaceutical controls rely on public adherence and adequate access. Experience shows neither is perfect, and, by themselves, pharmaceutical controls can be insufficient for the task. Second, especially in the context of an epidemic, where the velocity of change in risk is high, these controls may not be adequate for the risk mitigation need.

Therefore, as with other nonengineering control measures, pharmaceutical controls are vitally important but may be insufficient by themselves.

Elimination of the Hazard

Elimination of the hazard means the separation of sources of infection from the uninfected populace. Examples of such interventions might include stay-at-home orders to keep people from coming into contact with one another to minimize the risk of transmission or closing buildings or spaces to some or all people. Other examples of this kind of elimination strategy are social distancing (i.e., separating the source of infection by a distance calculated to mitigate the risk of transmission) and barriers between persons in a space. In the case of droplets, but not aerosols, barriers between people in a space can mitigate transmission risk (Wang et al. 2021).

Elimination-of-the-hazard strategies are highly dependent on compliance by the population; therefore, they are rely heavily on voluntary compliance. During normal times, threat levels are low enough that sloppy uptake and adherence are relatively unimportant. Variation in compliance during epidemics and high-risk locations may be highly problematic and will call on leaders to lead responsibly and effectively.

The recent experience with COVID-19 dramatically shows the potential variance in the uptake of such measures and the ensuing results for local, regional, national, and international populations.

Stay-at-home orders might be seen to be relatively low-cost, low-energy interventions. However, they also have serious economic implications for certain segments of the working population, as well as for the economy as a whole. Some workers, deemed essential, must continue to work through a time of elevated risk, creating stark inequities in terms of risk exposure. These factors accumulate as their enforcement endures over time.

Administrative Controls

Administrative controls are exercised by the entities that control access to and use of particular spaces. These strategies include shutting down buildings or spaces; limiting the number of people and duration of occupancy in buildings or spaces; and implementing requirements for vaccinations, testing, and PPE.

The strategy of shutting down buildings or spaces altogether, by definition, eliminates the risk within those buildings and spaces. The cost and energy/carbon impacts are both relatively low in terms of direct cost. However, the cost to an economic entity, the people who must derive their incomes from working there, the people who are denied services that might have come from the activities in the building, and the cost to the economy as a whole can be huge.

A more nuanced approach is to use administrative controls to limit the number and distance between people in a building or space, including limiting the amount of time that one or more persons are permitted into a space. The efficacy of this strategy will vary as a function of pathogen reproduction rates and the details and effectiveness of the implementation. Overall, however, this strategy can mitigate the costs of the building shutdown strategy while capturing many of the benefits and imposing additional costs to the entity implementing the administrative controls.

A third class of administrative controls is over the personal behaviors of the building occupants. That is, the entity controlling access to a building or space can require proof of vaccination or testing or use of PPE as a condition precedent to a person entering a space. This strategy uses the high efficacy of the individual strategies with an overlay of administrative control to enforce certain levels of risk mitigation. In general, this kind of strategy is a higher cost than administrative controls focused strictly

on numbers but with higher efficacy. Building owners must account for jurisdictional laws regulating the disclosure of personal health information when requiring roof of vaccination or testing.

Cleaning

Cleaning may provide a benefit when aerosolized or droplet pathogens may be deposited on surfaces where they have a long enough life to come into contact, either physical or re-entrainment in the air, with an uninfected person. Thorough cleaning in its many forms can greatly mitigate this risk where it occurs. However, evidence of the benefits of cleaning to reduce transmission of aerosolized pathogens is weak (Bueno de Mesquita et al. 2021).

Masking and PPE

Masking can either contain a pathogen if the wearer is infected or protect against a pathogen for noninfected persons. Evidence shows that this strategy can be highly effective and has very low costs and carbon impacts (Wang et al. 2021).

Barriers

The use of plastic barriers within a space may provide some mitigation against the spray of droplets at short distances, but only with corresponding modifications to ventilation systems (Capron et. al2022). In some cases, plastic barriers within rooms increase risk (Bueno de Mesquita 2021). The height of barriers is more impactful than the width of barriers. Evidence for the effectiveness of barriers is low, but costs and energy costs are also low.

Appendix B: Strength of Recommendations Taxonomy Analysis

Introduction

This appendix attempts to bridge the world of evidence-based medicine (EBM) and the imperative to use available evidence to make needed recommendations in the practical world of application of ventilation systems. Historically, the study of the effectiveness of engineering controls for infection risk mitigation has not had the kinds of investments in the research necessary to reach the levels demanded by the rigors of EBM. However, decisions must be made based on the best available evidence. Bringing these worlds together brings a level of transparency and rigor to the practical need for guidance to policymakers while also representing a call for further research to provide us with better data in the future.

Policymakers confront innumerable challenges in determining how to allocate incentives and penalties in guiding the public toward outcomes that best balance risks and rewards. The science of ventilation is still imprecise with respect to the specification of minimum rates to control the transmission of infectious aerosols. Thus, policymakers need to have the most rigorous, transparent information at their disposal with which to make needed determinations. Policymakers also need to prioritize research to better determine the effectiveness of the various strategies to permit better prescriptions in the future. The methodology used in this exercise takes an important step toward addressing this need.

Because we are dealing with interventions targeting health outcomes—we are using ventilation as an intervention to reduce the risk of infection—we have chosen to develop a version of a tool commonly used in EBM.

The essence of EBM is to provide guidance to practitioners and policymakers by integrating the best research evidence with clinical expertise and patient values (Sackett et al. 2000), as well as the setting and circumstances in which health interventions are being delivered (Guyatt et al. 2015). A central methodology for EBM is the use of Strength of Recommendation Taxonomy (SORT). In general, SORT methodologies try to assess the evidence supporting the use of a particular intervention, balanced against undesirable aspects of the intervention, such as side effects (Guyatt et al. 2015).

The direct translation of EBM methodologies to the science of ventilation is difficult due to the type of evidence generally available for informing ventilation decisions. This effort uses an appropriate SORT to provide both rigor and transparency in ways that should elevate the credibility of the recommendations.

Measuring Quality of Evidence

The SORT begins with an assessment of available evidence. Here, the quality of evidence was assessed using the following described methodology. A search question was developed for each intervention, comparing the outcome with and without the specific engineering measure, i.e., in areas with airborne pathogen transmission (population), what is the effect of air cleaning (UVGI) (intervention) on respiratory pathogens transmission (Outcome) compared with settings without UVGI technology (Control)? With the developed PICO (Population, Intervention, Control, Outcome), a literature search was done in JSTOR digital library, PubMed, and ScienceDirect.

Only systematic reviews addressing the specific intervention and respiratory pathogens were included. Only the six following papers were finally included:

- Dandnayak, D., L. Zhong, and L. Hartling. 2021. The impact of heating, ventilation, and air conditioning design features on the transmission of viruses, including the 2019 novel coronavirus: A systematic review of ultraviolet radiation. https://www.medrxiv.org/content/10.1101/2021.10.12.21264904v1.full.pdf.
- Liu, D.T., K.M. Philips, M.M. Speth, G. Besser, C.A. Mueller, and A.R. Sedaghat. 2021. Portable HEPA Purifiers to Eliminate Airborne SARS-CoV-2: A Systematic Review. *Otolaryngology—Head and Neck Surgery* 166(4). https://doi.org/10.1177/01945998211022636.
- NCCEH. 2021. A rapid review of the use of physical barriers in non-clinical settings and COVID-19 transmission. Vancouver, BC, Canada: National Collaborating Center for Environmental Health. https://ncceh.ca/documents/evidence-review/rapid-review-use-physical-barriers-non-clinical-settings-and-covid-19.
- Talic, S., S. Shah, H. Wild., D. Gasevic, A. Maharaj, Z. Ademi, X. Li, W. Xu, I. Mesa-Eguiagaray, J. Rostron, E. Theodoratou, X. Zhang, A. Motee, D. Liew, and D. Ilic. 2021. Effectiveness of public health measures in reducing the incidence of covid-19, SARS-CoV-2 transmission, and covid-19 mortality: systematic review and meta-analysis. BMJ 2021:375. https://doi.org/10.1136/BMJ-2021-068302.
- Thornton, G.M., B.A. Fleck, E. Kroeker, D. Dandnayak, N. Fleck, L. Zhong, and L. Hartling. 2021. The impact of heating, ventilation, and air conditioning design features on the transmission of viruses, including the 2019 novel coronavirus: a systematic review of ventilation and coronavirus. MedRxiv 2021.10.08.21264765. https://doi.org/10.1101/2021.10.08.21264765.
- WHO. 2019. Non-pharmaceutical public health measures for mitigating the risk and impact of epidemic and pandemic influenza. Geneva: World Health Organization. https://www.who.int/publications/i/item/non-pharmaceutical-public-health-measuresfor-mitigating-the-risk-and-impact-of-epidemic-and-pandemic-influenza.

While the quality of evidence from the strict perspective of EBM is low, another class of studies, properly classified as *natural experiments*, has gained attention in areas where controlled trials are difficult (DiNardo 2008, 2010). Indeed, the 2021 Nobel Prize in Economics was awarded to pioneers in the use of natural experiments. In some sense, the kinds of studies generally available with respect to the value of ventilation in mitigating risk, as powerfully exemplified by the work of the ASHRAE Epidemic Task Force during the COVID crisis, fall squarely in this domain. And, while the worlds of science and law may have an uneasy relationship, various legal standards for decision-making use a preponderance of such evidence in the face of uncertainty—the kind of uncertainty that inevitably faces policymakers. In coming to their conclusions, these experts carefully assembled for this Position Document must rely heavily on such natural experiments, along with the fundamental, inviolable laws of physics combined with an understanding of exposure and dose to inform their judgments. And, so, we have expressed the available evidence from the strict perspective of EBM and the indirect evidence from the perspective of the natural experiments and fundamental science currently available to us.

Assessing the Benefit, Cost, and Energy/Carbon Impacts of an Intervention

A key insight for SORT is the balance between "the desirable and undesirable consequences of the alternative management strategies, on the basis of the best estimates of those consequences" (Guyatt et al. 2008). In our case, the benefits are impossible to quantify. That is, given the wide range of pathogens of different virulence and infectivity, coupled with the uncertain adoption of other nonventilation interventions, the line-drawing problem associated with ventilation strategies, e.g., (how much better are four air changes per hour than two?), and the difficulty of predicting the frequency of occurrence, make the benefits impossible to state with precision. Therefore, we rely on a multidisciplinary, expert-consensus-based estimate of effectiveness using the Delphi Technique. (Yousuf 2007).

The Delphi Technique obtains consensus within a panel of experts through a series of questionnaires that are fed back to the panel after each subsequent round. It was the most suitable method for this committee because:

- The Delphi Technique gathers opinion without the need to bring panelists together physically, which is especially problematic with a cohort of geographically dispersed experts.
- Questionnaires are completed independently and confidentially, preventing the dominance of particular individuals and allowing participants to express their ideas without worry of being associated with those ideas. This could not be achieved using focus group discussion.
- The feedback process encourages participants to consider items raised by others that they may have missed themselves and allows them to change their opinion throughout the process (Couper 1984). It also presents the group collective opinion in a nonadversarial manner (Hasson et al. 2000). This type of feedback mechanism is absent from direct interviews (Smithson 2000).

The technique involves three basic steps.

The first survey or questionnaire sent to the panel of experts (in this case, the members of this committee) asks for a list of opinions involving experiences and judgments and a list of predictions. In the second round, a copy of the collective list is sent to each expert, and the expert is asked to rate each item by the criterion of importance provided in the survey. The third questionnaire includes the list, the ratings indicated, and the consensus. The experts are asked to either revise their opinions or discuss their reasons for not reaching a consensus with the group.

The cost of each item was assessed as an "average" of life-cycle cost, including both the first and ongoing costs. These costs are a kind of aggregate average and do not necessarily reflect the relative costs in any particular location. Note that this estimate is relative in that it distinguishes between absolute costs and not costs in the context of available resources. So, for example, one strategy might be considered low-cost in a relatively affluent setting but high-cost in a relatively low-resource setting. Nonetheless, in either event, it will be lower in cost than other alternatives, so we note it to be a low-cost strategy.

The second dimension of cost is the cost of energy consumption and resulting carbon emissions. Recognizing the science and the urgency of the need to address climate change, together with the heavy influence of the built environment on this critical issue, ASHRAE has recently created a team to

study ways to decarbonize buildings. Consistent with the science and the direction of this organization, we thus provide relative estimates of the lifetime emissions potential of the strategies under consideration. Obviously, the urgency of an epidemic may outweigh the much more diffuse and longer-range impacts of climate change associated with a particular strategy. However, we also recognize that the mass deployment of a particular strategy higher in global warming potential (GWP) will create a permanent source of emissions. So, in comparing two potential strategies, each with similar evidence and benefits, we should prefer the solution with a lower GWP.

Recommendations

The final step in a SORT is to reach a recommendation based on the strength of evidence and the balance between desirable and undesirable aspects of a particular intervention.

Some versions of SORT use algorithms to derive the strength of recommendation from the Benefit, Cost, and Strength of Evidence. In our assessment, due to the relative lack of definitive research, we again used the Delphi Technique to best determine the consensus of our committee of experts. The resulting table expresses our best attempt to tier our recommended measures for risk mitigation based on the best evidence we were able to assemble. This exercise indicates a need for multidisciplinary, in-depth research involving these techniques and a large pool of subject matter experts from a wide variety of disciplines.

Summary of Strategies

The current evidence of the association between ventilation rate and airborne infection is weak in terms of study design. However, there is solid indirect evidence to show that increased ventilation and related strategies discussed herein are associated with a reduced risk of airborne infection (Li et al. 2007). Ventilation mitigates risk but the minimum ventilation requirements to mitigate the risk of infectious aerosols demand further investigation.

We acknowledge that, from the strict perspective of rigorous evidence-based medicine, the available evidence has low quality due to the specific set of methods and procedures used to collect and analyze data in ecological and retrospective studies. The ethical limitations, the multiple factors involved in airborne mechanisms, and the specificity of indoor ventilation dynamics urge an innovative methodology to produce solid evidence to inform building environment regulatory bodies and public-health institutions.

Strategy	**Quality of Evidence (from EBM perspective)**	**Indirect Evidence**	**Magnitude of Benefit**	**Life-Cycle Cost**	**Energy and Carbon**	**Strength of Recommendation**
Physical distancing	Moderate	High*	Moderate	Low	Low	Strong recommendation
Barriers between occupants	Low	Low*	Low	Moderate	Low	Conditional recommendation
Surface and object cleaning	Low	Moderate*	Low	Low	Low	Conditional recommendation
Face mask	Moderate	High*	High	Low	Low	Strong recommendation
Right-sized ventilation—natural	Low	High**	Moderate	Low	Low	Strong recommendation
Right-sized ventilation—mechanical	Low	High**	High	High	High	Strong recommendation
Filtration (requires mechanical ventilation)	Moderate	High **	Moderate	Moderate	High	Recommendation
Air Cleaning (UVGI)	Moderate	High **	Moderate	High	Moderate	Conditional recommendation
Air Cleaning (Other)	None	Low **	Low	High	Moderate	Weak recommendation
Indoor airflow patterns	Moderate	High **	High	Moderate	Low	Recommendation
Humidity control (requires mechanical ventilation)	None	Low **	Low	High	High	Weak recommendation

* Capron et al. 2022
** de Mesquita et al. (2022)

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