ANNUAL REVIEWS

Annual Review of Chemical and Biomolecular Engineering

Airborne Transmission of SARS-CoV-2: Evidence and Implications for Engineering Controls

V. Faye McNeill

Department of Chemical Engineering and Department of Earth and Environmental Sciences, Columbia University, New York, NY, USA; email: vfm2103@columbia.edu

Annu. Rev. Chem. Biomol. Eng. 2022. 13:123–40

First published as a Review in Advance on March 17, 2022

The *Annual Review of Chemical and Biomolecular Engineering* is online at chembioeng.annualreviews.org

https://doi.org/10.1146/annurev-chembioeng-092220-111631

Keywords

coronavirus disease 2019, COVID-19, aerosol, indoor air, ventilation, filtration, pathogens

Abstract

Since late 2019, severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has spread globally, causing a pandemic (coronavirus disease 2019, or COVID-19) with dire consequences, including widespread death, long-term illness, and societal and economic disruption. Although initially uncertain, evidence is now overwhelming that SARS-CoV-2 is transmitted primarily through small respiratory droplets and aerosols emitted by infected individuals. As a result, many effective nonpharmaceutical interventions for slowing virus transmission operate by blocking, filtering, or diluting respiratory aerosol, particularly in indoor environments. In this review, we discuss the evidence for airborne transmission of SARS-CoV-2 and implications for engineering solutions to reduce transmission risk.

INTRODUCTION: THE COVID-19 PANDEMIC

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) first emerged in Wuhan, China, in December 2019 (1, 2), then spread across the world before the global threat posed by the virus owing to its high transmissibility and pathogenicity (3) was fully recognized. Catastrophic early "first waves" of infections, hospitalizations, and deaths overwhelmed the healthcare systems and infrastructure in major population centers in early 2020 (see the sidebar titled Is SARS-CoV-2 Transmission Connected to Air Pollution?). The World Health Organization (WHO) declared coronavirus disease 2019 (COVID-19) a pandemic on March 11, 2020 (4). Policy makers struggled to contain the novel virus amid incomplete information about its modes of transmission, a lack of readily available testing or treatment options, and shortages of personal protective equipment (PPE) for healthcare workers and other critical supplies. Subsequent local waves ripped through the global population throughout the remainder of 2020 and 2021, with variations in timing and severity depending on many factors, including local policies regarding lockdowns, travel restrictions, or mask mandates and patterns in human behavior, such as increased rates of indoor gatherings due to inclement weather (5) and major holidays (6), as well as possible impacts of environmental conditions on virus transmission (7). Starting in late 2020, highly effective vaccines against COVID-19 (8–11) started to become available in the United States, China, Israel, and parts of Europe. However, rollout to the rest of the world has been slow, particularly in the Global South (12). In Spring 2021, B.1.617.2 (Delta), a new, more infectious (13) variant of SARS-CoV-2, emerged, leading to hundreds of millions of infections and more than one million deaths across India, amid widespread oxygen shortages (14). The Delta variant upended the status quo in nations such as Vietnam that had previously contained the virus through lockdowns, travel restrictions, and other nonpharmaceutical interventions (NPIs) (15). Surges in breakthrough infections among fully vaccinated individuals and outbreaks involving vaccinated persons as key transmission links (16) also challenged prevailing assumptions about the spread of the virus through highly vaccinated populations (17), with implications for masking and testing policies.

The urgent need to control the spread of SARS-CoV-2 has resulted in a massive effort among the public health, medical, and scientific research communities, amid lockdowns and crisis conditions, to develop an understanding of the virus and its mechanisms of transmission and

IS SARS-COV-2 TRANSMISSION CONNECTED TO AIR POLLUTION?

Data from the early stages of the COVID-19 pandemic in Italy (126, 127), the United States (128), and England (129) suggested a connection between exposure to particulate matter (PM) in the ambient atmosphere and COVID-19 deaths. Some hypothesized, based on this connection and some observations of viral RNA in outdoor PM samples (130), that the transmission of SARS-CoV-2 was enhanced by the coagulation of aerosols containing the virus with ambient PM, making PM a vector for transmission (131, 132). This is unlikely for several reasons, including the lack of evidence for long-range outdoor transmission (133); the physics of aerosol coagulation, which does not favor the coalescence of similarly sized particles (134); and inconsistency with epidemiological trends in highly polluted areas across the Global South.

The most likely explanation for the association of COVID-19 mortality and morbidity with air pollution lies in the well-known effects of long-term exposure to air pollution on human health. PM exposure is associated with many of the medical conditions that put individuals at high risk for complications related to COVID-19, including respiratory and cardiovascular conditions and diabetes (135). It also produces an inflammatory state in the body (126), which increases susceptibility to respiratory infections (136).

infection, as well as response strategies. The resulting rapidly evolving scientific landscape has led to a need for continuously updated public guidance. Two major advances in the understanding of SARS-CoV-2 transmission, made as the pandemic unfolded in real time, shaped policy responses. The first was the recognition, based on analysis of social media data from China and epidemiological modeling, that transmission by undocumented (mostly asymptomatic or paucisymptomatic) infected individuals was a major driver of SARS-CoV-2 spread (18). It became clear that isolating the ill was not sufficient to contain the virus, and that it would be necessary to track exposures (contact tracing) and quarantine asymptomatic contacts until the potentially infectious period had passed. The second advance was the accumulation of evidence, through epidemiological studies and measurements, that a significant proportion of SARS-CoV-2 spread likely occurs via inhalation of virus-containing respiratory aerosols and small droplets by a susceptible individual (19), rather than through surface contact (fomite transfer) or large droplet transfer (close contact), both of which were heavily emphasized by public health authorities at the outset of the pandemic. Effective NPIs for slowing airborne virus transmission (i.e., transmission via inhalation) operate by physically blocking, filtering, or diluting respiratory aerosol and droplets. The implications of airborne transmission of a respiratory virus for public health guidelines for reducing transmission risk are different, and in some cases opposite, from those for surface transmission. For example, some public health agencies, including the WHO and the US Centers for Disease Control and Prevention (CDC), discouraged the use of face coverings (mask wearing) at the outset of the pandemic. This was based in part on the need to reserve medical-grade PPE for healthcare workers, but also on the hypotheses that touching used masks may promote surface transfer and face touching (20) and that mask wearing could impart a false sense of security and result in relaxed vigilance regarding other activities (such as handwashing) (21). However, since late spring of 2020, mask wearing has become widely accepted as an effective NPI to slow the spread of SARS-CoV-2 (22–24).

In this article, we review the body of knowledge surrounding the mechanisms of transmission of SARS-CoV-2, which overwhelmingly point to airborne spread of the virus through the respiratory emissions (droplets and aerosols) of infected individuals being the primary route. We also discuss the implications of airborne spread for the most effective engineering solutions to be used as part of a layered approach to slowing transmission.

RESPIRATORY EMISSIONS AND MODES OF PATHOGEN TRANSMISSION

Droplets and aerosols containing saliva and respiratory fluid are expelled from people's mouths and noses when sneezing (25, 26), coughing (27, 28), talking (28–31), singing (32–34), or breathing (35, 36). The quantity and size distribution of emitted droplets and aerosols vary depending on the mode of emission (27) and the physiology of the individual (37). Large variation in emission rates from person to person has been observed and may be connected to the superspreader phenomenon, in which a single infected individual transmits to a large group, whereas others do not (30). The size distribution for droplets and aerosols emitted by coughing or talking has been observed to be multimodal, with one peak at >100 μm (large droplets) (38) and others between 1 μm and 5 μm (aerosols) (27, 36). Only small aerosols (<2 μm) are produced during normal breathing (35, 36). For an individual infected with a respiratory virus such as SARS-CoV-2, the expelled droplets and aerosols may contain varying amounts of live virus, depending on biological factors (e.g., illness stage, rates of viral replication and shedding) and the respiratory activity causing the emission (33, 39, 40).

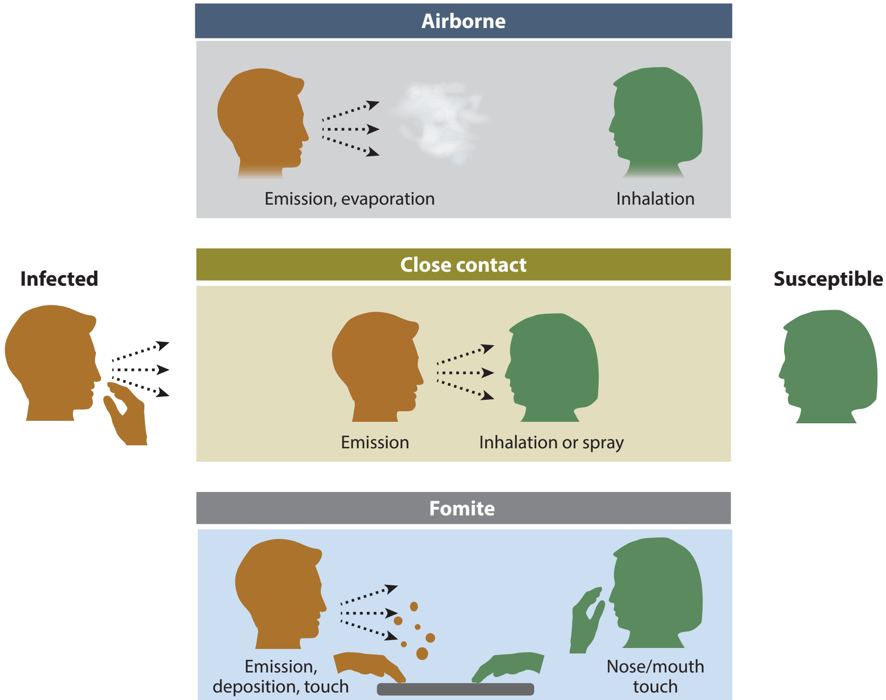

Figure 1

Modes of virus transmission. Figure adapted with permission from Tellier et al. (41) (CC BY 4.0).

Once emitted in droplets and aerosols, live virus may be transmitted to a susceptible individual via three major pathways (**Figure 1**):

1. Inhalation of smaller droplets and aerosols (airborne transmission)
2. Spray of droplets at close range into the eyes, nose, or mouth (close contact)
3. Deposition of large, ballistic droplets onto surfaces, or an infected person with virus on their hands touching a surface, followed by transfer to the fingers of the susceptible individual, who later touches their eyes, nose, or mouth (fomite transmission)

The fate of respiratory droplets and aerosols, and therefore the relative importance of the three transmission pathways, is connected to their aerodynamics. The movements of large droplets (>100 μm) are dominated by their inertia. They settle rapidly (<10 s) and impact on nearby surfaces within ∼1 m of the source. These deposited droplets may create the first step of the fomite transmission pathway, after which deposited viruses may be transferred from surfaces to fingers (42), or they may come into direct contact with a nearby (<1 m) susceptible individual (43). Smaller droplets and aerosols stay airborne longer and may be inhaled by others. They may be transported farther (although concentration remains highest closest to the source) and may accumulate in poorly ventilated spaces. The aqueous portion of small droplets may evaporate, leaving behind smaller aerosols composed of salts, surfactants, proteins (e.g., mucin), and possibly pathogens (44). Coleman et al. (33) observed recently that 85% of total emitted viral load in respiratory emissions of SARS-CoV-2 carriers is contained in aerosols with diameter ≤5 μm. By affecting the particle size distribution and particle phase, the evaporation process influences the lifetime, transport, and inhalation dynamics (45) of the airborne droplet/particle population, as well as virus survival (44, 46). Some confusion among the medical and engineering disciplines about the terminology of droplet versus aerosol has hindered the discussion about airborne transmission of SARS-CoV-2. A functional size-based definition places a cutoff of >100 μm for droplets, with smaller particles being called aerosols (38). This is also consistent with the multimodal size distributions observed in respiratory emissions (27, 33–36).

Besides respiratory aerosols, there is evidence for transmission of some respiratory viruses via fecal aerosol. Aerosolization of virus expelled in feces may occur at various points in the wastewater system or from toilet flush (47). A major 2003 SARS1 (severe acute respiratory syndrome 1) outbreak in the Amoy Gardens apartment complex in Hong Kong was attributed to the spread of virus-containing aerosol through sewer gas, which entered apartments through dry water traps (48). Similar but smaller-scale cases of SARS-CoV-2 transmission have been observed in Hong Kong (49) and Guangzhou, China (50). Detection of SARS-CoV-2 RNA in wastewater has emerged as a useful community-level public health surveillance strategy (51), but water-based transmission of the virus has not been reported (52).

EVIDENCE FOR AIRBORNE TRANSMISSION OF SARS-COV-2

Airborne transmission of other viral pathogens, including influenza (53, 54) and SARS-CoV-1 (55, 56), is well-known (57, 58). However, in the absence of much information about the novel virus, and based on comparison of epidemiological parameters (reproduction number and secondary attack rate) to those of other airborne viruses, such as measles (59), many public health officials assumed in early 2020 that SARS-CoV-2 transmission occurred primarily through fomite transfer and close contact (large droplets). In the ensuing months, studies demonstrated SARS-CoV-2 persistence on surfaces (60) and the transmission from virus-doped surfaces to fingers of a test subject (42). However, there has been no clinical evidence of fomite transfer of SARS-CoV-2 between humans (61), and droplet transmission has been shown to occur only at very short range (<1 m) (43).

Meanwhile, evidence supporting airborne transmission being a dominant pathway for the spread of the SARS-CoV-2 virus has accumulated. This evidence has come from three major sources: (*a*) retrospective epidemiological studies of outbreaks, (*b*) direct observations of virus in aerosols, and (c) animal studies investigating modes of transmission.

Investigative case studies of outbreaks in an air-conditioned restaurant in Guangzhou, China (62); a call center in Seoul, South Korea (63); the *Diamond Princess* cruise ship (64); and choir singing in churches in the United States (65) and Australia (66) eliminated transmission through other pathways as a possibility (e.g., close contact in elevators or fomite transmission through shared food or beverages) and identified airborne transmission as the most likely route. The modeling results of Miller et al. (65) pointed to the highly variable quanta emission rate for SARS-CoV-2, particularly when superspreaders are considered. The highly variable ability of infected individuals to transmit the virus (overdispersion) connected to SARS-CoV-2 superspreading events is best explained by airborne transmission (67) and is consistent with the observed variability in viral load and quantity of respiratory emissions from infected individuals (33, 37).

Direct observations of SARS-CoV-2 genetic material in aerosols (60, 68), or on surfaces reachable only by aerosols, such as hospital room air vents (69, 70), provided early support for the physical plausibility of airborne transmission. However, as studies of influenza have shown, observations of genetic material are not necessarily a good indicator of infectious potential of the virus (54). Using the BioSpot-VIVAS technique, Lednicky et al. (71) detected viable SARS-CoV-2 virus for the first time in aerosol in the hospital room of an infected patient. The BioSpot-VIVAS maintains the integrity of the virus upon sampling by condensing water vapor onto the sampled aerosol particles to increase their size (and thus inertia), before inertially impacting them at low velocity into a liquid medium (72). More recent studies involving analysis of the respiratory emissions of infected patients provide additional indirect support for aerosol transmission of SARS-CoV-2: 85% of total emitted SARS-CoV-2 viral load was observed to be present on small, inhalable aerosol particles ($D_p \leq 5$ μm) (33).

For ethical reasons, controlled observations of SARS-CoV-2 transmission have been possible only in animal studies. Airborne transmission was observed between ferrets in enclosures separated by steel grids at a distance of 10 cm (73) and at a distance of more than 1 m (74). Close-contact transmission was also observed (73, 75). Both airborne SARS-CoV-2 transmission and fomite transmission were observed in hamsters; airborne transmission was more effective (76).

IMPLICATIONS OF AIRBORNE TRANSMISSION OF COVID FOR ENGINEERING INTERVENTIONS

Layered risk reduction, including a combination of NPIs along with vaccines and other public health interventions, has emerged as an effective strategy for managing the COVID-19 pandemic (**Figure 2**). The layered approach, or "Swiss cheese" model (77), is effective both because various interventions are insufficient on their own and because of the social and behavioral aspects of adoption of various interventions (78).

Table 1 categorizes common NPIs in terms of the SARS-CoV-2 transmission pathways disrupted by each. For some NPIs, the responsibility is placed on individuals (e.g., mask wearing, hand hygiene). For others (surface disinfection, ventilation, air filtration), the onus and the cost lie with institutions and those responsible for maintaining the indoor environment, such as building managers. Note that other public health interventions, such as testing, quarantine, and contact tracing, are also effective elements of a layered risk-management approach, regardless of the transmission route, but here we focus on physically based engineering interventions.

In early 2020, WHO and CDC recommendations for prevention of transmission focused on avoiding close contact (within 1 m) with symptomatic infected individuals (79) and handwashing

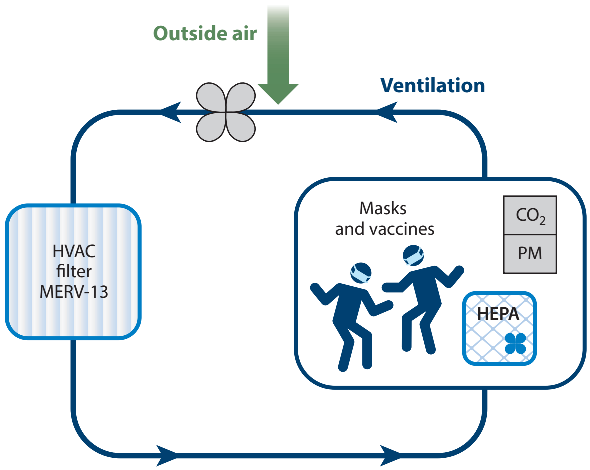

Figure 2

Adequate ventilation, air filtration, masks, vaccines, and indoor air-quality monitoring contribute to a layered approach for reducing SARS-CoV-2 transmission risk. Abbreviations: HEPA, high-efficiency particulate air filter; HVAC, heating, ventilation, and air conditioning; MERV, Minimum Efficiency Reporting Value; PM, particulate matter; SARS-CoV-2, severe acute respiratory syndrome coronavirus 2.

Table 1 Nonpharmaceutical interventions for reducing transmission of SARS-CoV-2 (severe acute respiratory syndrome coronavirus 2)

Transmission mode	Intervention (source/ infected individual)	Intervention (receptor/ susceptible individual)	Intervention (environmental)
Fomite (surface) transfer	Mask, hand hygiene	Hand hygiene	Surface disinfection
Close contact (large droplets)	Mask, physical distancing	Face shield, eye protection, physical distancing	Plexiglass barriers
Airborne transmission	Mask, physical distancing	Filtering mask, physical distancing	Ventilation, air filtration

(80). The fundamental assumption behind this advice was that the dominant transmission pathways were large droplet and surface transmission (as well as symptomatic-only transmission). As evidence accumulated favoring the importance of airborne transmission at short and room scale, public health guidance evolved to include precautions that specifically target those pathways: ventilation and filtration of indoor air (81), face coverings for the reduction of respiratory emissions (24), higher-quality filtering (respirator) masks to reduce inhalation of virion, and physical distancing of 6 ft or more. Besides reducing the spread of SARS-CoV-2, these interventions also led to dramatic reductions in other airborne illnesses, such as influenza in the United States during the 2020–2021 flu season (82).

Masks

The wearing of face coverings disrupts SARS-CoV-2 transmission, regardless of transmission pathway, by reducing the emission of respiratory droplets and aerosols from an infected individual (39). After the initial hesitancy on the part of US public health authorities to recommend universal mask wearing, owing in part to PPE shortages, cloth or improvised face coverings were encouraged as source control. Epidemiological evidence exists for the effectiveness of mask mandates in decreasing SARS-CoV-2 transmission rates in the United States (23). The effectiveness of masks and face coverings of different types, as well as plexiglass face shields, at reducing aerosol emissions during simulated coughs has been investigated. These studies found that face shields are not effective source control for respiratory aerosols (83–85). Asadi et al. (86) tested the ability of cloth and surgical masks, a microfiber neck gaiter, and KN95 and N95 respirators to control outward emission of aerosols by live subjects. They found that surgical and KN95 masks reduced particle emissions by a factor of six. Contrary to popular perception, vented N95 masks did not allow free emission of aerosols, likely due to aerosol impaction during flow through the valve. The same group also investigated the effects of mask fit on respiratory aerosol emission, finding that aerosol leakage from the gaps in an imperfectly fitted surgical mask was much less than emission from an unmasked individual: A leaky mask reduced emissions from talking and coughing by 70% and 90%, respectively, compared to no mask (87). However, infectious (culture-positive) SARS-CoV-2 has been detected in emissions from infected individuals wearing loose-fitting masks (39). Recommendations for double-masking (layering a surgical mask underneath a tight-fitting cloth mask) from the CDC and other groups in early 2021 were motivated primarily by the potential for improved fit and reduced leakiness (88).

Face coverings also protect the wearer by filtering inhaled air to differing degrees depending on the mask material and the fit. Prior to the COVID-19 pandemic, the focus of most mask studies was on the filtration capacity of mask material against inhalation of particulate matter (PM). Perhaps counterintuitively, filtration of aerosol particles via a fibrous filter material does not generally occur via sieving (**Figure 3**). The main mechanisms of filtration for particles smaller than 2.5 μm are (*a*) inertial impaction as the particles attempt to move around the filter fibers, (*b*) interception

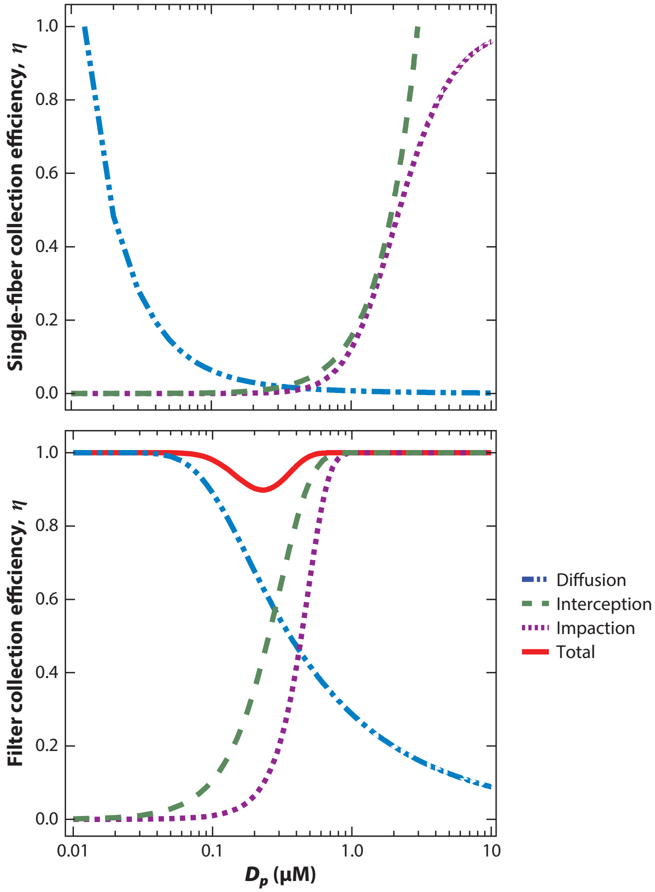

Figure 3

Filtration efficiency as a function of particle size for a 1.5-mm-thick filter with 2.88-μm diameter fibers and solidity of 0.083 [typical for N95 respirator material (90)]. Calculations following Bulejko (91).

of the particle streamline by the fiber, or (*c*) diffusion of very small particles into a fiber due to Brownian motion (89). The collection efficiency as a result of each mechanism depends on the particle size.

As a result of these mechanisms, multiple layers of a loose-weave material can be an effective filter medium for particles smaller than the pore size of the weave. Many studies have been conducted on the filter efficiency of different types of cloth and other materials used for homemade face coverings. Most of these studies have been conducted by using samples of mask material in filter cartridges, and therefore they provide the maximum filtration efficiency achievable, without taking fit into account (92–97). Some studies have been conducted on mannequins for additional realism in fit (85, 98). Overall, these studies have shown that filtration efficiency is highest for heavier-weight material (92, 95) with multiple layers (93, 94, 96, 99). The filtration efficiency of cloth mask material withstands multiple cycles of washing and reuse (92, 97).

Respirator masks are commercially made, tight-fitting masks made of synthetic fibrous filter material. These masks are designed to protect workers from inhalation of fine particles and are recommended PPE for healthcare workers performing aerosol-generating procedures. As such, their performance is regulated by occupational health and safety authorities. The US N95 standard prescribes at least 95% filtration efficiency for particles of 0.3 μm in diameter. This particle size is cited frequently in filtration standards because it is the most challenging to filter, being too small for effective inertial impaction and too large for the diffusion mechanism. Therefore, higher filtration efficiencies can be expected for larger and smaller particle sizes. International standards KN95 (China), KF94 (South Korea), and FFP2 (Europe) are similar to N95. These respirator-type masks require fit testing for use in healthcare settings.

Ventilation

Adequate ventilation with clean air is a necessity for healthy indoor spaces. Indoor spaces have several unique, intense pollution sources, and inadequate ventilation can lead to their buildup, potentially resulting in negative health impacts, including "sick building syndrome." Poor ventilation is associated with negative educational outcomes (100, 101) and decreased cognitive performance (102). Humans themselves are a major emission source indoors, so inadequate ventilation can also lead to a buildup of respiratory emissions from the occupants, including potentially pathogen-containing aerosols and CO_2. Trends since the mid-twentieth century toward more airtight buildings and energy efficiency have come with reduced outdoor air ventilation as a tradeoff, because increased outdoor air intake leads to higher cooling and heating requirements. Investigations of COVID-19 outbreaks have shown a direct association between insufficient ventilation rates and increased infection transmission (65).

The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) and other groups recommend a minimum ventilation turnover frequency of three air exchanges per hour, with six or more exchanges per hour being ideal (103, 104). Insufficiently ventilated spaces may use supplementary room-level air filtration. Room-level ventilation data are not available for many shared spaces, because prior to the COVID-19 pandemic the focus of ventilation standards was ensuring the supply of sufficient oxygen to the room rather than preventing stagnation of room air. McNeill et al. (105) outline approaches for characterizing room-level ventilation.

In the United States, most public buildings constructed since the mid-twentieth century are equipped with mechanical heating, ventilation, and air conditioning (HVAC) systems, which circulate a combination of outdoor air and filtered, conditioned air through ducts in the building. For these buildings, ventilation can be characterized by measuring airflow through the ducts. However, many homes and educational spaces, especially in older buildings in the Northeast and temperate areas on the West Coast, are naturally ventilated. For buildings that were designed for cross flow, natural ventilation can be very efficient, far exceeding minimum standards as long as doors and windows remain open (105, 106). However, naturally ventilated spaces in the Northeast, designed to keep heat in during the winter, often require supplemental air filtration to meet ASHRAE recommendations (105).

In situ monitoring of CO_2 and PM can provide indirect indicators of ventilation (105, 107). CO_2, which at the time of writing typically has a background value of approximately 415 ppm in North America (108), may build up indoors when people are present, owing to their exhaled emissions. A steady-state value between 600 and 800 ppm CO_2 has been suggested as a guideline for a well-ventilated space under full occupancy (104). PM monitoring data must be interpreted carefully in the context of COVID-19, because respiratory aerosols are likely small in number compared to the dominant contribution of other background sources (109), but they can give an indicator of indoor and outdoor air quality, ventilation, and filtration. If different PM sizes are measured, information can be inferred about particulate dynamics in the space, such as deposition. These and other types of ventilation data can be used to support decision making regarding, e.g., HVAC scheduling and placement of portable air filters (105). Collection and communication of these data to users of a space can build trust and relieve anxieties about returning to full occupancy. The use of low-cost sensors provides the opportunity for occupants in the space to be engaged in data collection, providing a sense of agency regarding COVID-19 safety and indoor air quality (110).

Filtration

Filtration of indoor air is an additional strategy for reducing aerosol levels in the indoor environment. Ventilation and filtration together were shown to reduce surface and aerosol viral loads from COVID-19 patients in a controlled chamber (40). Filtration is a key element of recirculating mechanical HVAC systems. After the beginning of the COVID-19 pandemic, ASHRAE specified that central HVAC filters should be upgraded to Minimum Efficiency Reporting Value (MERV)-13 or better (111). MERV-13-rated HVAC filters are rated to capture 0.3–1.0-μm particles with an efficiency of 85% or greater (112), with >90% efficiency at larger sizes (see the section titled Masks and **Figure 3** for additional discussion of air filtration physics). However, filtration efficiency at 0.3 μm was observed to vary from 61.8% to 95.1% for MERV-13 filters of various construction (113).

Alternatively, portable air cleaners with filtration are used as a mitigation measure in rooms with inadequate ventilation. Units consisting of fans and high-efficiency particulate air (HEPA) filters are readily available in the United States, or improvised units consisting of box fans and MERV-13 filters may be constructed (114). Owing to the airflow component, these units are rated by room size, and in a small room they may increase the effective ventilation by up to three air exchanges per hour. The HEPA standard corresponds to 99.97% or better removal of 0.3-μm particles. In a randomized control test of HEPA filters in dormitories, 11–82% reductions in $PM_{2.5}$ concentrations were observed (115). The reduction of $PM_{2.5}$ in classrooms with HEPA filtration has also been demonstrated (116).

Commercially available filtration units often come with accessories such as UV lamps, ionizers, or PM sensors. Ionizers are generally not recommended for COVID-19 risk-reduction applications because they can generate gas-phase oxidants, which degrade indoor air quality, lead to the formation of secondary PM, and potentially harm human health (117–122). Testing of these units and other electronic air cleaners is not standardized, and more studies are warranted (117, 118). PM sensors, if they are used in a control loop with the filter, should be bypassed, because the background level of PM will generally be dominated by sources other than respiratory aerosols (109). The unit should remain on while the room is occupied (or during short breaks in occupancy).

Other Interventions

Some NPIs have persisted in recommendations or have otherwise maintained popularity for reasons that are not supported by scientific evidence. For example, surface disinfection and the erection of plexiglass barriers were prioritized throughout post-lockdown reopenings, despite being ineffective against airborne transmission of SARS-CoV-2. Another example is physical distancing guidelines. Initially 3 ft/1 m, official recommendations in the United States converged in mid-2020 on 6 ft of physical distance for avoiding the exchange of potentially infective respiratory droplets and aerosols. The 6-ft recommendation was devised based on observations made in the mid-twentieth century for the transmission of tuberculosis in hospital environments (123). Six feet is sufficient to avoid close contact, and the concentration of emitted airborne particles decreases with distance from the source (40). However, small particles have sufficiently long airborne lifetime that they could travel farther than six feet (124), and particles and droplets may be forcefully ejected by a sneeze or cough more than three times that distance (25, 26). The flip side of social distancing is reduced occupancy, reducing the number of susceptible individuals in range for a spreading event. However, reduced occupancy, especially in schools, has been a major source of social disruption. In the spring of 2020, a study of elementary schools in Massachusetts showed no difference in rates of transmission among masked children at 3 ft or 6 ft of distance (125), leading many schools to reduce distancing requirements and return to full capacity. Further studies of this issue are warranted as new variants become dominant and vaccines become available to the school-aged population.

OUTLOOK

A preponderance of evidence from epidemiological studies and direct observations points to transmission of SARS-CoV-2 being primarily airborne. An interdisciplinary approach, involving cooperation among engineers, epidemiologists, infectious disease specialists, virologists, and clinicians, has been necessary to respond to and manage the pandemic in the evolving information landscape as new scientific and medical information has become available. Further coordination with the social sciences is also needed to combat misinformation and develop strategies to improve the adoption of public health interventions.

As we move into a stage in which vaccines are widely available and intensive, short-term measures for preventing the spread of SARS-CoV-2 are not sustainable, long-term investment in interventions that contribute to a healthy environment but rely less on personal responsibility, such as ventilation and filtration, is desirable. Besides reduction in the transmission risk for SARS-CoV-2 and other pathogens, these interventions will lead to improved indoor air quality, with health co-benefits.

SUMMARY POINTS

- Epidemiological evidence and direct observations indicate that SARS-CoV-2 is airborne: It is spread primarily through the inhalation of small respiratory droplets and aerosols.
- A layered approach that includes interventions targeting airborne transmission, such as masks, ventilation, and air filtration, reduces the risk of SARS-CoV-2 transmission.
- Designing indoor spaces with sufficient ventilation and air filtration will have multiple co-benefits for indoor air quality and reduced transmission of infectious diseases (SARS-CoV-2 and others).

DISCLOSURE STATEMENT

The author is not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

V.F.M. acknowledges the Columbia University School of Engineering and Applied Sciences and the Alfred P. Sloan Foundation Chemistry of Indoor Environments program for financial support and Prof. Nga Lee (Sally) Ng, Prof. Linsey Marr, Prof. Jeffrey Shaman, Prof. Sandra Albrecht, and Prof. Marco Giometto for helpful discussions.

LITERATURE CITED

1. Wu F, Zhao S, Yu B, Chen Y-M, Wang W, et al. 2020. A new coronavirus associated with human respiratory disease in China. *Nature* 579(7798):265–69
2. Zhou P, Yang X-L, Wang X-G, Hu B, Zhang L, et al. 2020. A pneumonia outbreak associated with a new coronavirus of probable bat origin. *Nature* 579(7798):270–73
3. Hu B, Guo H, Zhou P, Shi Z-L. 2021. Characteristics of SARS-CoV-2 and COVID-19. *Nat. Rev. Microbiol.* 19(3):141–54
4. Ghebreyesus TA. 2020. *WHO Director-General's opening remarks at the media briefing on COVID-19*. Speech, March 11. **https://www.who.int/director-general/speeches/detail/who-director-general-s-opening-remarks-at-the-media-briefing-on-covid-19---11-march-2020**
5. Carlson CJ, Gomez ACR, Bansal S, Ryan SJ. 2020. Misconceptions about weather and seasonality must not misguide COVID-19 response. *Nat. Commun.* 11(1):4312
6. Peacock JE Jr., Herrington DM, Edelstein SL, Seals AL, Plumb ID, et al. 2022. Survey of adherence with COVID-19 prevention behaviors during the 2020 Thanksgiving and winter holidays among members of the COVID-19 Community Research Partnership. *J. Community Health* 47:71–78
7. Ma Y, Pei S, Shaman J, Dubrow R, Chen K. 2020. Role of meteorological factors in the transmission of SARS-CoV-2 in the United States. *Nat. Commun.* 12:3602
8. Oliver SE. 2020. The Advisory Committee on Immunization Practices' interim recommendation for use of Pfizer-BioNTech COVID-19 Vaccine—United States, December 2020. *MMWR Morb. Mortal. Wkly. Rep.* 69:1922–24
9. Oliver SE. 2021. The Advisory Committee on Immunization Practices' interim recommendation for use of Moderna COVID-19 vaccine—United States, December 2020. *MMWR Morb. Mortal. Wkly. Rep.* 69:1653–56
10. Oliver SE. 2021. The Advisory Committee on Immunization Practices' interim recommendation for use of Janssen COVID-19 vaccine—United States, February 2021. *MMWR Morb. Mortal. Wkly. Rep.* 70:329–32
11. Voysey M, Costa Clemens SA, Madhi SA, Weckx LY, Folegatti PM, et al. 2021. Safety and efficacy of the ChAdOx1 NCoV-19 Vaccine (AZD1222) against SARS-CoV-2: an interim analysis of four randomised controlled trials in Brazil, South Africa, and the UK. *Lancet* 397(10269):99–111
12. Bloomberg.com. 2021. *More than 6.57 billion shots given: Covid-19 Tracker*. Graphics, Bloomberg.com, accessed Oct. 2021. **https://www.bloomberg.com/graphics/covid-vaccine-tracker-global-distribution/**
13. Li B, Deng A, Li K, Hu Y, Li Z, et al. 2021. Viral infection and transmission in a large, well-traced outbreak caused by the SARS-CoV-2 delta variant. medRxiv. 2021.07.07.21260122. **https://doi.org/10.1101/2021.07.07.21260122**
14. Gamio L, Glanz J. 2021. Just how big could India's true Covid toll be? *New York Times*, May 25. **https://www.nytimes.com/interactive/2021/05/25/world/asia/india-covid-death-estimates.html**
15. Langley W. 2021. Coronavirus latest: Vietnam becomes latest zero-case country to impose local lockdown as variant spreads. *Financial Times*, Aug. 20. **https://www.ft.com/content/bfaf3146-469e-4d0f-bdd6-3eaa3c7a9cd6**
16. Brown CM. 2021. Outbreak of SARS-CoV-2 infections, including COVID-19 vaccine breakthrough infections, associated with large public gatherings—Barnstable County, Massachusetts, July 2021. *MMWR Morb. Mortal. Wkly. Rep.* 70:1059–62
17. Cent. Dis. Control Prev. 2021. Interim public health recommendations for fully vaccinated people. Accessed Aug. 19, 2021. **https://www.cdc.gov/coronavirus/2019-ncov/vaccines/fully-vaccinated-guidance.html**
18. **Li R, Pei S, Chen B, Song Y, Zhang T, et al. 2020. Substantial undocumented infection facilitates the rapid dissemination of novel coronavirus (SARS-CoV-2). *Science* 368(6490):489–93**

18. Epidemiological evidence for asymptomatic transmission of SARS-CoV-2.

19. Greenhalgh T, Jimenez JL, Prather KA, Tufekci Z, Fisman D, Schooley R. 2021. Ten scientific reasons in support of airborne transmission of SARS-CoV-2. *Lancet* 397(10285):1603–5
20. Tao Z, Dong J, Culleton R. 2020. The use of facemasks may not lead to an increase in hand-face contact. *Transbound. Emerg. Dis.* 67(6):3038–40

21. Molteni M. 2020. How masks went from don't-wear to must-have during the coronavirus pandemic. *Wired*, July 2. **https://www.wired.com/story/how-masks-went-from-dont-wear-to-must-have/**
22. World Health Organ. 2020. *Update: STAG-IH Views on Mask Use by the General Public*. Rep. World Health Organ., Geneva. **https://www.who.int/emergencies/diseases/strategic-and-technical-advisory-group-for-infectious-hazards/Final_Update_STAG-IH_views_on_mask_use_by_the_general_public-25May2020.pdf?ua=1 May 25**
23. **Lyu W, Wehby GL. 2020. Community use of face masks and COVID-19: evidence from a natural experiment of state mandates in the US. *Health Aff*. 39(8):1419–25**
24. Prather KA, Wang CC, Schooley RT. 2020. Reducing transmission of SARS-CoV-2. *Science* 368(6498):1422–24
25. Bourouiba L. 2016. A sneeze. *N. Engl. J. Med.* 375(8):e15
26. Bourouiba L. 2020. Turbulent gas clouds and respiratory pathogen emissions: potential implications for reducing transmission of COVID-19. *J. Am. Med. Assoc.* 323(18):1837–38
27. Johnson GR, Morawska L, Ristovski ZD, Hargreaves M, Mengersen K, et al. 2011. Modality of human expired aerosol size distributions. *J. Aerosol Sci.* 42(12):839–51
28. Asadi S, Bouvier N, Wexler AS, Ristenpart WD. 2020. The coronavirus pandemic and aerosols: Does COVID-19 transmit via expiratory particles? *Aerosol Sci. Technol.* 54:635–38
29. Anfinrud P, Stadnytskyi V, Bax CE, Bax A. 2020. Visualizing speech-generated oral fluid droplets with laser light scattering. *N. Engl. J. Med.* 382:2061–63
30. **Asadi S, Wexler AS, Cappa CD, Barreda S, Bouvier NM, Ristenpart WD. 2019. Aerosol emission and superemission during human speech increase with voice loudness. *Sci. Rep.* 9:2348**
31. Asadi S, Wexler AS, Cappa CD, Barreda S, Bouvier NM, Ristenpart WD. 2020. Effect of voicing and articulation manner on aerosol particle emission during human speech. *PLOS ONE* 15(1):e0227699
32. Gregson FKA, Watson NA, Orton CM, Haddrell AE, McCarthy LP, et al. 2021. Comparing aerosol concentrations and particle size distributions generated by singing, speaking and breathing. *Aerosol Sci. Technol.* 55(6):681–91
33. Coleman KK, Tay DJW, Sen Tan K, Ong SWX, Son TT, et al. 2021. Viral load of SARS-CoV-2 in respiratory aerosols emitted by COVID-19 patients while breathing, talking, and singing. *Clin. Infect. Dis.* 6:ciab691
34. Alsved M, Matamis A, Bohlin R, Richter M, Bengtsson P-E, et al. 2020. Exhaled respiratory particles during singing and talking. *Aerosol Sci. Technol.* 54(11):1245–48
35. Scheuch G. 2020. Breathing is enough: for the spread of influenza virus and SARS-CoV-2 by breathing only. *J. Aerosol Med. Pulm. Drug Deliv.* 33(4):230–34
36. Morawska L, Johnson GR, Ristovski ZD, Hargreaves M, Mengersen K, et al. 2009. Size distribution and sites of origin of droplets expelled from the human respiratory tract during expiratory activities. *J. Aerosol Sci.* 40(3):256–69
37. Edwards DA, Ausiello D, Salzman J, Devlin T, Langer R, et al. 2021. Exhaled aerosol increases with COVID-19 infection, age, and obesity. *PNAS* 118(8):e2021830118
38. Prather KA, Marr LC, Schooley RT, McDiarmid MA, Wilson ME, Milton DK. 2020. Airborne transmission of SARS-CoV-2. *Science* 370(6514):303–4
39. Adenaiye OO, Lai J, Bueno de Mesquita PJ, Hong F, Youssefi S, et al. 2021. Infectious severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) in exhaled aerosols and efficacy of masks during early mild infection. *Clin. Infect. Dis.* In press. **https://doi.org/10.1093/cid/ciab797**
40. **Parhizkar H, Dietz L, Olsen-Martinez A, Horve P, Barnatan L, et al. 2021. Quantifying human and environmental viral load relationships amidst mitigation strategies in a controlled chamber with participants having COVID-19. *Res. Square*. In press. https://doi.org/10.21203/rs.3.rs-940891/v1**
41. Tellier R, Li Y, Cowling BJ, Tang JW. 2019. Recognition of aerosol transmission of infectious agents: a commentary. *BMC Infect. Dis.* 19:101
42. Anderson CE, Boehm AB. 2021. Transfer rate of enveloped and non-enveloped viruses between fingerpads and surfaces. bioRxiv. 2021.06.22.449538. **https://doi.org/10.1101/2021.06.22.449538**
43. Chen W, Zhang N, Wei J, Yen H-L, Li Y. 2020. Short-range airborne route dominates exposure of respiratory infection during close contact. *Build. Environ.* 176:106859

23. Epidemiological evidence for the effectiveness of mask mandates.

30. Demonstration of aerosol superemission during speech.

40. Demonstration that ventilation and air filtration reduce aerosol viral load in controlled study.

44. Laboratory study of the evaporation process in respiratory droplets.

44. **Vejerano EP, Marr LC. 2018. Physico-chemical characteristics of evaporating respiratory fluid droplets. *J. R. Soc. Interface* 15(139):20170939**
45. Lepistö T, Kuuluvainen H, Juuti P, Järvinen A, Arffman A, Rönkkö T. 2020. Measurement of the human respiratory tract deposited surface area of particles with an electrical low pressure impactor. *Aerosol Sci. Technol.* 54(8):958–71
46. Fedorenko A, Grinberg M, Orevi T, Kashtan N. 2020. Survival of the enveloped bacteriophage Phi6 (a surrogate for SARS-CoV-2) in evaporated saliva microdroplets deposited on glass surfaces. *Sci. Rep.* 10(1):22419
47. Lin K, Marr LC. 2017. Aerosolization of Ebola virus surrogates in wastewater systems. *Environ. Sci. Technol.* 51(5):2669–75
48. McKinney KR, Gong YY, Lewis TG. 2006. Environmental transmission of SARS at Amoy Gardens. *J. Environ. Health* 68(9):26–30; quiz 51–52
49. Leung K, Leung C, Ho-Him C. 2020. Coronavirus: at least 10 households evacuated from Hong Kong public housing block in Tai Po over multiple infections. *South China Morning Post*, March 14. **https://www.scmp.com/news/hong-kong/health-environment/article/3075228/coronavirus-another-public-housing-estate-hong**
50. Kang M, Wei J, Yuan J, Guo J, Zhang Y, et al. 2020. Probable evidence of fecal aerosol transmission of SARS-CoV-2 in a high-rise building. *Ann. Intern. Med.* 173(12):974–80
51. Peccia J, Zulli A, Brackney DE, Grubaugh ND, Kaplan EH, et al. 2020. Measurement of SARS-CoV-2 RNA in wastewater tracks community infection dynamics. *Nat. Biotechnol.* 38(10):1164–67
52. Guo M, Tao W, Flavell RA, Zhu S. 2021. Potential intestinal infection and faecal-oral transmission of SARS-CoV-2. *Nat. Rev. Gastroenterol. Hepatol.* 18(4):269–83
53. Yang W, Marr LC. 2011. Dynamics of airborne influenza A viruses indoors and dependence on humidity. *PLOS ONE* 6(6):e21481
54. Yan J, Grantham M, Pantelic J, Bueno de Mesquita PJ, Albert B, et al. 2018. Infectious virus in exhaled breath of symptomatic seasonal influenza cases from a college community. *PNAS* 115(5):1081–86
55. Li Y, Huang X, Yu ITS, Wong TW, Qian H. 2005. Role of air distribution in SARS transmission during the largest nosocomial outbreak in Hong Kong. *Indoor Air* 15(2):83–95
56. Yu ITS, Wong TW, Chiu YL, Lee N, Li Y. 2005. Temporal-spatial analysis of severe acute respiratory syndrome among hospital inpatients. *Clin. Infect. Dis.* 40(9):1237–43
57. Wang CC, Prather KA, Sznitman J, Jimenez JL, Lakdawala SS, et al. 2021. Airborne transmission of respiratory viruses. *Science* 373(6558):eabd9149
58. Morawska L, Cao J. 2020. Airborne transmission of SARS-CoV-2: The world should face the reality. *Environ. Int.* 139:105730
59. Klompas M, Baker MA, Rhee C. 2020. Airborne transmission of SARS-CoV-2: theoretical considerations and available evidence. *J. Am. Med. Assoc.* 324(5):441–42
60. van Doremalen N, Bushmaker T, Morris DH, Holbrook MG, Gamble A, et al. 2020. Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. *N. Engl. J. Med.* 382(16):1564–67
61. Goldman E. 2020. Exaggerated risk of transmission of COVID-19 by fomites. *Lancet Infect. Dis.* 20(8):892–93
62. Lu J, Gu J, Li K, Xu C, Su W, et al. 2020. COVID-19 outbreak associated with air conditioning in restaurant, Guangzhou, China, 2020. *Emerg. Infect. Dis. J.* 26(7):1628–31
63. Park SY, Kim Y-M, Yi S, Lee S, Na B-J, et al. 2020. Coronavirus disease outbreak in call center, South Korea. *Emerg. Infect. Dis. J.* 26(8):1666–70
64. Azimi P, Keshavarz Z, Cedeno Laurent JG, Stephens B, Allen JG. 2021. Mechanistic transmission modeling of COVID-19 on the *Diamond Princess* cruise ship demonstrates the importance of aerosol transmission. *PNAS* 118(8):e2015482118
65. Miller SL, Nazaroff WW, Jimenez JL, Boerstra A, Buonanno G, et al. 2021. Transmission of SARS-CoV-2 by inhalation of respiratory aerosol in the Skagit Valley Chorale superspreading event. *Indoor Air* 31(2):314–23
66. Katelaris AL, Wells J, Clark P, Norton S, Rockett R, et al. 2021. Epidemiologic evidence for airborne transmission of SARS-CoV-2 during church singing, Australia, 2020. *Emerg. Infect. Dis. J.* 27(6):1677–80

67. Chaudhuri S, Kasibhatla P, Mukherjee A, Pan W, Morrison G, et al. 2021. Analysis of overdispersion in airborne transmission of Covid-19. medRxiv 21263801. **https://doi.org/10.1101/2021.09.28.21263801**
68. Liu Y, Ning Z, Chen Y, Guo M, Liu Y, et al. 2020. Aerodynamic analysis of SARS-CoV-2 in two Wuhan hospitals. *Nature* 582(7813):557–60
69. Ong SWX, Tan YK, Chia PY, Lee TH, Ng OT, et al. 2020. Air, surface environmental, and personal protective equipment contamination by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) from a symptomatic patient. *J. Am. Med. Assoc.* 323(16):1610–12
70. Santarpia JL, Herrera VL, Rivera DN, Ratnesar-Shumate S, Reid SP, et al. 2021. The size and culturability of patient-generated SARS-CoV-2 aerosol. *J. Expo. Sci. Environ. Epidemiol.* In press. **https://doi.org/10.1038/s41370-021-00376-8**
71. **Lednicky JA, Lauzardo M, Fan ZH, Jutla A, Tilly TB, et al. 2020. Viable SARS-CoV-2 in the air of a hospital room with COVID-19 patients. *Int. J. Infect. Dis.* 100:476–82**

71. First detection of viable SARS-CoV-2 in aerosols in the hospital room of a COVID-19 patient.

72. Lednicky J, Pan M, Loeb J, Hsieh H, Eiguren-Fernandez A, et al. 2016. Highly efficient collection of infectious pandemic influenza H1N1 virus 2009 through laminar-flow water based condensation. *Aerosol Sci. Technol.* 50(7):i–iv
73. Richard M, Kok A, de Meulder D, Bestebroer TM, Lamers MM, et al. 2020. SARS-CoV-2 is transmitted via contact and via the air between ferrets. *Nat. Commun.* 11(1):3496
74. Kutter JS, de Meulder D, Bestebroer TM, Lexmond P, Mulders A, et al. 2021. SARS-CoV and SARS-CoV-2 are transmitted through the air between ferrets over more than one meter distance. *Nat. Commun.* 12(1):1653
75. Kim Y-I, Kim S-G, Kim S-M, Kim E-H, Park S-J, et al. 2020. Infection and rapid transmission of SARS-CoV-2 in ferrets. *Cell Host Microbe* 27(5):704–9.e2
76. Port JR, Yinda CK, Owusu IO, Holbrook M, Fischer R, et al. 2021. SARS-CoV-2 disease severity and transmission efficiency is increased for airborne compared to fomite exposure in Syrian hamsters. *Nat. Commun.* 12(1):4985
77. Roberts S. 2020. The Swiss cheese model of pandemic defense. *New York Times*, Dec. 5. **https://www.nytimes.com/2020/12/05/health/coronavirus-swiss-cheese-infection-mackay.html**
78. Glanz K, Bishop DB. 2010. The role of behavioral science theory in development and implementation of public health interventions. *Annu. Rev. Public Health* 31:399–418
79. World Health Organ. 2020. *Modes of transmission of virus causing COVID-19: implications for IPC precaution recommendations*. Sci. brief, World Health Organ. **https://www.who.int/news-room/commentaries/detail/modes-of-transmission-of-virus-causing-covid-19-implications-for-ipc-precaution-recommendations**
80. Cent. Dis. Control Prev. 2020. Hand hygiene recommendations. Accessed Aug. 18. **https://www.cdc.gov/coronavirus/2019-ncov/hcp/hand-hygiene.html**
81. Morawska L, Tang JW, Bahnfleth W, Bluyssen PM, Boerstra A, et al. 2020. How can airborne transmission of COVID-19 indoors be minimised? *Environ. Int.* 142:105832
82. Cent. Dis. Control Prev., Natl. Cent. Immun. Respir. Dis. 2021. *FLUVIEW: A Weekly Influenza Surveillance Report Prepared by the Influenza Division*. **https://www.cdc.gov/flu/weekly/index.htm**
83. Lindsley WG, Blachere FM, Law BF, Beezhold DH, Noti JD. 2021. Efficacy of face masks, neck gaiters and face shields for reducing the expulsion of simulated cough-generated aerosols. *Aerosol Sci. Technol.* 55(4):449–57
84. Li L, Niu M, Zhu Y. 2021. Assessing the effectiveness of using various face coverings to mitigate the transport of airborne particles produced by coughing indoors. *Aerosol Sci. Technol.* 55(3):332–39
85. Pan J, Harb C, Leng W, Marr LC. 2021. Inward and outward effectiveness of cloth masks, a surgical mask, and a face shield. *Aerosol Sci. Technol.* 55(6):718–33
86. Asadi S, Cappa CD, Barreda S, Wexler AS, Bouvier NM, Ristenpart WD. 2020. Efficacy of masks and face coverings in controlling outward aerosol particle emission from expiratory activities. *Sci. Rep.* 10(1):15665
87. Cappa CD, Asadi S, Barreda S, Wexler AS, Bouvier NM, Ristenpart WD. 2021. Expiratory aerosol particle escape from surgical masks due to imperfect sealing. *Sci. Rep.* 11:12110

88. Brooks JT. 2021. Maximizing fit for cloth and medical procedure masks to improve performance and reduce SARS-CoV-2 transmission and exposure, 2021. *MMWR Morb. Mortal. Wkly. Rep.* 70:254–57
89. Brown RC. 1993. *Air Filtration: An Integrated Approach to the Theory and Applications of Fibrous Filters*. Oxford, UK: Pergamon
90. Lam T-N, Wu C-H, Huang S-H, Ko W-C, Huang Y-L, et al. 2019. Multi-scale microstructure investigation for a $PM_{2.5}$ air-filter efficiency study of non-woven polypropylene. *Quantum Beam Sci*. 3(4):20
91. Bulejko P. 2018. Numerical comparison of prediction models for aerosol filtration efficiency applied on a hollow-fiber membrane pore structure. *Nanomaterials* 8(6):447
92. Hao W, Xu G, Wang Y. 2021. Factors influencing the filtration performance of homemade face masks. *J. Occup. Environ. Hyg.* 18(3):128–38
93. Drewnick F, Pikmann J, Fachinger F, Moormann L, Sprang F, Borrmann S. 2021. Aerosol filtration efficiency of household materials for homemade face masks: influence of material properties, particle size, particle electrical charge, face velocity, and leaks. *Aerosol Sci. Technol.* 55(1):63–79
94. Zangmeister CD, Radney JG, Vicenzi EP, Weaver JL. 2020. Filtration efficiencies of nanoscale aerosol by cloth mask materials used to slow the spread of SARS-CoV-2. *ACS Nano* 14(7):9188–200
95. Rengasamy S, Eimer B, Shaffer RE. 2010. Simple respiratory protection—evaluation of the filtration performance of cloth masks and common fabric materials against 20–1000 nm size particles. *Ann. Occup. Hyg.* 54(7):789–98
96. Konda A, Prakash A, Moss GA, Schmoldt M, Grant GD, Guha S. 2020. Aerosol filtration efficiency of common fabrics used in respiratory cloth masks. *ACS Nano* 14(5):6339–47
97. Sankhyan S, Heinselman KN, Ciesielski PN, Barnes T, Himmel ME, et al. 2021. Filtration performance of layering masks and face coverings and the reusability of cotton masks after repeated washing and drying. *Aerosol Air Qual. Res.* 21(11):210117
98. Dang AJ, Kumfer BM, Bertroche JT, Glidden JO, Oxford CR, et al. 2021. Challenges in predicting the filtration performance of a novel sewn mask: scale-up from filter holder to mannequin measurements. *Aerosol Air Qual. Res.* 21(6):200629
99. Joo T, Takeuchi M, Liu F, Rivera MP, Barr J, et al. 2021. Evaluation of particle filtration efficiency of commercially available materials for homemade face mask usage. *Aerosol Sci. Technol.* 55(8):930–42
100. Wargocki P, Porras-Salazar JA, Contreras-Espinoza S, Bahnfleth W. 2020. The relationships between classroom air quality and children's performance in school. *Build. Environ.* 173:106749
101. Corsi R, Miller SL, VanRy MG, Marr LC, Cadet LR, et al. 2021. *Designing infectious disease resilience into school buildings through improvements to ventilation and air cleaning*. Rep., Lancet COVID-19 Commission Task Force Safe Work, Safe School, Safe Travel, April. **https://uvresources.com/wp-content/uploads/2021/05/SafeWorkTFDesiginingfectiousdiseaseresilienceApril2021.pdf**
102. Zhang X, Wargocki P, Lian Z, Thyregod C. 2017. Effects of exposure to carbon dioxide and bioeffluents on perceived air quality, self-assessed acute health symptoms, and cognitive performance. *Indoor Air* 27(1):47–64
103. ASHRAE. 2019. *Ventilation for acceptable indoor air quality 2019*. Stand., ANSI/ASHRAE Standing Stand. Proj. Comm. 62.1, ASHRAE, Peachtree Corners, GA
104. Jones E, Young A, Clevenger K, Salimifard P, Wu E, et al. 2020. *Healthy schools: risk reduction strategies for reopening schools.* Rep., T.H. Chan School Public Health Healthy Build. Program, Harvard Univ., Cambridge, MA. **https://schools.forhealth.org/risk-reduction-strategies-for-reopening-schools/**

105. Methods for evaluating ventilation on a room level in mechanically and naturally ventilated spaces.

105. McNeill VF, Corsi R, Huffman JA, Maeng DY, King C, et al. 2022. Room-level ventilation in schools and universities. *Atmos. Environ. X* 13:100152
106. Howard-Reed C, Wallace LA, Ott WR. 2002. The effect of opening windows on air change rates in two homes. *J. Air Waste Manag. Assoc.* 52(2):147–59
107. Peng Z, Jimenez JL. 2021. Exhaled CO_2 as a COVID-19 infection risk proxy for different indoor environments and activities. *Environ. Sci. Technol. Lett.* 8(5):392–97
108. NOAA. 2021. *Trends in atmospheric carbon dioxide*. Trends, NOAA Glob. Monit. Lab., Boulder, CO, accessed Oct. 2021. **https://www.esrl.noaa.gov/gmd/ccgg/trends/mlo.html**
109. Abbatt JPD, Wang C. 2020. The atmospheric chemistry of indoor environments. *Environ. Sci. Process. Impacts* 22:25–48

110. Schaefer T, Kieslinger B, Fabian CM. 2020. Citizen-based air quality monitoring: the impact on individual citizen scientists and how to leverage the benefits to affect whole regions. *Citiz. Sci. Theory Pract.* 5(1):6
111. ASHRAE Epidemic Task Force. 2021. *Core recommendations for reducing airborne infections aerosol exposure*. Resour., ASHRAE, Peachtree Corners, GA. **https://www.ashrae.org/file%20library/technical%20resources/covid-19/core-recommendations-for-reducing-airborne-infectious-aerosol-exposure.pdf**
112. ASHRAE. 2021. *Filtration/disinfection*. Resour., ASHRAE, Peachtree Corners, GA. **https://www.ashrae.org/technical-resources/filtration-disinfection**
113. Berger D, Eichfeld C. 2020. Preliminary evaluation of the filtration efficiency of alternative mask filter materials. *Penn State J. Med.* 1. **https://doi.org/10.26209/psjm61989**
114. Rosenthal J. 2021. IAQ research-practice in action: the Corsi/Rosenthal box air cleaner. *Tex-Air Filters*, July 24. **https://www.texairfilters.com/iaq-research-practice-in-action-the-corsi-rosenthal-box-air-cleaner**
115. Zhu Y, Song X, Wu R, Fang J, Liu L, et al. 2021. A review on reducing indoor particulate matter concentrations from personal-level air filtration intervention under real-world exposure situations. *Indoor Air* 31(6):1707–21
116. Curtius J, Granzin M, Schrod J. 2021. Testing mobile air purifiers in a school classroom: reducing the airborne transmission risk for SARS-CoV-2. *Aerosol Sci. Technol.* 55(5):586–99
117. Joo T, Rivera-Rios JC, Alvarado-Velez D, Westgate S, Ng NL. 2021. Formation of oxidized gases and secondary organic aerosol from a commercial oxidant-generating electronic air cleaner. *Environ. Sci. Technol. Lett.* 8(8):691–98
118. Zaatari M, Harmon M. 2021. Open letter to address the use of electronic air cleaning equipment in buildings. *Medium.com*, April 12. **https://medium.com/open-letter-to-address-the-use-of-electronic-air/no-to-ionizers-plasma-uvpco-bc1570b2fb9b**
119. Weber L, Jewett C. 2021. Schools spending millions on air purifiers often sold using overblown claims. *CNN*, May 11. **https://www.cnn.com/2021/05/03/health/air-filter-covid-scams-khn/index.html**
120. Waring MS, Siegel JA. 2011. The effect of an ion generator on indoor air quality in a residential room. *Indoor Air* 21(4):267–76
121. Zeng Y, Manwatkar P, Laguerre A, Beke M, Kang I, et al. 2021. Evaluating a commercially available in-duct bipolar ionization device for pollutant removal and potential byproduct formation. *Build. Environ.* 195:107750
122. Collins DB, Farmer DK. 2021. Unintended consequences of air cleaning chemistry. *Environ. Sci. Technol.* 55(18):12172–79
123. Riley RL, Wells WF, Mills CC, Nyka W, McLean RL. 1957. Air hygiene in tuberculosis: quantitative studies of infectivity and control in a pilot ward. *Am. Rev. Tuberc. Pulm. Dis.* 75(3):420–31
124. Bazant MZ, Bush JWM. 2021. A guideline to limit indoor airborne transmission of COVID-19. *PNAS* 118(17):e2018995118
125. van den Berg P, Schechter-Perkins EM, Jack RS, Epshtein I, Nelson R, et al. 2021. Effectiveness of three versus six feet of physical distancing for controlling spread of coronavirus disease 2019 among primary and secondary students and staff: a retrospective, statewide cohort study. *Clin. Infect. Dis.* 73(10):1871–78
126. Conticini E, Frediani B, Caro D. 2020. Can atmospheric pollution be considered a co-factor in extremely high level of SARS-CoV-2 lethality in Northern Italy? *Environ. Pollut.* 261:114465
127. Comunian S, Dongo D, Milani C, Palestini P. 2020. Air pollution and COVID-19: the role of particulate matter in the spread and increase of COVID-19's morbidity and mortality. *Int. J. Environ. Res. Public Health* 17(12):4487
128. Wu X, Nethery RC, Sabath MB, Braun D, Dominici F. 2020. Air pollution and COVID-19 mortality in the United States: strengths and limitations of an ecological regression analysis. *Sci. Adv.* 6(45):eabd4049
129. Travaglio M, Yu Y, Popovic R, Selley L, Leal NS, Martins LM. 2021. Links between air pollution and COVID-19 in England. *Environ. Pollut.* 268:115859
130. Setti L, Passarini F, De Gennaro G, Barbieri P, Perrone MG, et al. 2020. SARS-Cov-2 RNA found on particulate matter of Bergamo in Northern Italy: first evidence. *Environ. Res.* 188:109754

131. Setti L, Passarini F, De Gennaro G, Barbieri P, Licen S, et al. 2020. Potential role of particulate matter in the spreading of COVID-19 in Northern Italy: first observational study based on initial epidemic diffusion. *BMJ Open* 10(9):e039338
132. Barakat T, Muylkens B, Su B-L. 2020. Is particulate matter of air pollution a vector of Covid-19 pandemic? *Matter* 3(4):977–80
133. Bulfone TC, Malekinejad M, Rutherford GW, Razani N. 2021. Outdoor transmission of SARS-CoV-2 and other respiratory viruses: a systematic review. *J. Infect. Dis.* 223(4):550–61
134. Seinfeld JH, Pandis SN. 2016. *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change*. Hoboken, NJ: John Wiley & Sons. 3rd ed.
135. Brauer M, Freedman G, Frostad J, van Donkelaar A, Martin RV, et al. 2016. Ambient air pollution exposure estimation for the global burden of disease 2013. *Environ. Sci. Technol.* 50(1):79–88
136. Becker S, Soukup JM. 1999. Exposure to urban air particulates alters the macrophage-mediated inflammatory response to respiratory viral infection. *J. Toxicol. Environ. Health A* 57(7):445–57