THE ROLE OF BUILDING VENTILATION AND FILTRATION IN REDUCING RISK OF AIRBORNE VIRAL TRANSMISSION IN SCHOOLS, ILLUSTRATED WITH SARS-COV-2

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Summary

Long-range airborne transmission of multiple infectious diseases within buildings has been well documented. Growing evidence suggests that transmission by small airborne particles (aerosols) may also be an important route for SARS-CoV-2, the virus causing the novel coronavirus disease COVID-19, especially in enclosed environments with poor ventilation and high occupant density. This paper presents an interactive tool, based on existing risk-estimation models, that calculates the effects of classroom ventilation rates and filtration efficiency, as well as wearing masks, on the relative risk of long-range airborne transmission. We demonstrate the model using an example of the current COVID-19 pandemic in a hypothetical classroom setting with one asymptomatic infected individual. We model five scenarios representing a range of ventilation rates potentially encountered in California schools, including a “no ventilation” scenario. We quantify, with respect to the risk of infection by long-range small aerosols, the expected relative risk reductions that could be achieved with different improvements in ventilation and air filtration. For all modeled ventilation rates, the relative risk of infection was lowest with use of both an enhanced air filtration method (either a MERV 13 filter or portable air cleaners) and face masks. We discuss the potential that improved classroom ventilation and filtration strategies offer for reducing the spread of COVID-19 in particular and note the potential for enhanced ventilation to provide broader health benefits for those in the classroom.

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Practical Implications

Based on our modeling assumptions and results, protective strategies that can substantially reduce the risk of long-range airborne transmission of SARS CoV-2 in classrooms include:

- Mask wearing: Teachers and students should wear masks – this practice reduces this risk by more than half, regardless of the rate of ventilation or filtration of air in the classroom.

- Outdoor air ventilation: The ventilation system should provide at least the California Title 24 code-required minimum ventilation rate. Note that if there was *no ventilation* and *no filtration*, the risk of long-range airborne infection would be *over six times as high as* that for a classroom with code-required ventilation and a MERV 8 filter.

- Filtration: Ventilation system filters should be MERV-rated (e.g., MERV 13 or better) as well as properly installed (i.e., no gaps that would allow air to bypass the filter) and filters should be properly maintained (i.e., replaced as often as recommended). MERV-rated filters can provide substantial protection, especially if ventilation is poor.

- In-room (portable) air cleaners: Devices, with high efficiency filtration, can provide substantial additional protection, especially in naturally ventilated classrooms (those in which air is supplied only through open windows or doors) or in classrooms with non-functioning or poorly functioning ventilation systems, if the clean air delivery rate (CADR) is sufficient (i.e., at least 2/3 of the floor area). Multiple devices per classroom may be necessary.

Do not use air cleaning devices that generate harmful pollutants (i.e., ionization devices or ozone generators), or devices of unproven effectiveness.

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Airborne transmission of infectious respiratory viruses and the potential role of ventilation in reducing exposure

The three primary modes of possible transmission of infectious respiratory viruses are: (1) short-range exposure to large and small respiratory droplets that people release when breathing, speaking, singing, coughing, or sneezing; (2) contact with surfaces that have been contaminated through touch or droplet deposition (fomites), such as doorknobs or desktops, and viral transfer to the nose, mouth, or eyes; and (3) long-range airborne transmission through inhalation of smaller, virus-containing aerosols (Figure 1).[1]

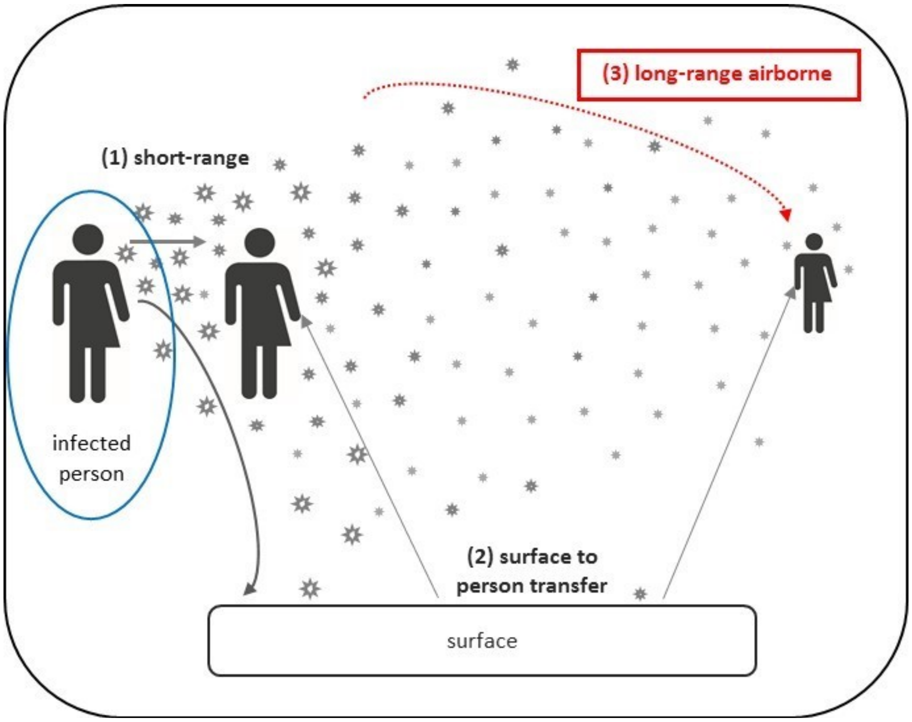


Figure 1. Routes of transmission from a case to a susceptible individual: (1) short-range, small and large respiratory droplet exposure, (2) surface contact, and (3) long-range airborne transmission. The figure shows how a susceptible person can encounter aerosols in a range of sizes if sufficiently close to an infected person; the larger particles settle out of the air, but the smaller particles can remain airborne, accumulate, and travel farther from the infected person.

Researchers, in considering routes of viral exposures in the current pandemic, now question the common assumption that emitted infectious particles can be divided neatly into two size categories: *large droplets* that directly reach another person or fall quickly to the ground and *small droplets* (that dry to droplet nuclei) that remain airborne. In fact, respiratory droplets are known to be generated in a continuum of sizes by normal breathing, speaking, and throat clearing as well as by explosive emissions from sneezing and coughing.[2-9] This paper focuses on "long-range airborne transmission by small aerosols," or more briefly, "airborne transmission." We define this as disease transmission involving the range of particle or droplet sizes sufficiently small to remain suspended in air for minutes to hours, thus allowing them to *accumulate over time* in enclosed spaces and to *travel long distances* from the infected person who generated them (route 3 in Figure 1). We note that different fields use different terminology, e.g., aerosol, droplet, particle, or airborne agent. In this paper, which cites evidence from many sources, we use several terms interchangeably to refer to respiratory particles that may contain SARS-CoV-2.

Evidence for airborne transmission of SARS-CoV-2

The World Health Organization (WHO) and the U.S. Centers for Disease Control and Prevention (CDC) have stated that, according to current evidence, SARS-CoV-2, the virus that causes the current pandemic disease COVID-19, is transmitted primarily from person to person. By this they mean through either short-range, large and small respiratory droplets or contaminated fomites[10-12] (routes 1 and 2 in Figure 1). These transmission mechanisms and appropriate control/prevention strategies are addressed in published guidance on reducing disease transmission in schools during this pandemic.[13-15] At first, these organizations recognized only limited specific procedures or treatments, primarily in medical settings, as generating small aerosols that could spread through airborne transmission (route 3 in Figure 1). In July, however, WHO reviewed more recent evidence and concluded that "the role and extent of airborne transmission outside of health care facilities, and in particular in close settings with poor ventilation, also requires further study."[12]

Other organizations and professional groups have stated different positions. The *Standing Committee on Emerging Infectious Diseases and 21st Century Health Threats* found that "currently available research supports the possibility that SARS-CoV-2 could be spread via bioaerosols generated by patients' exhalation," without defining "bioaerosols." The Chinese National Health Commission (NHC) suggested that long-range aerosol transmission may occur in crowded and poorly ventilated enclosures or spaces.[16] A growing number of professionals from diverse fields have argued that airborne transmission is possible in circumstances beyond the limited ones that WHO and CDC originally recognized and that appropriate measure, such as improved ventilation and filtration efficiency, are also needed.[2-6,17-38]

There is both direct and indirect evidence supporting probable long-range airborne transmission. The direct evidence involves research on SARS-CoV-2 (from field studies in environments where the virus is known to be present or experimental aerosol and animal studies with the virus) or review of epidemiologic data from studies of confirmed transmission of COVID-19. The indirect evidence is from knowledge of the virology of respiratory disease agents and modeling of particle movement in indoor spaces. Appendix 1 lists databases of recent research pertaining to this question as well as brief descriptions of studies cited in this paper, not all yet peer reviewed and thus potentially subject to change. Not covered in this review are studies of exposure due to aerosolization of fecal matter;[39,40] although such transmission may occur in school restrooms, and may warrant additional control strategies, the focus of our paper is the classroom environment, where students spend the majority of their time at school. Other guidance documents on school reopening address appropriate precautions regarding ventilation for restrooms and adequate handwashing facilities.[15,41-49]

Direct evidence from field studies includes detection of SARS-CoV-2 in air samples ≥4 m from a COVID-19 patient and on surfaces in patient rooms where large droplet deposition is less likely than small aerosol spread, e.g., under a patient's bed; on a supply or exhaust air vent, outlet, damper, louvre, or grate; and on air outlet filters and fans.[50-57] Aerosol transport may explain these findings, because virus-containing particles were detected in size ranges sufficiently small to remain airborne and travel long distances.[53,58] More convincingly, viral RNA has been recovered within a hospital air handling unit on prefilters (of mixed outdoor and return air), on final filters (after the supply air fan), and on supply air dampers[56] as well as on exhaust filters and the surface of central air ducts up to 56 m from patient areas.[57]

Direct evidence from experimental research has found that SARS-CoV-2, aerosolized and kept suspended artificially in an environmental chamber with a rotating drum, remained viable (i.e., retained replication competence) for up to 16 h.[59,60] SARS-CoV-2 also was more efficiently aerosolized than SARS-CoV and another coronavirus, the causative agent of MERS.[59] Animal studies have demonstrated infection in mice,[61] hamsters,[62-64] ferrets,[65,66] and monkeys[67] with various strains of the SARS-CoV-2 virus via aerosol exposure.[61,67] Infection occurred not only through contact between donor and naïve animals housed together,[62,63,65,68] but also between donor and naïve animals in individual cages separated by a surgical mask or permeable partition.[62,64-66] The latter suggests airborne or droplet transmission over short distances.

Epidemiologic investigation of large and small outbreaks has identified possible airborne transmission of SARS-CoV-2 in crowded or poorly ventilated indoor settings, which may explain some community spread of COVID-19.[69-72] Some have suggested that airborne transmission may explain infection of persons who did not have close or frequent contact with cases,[73] other attendants at meetings,[71,74] passengers on a bus including those seated remotely,[71] and chorus members who reported no physical or close contact.[75] Also, this route has been suggested as a plausible explanation for the documented transmission from asymptomatic or pre-symptomatic cases—i.e., transmission from an infected person with no symptoms through small aerosols emitted by normal breathing or speaking[6,8,17,19,30,76-79]—although transmission by occasional larger respiratory droplets or fomite contact cannot be ruled out in such episodes and in the other examples.[73] In one study, PCR cycle times were similar for symptomatic and asymptomatic, isolated patients, but viral loads in the latter decreased more slowly from time of diagnosis to discharge.[80]

Indirect virologic evidence includes what is known about respiratory disease agents generally and SARS-CoV-2 specifically: (a) other viruses spread as aerosols either primarily or in addition to other routes;[4,17,28,81,82] and (b) the similarity of SARS-CoV-2 to other coronaviruses that are transmitted as aerosols.[4,17,28,81,83]

Additional indirect evidence comes from imaging and size-fractionated air sampling, showing that both symptomatic and healthy persons emit particles from the upper and lower respiratory tracts when breathing, speaking, coughing, and sneezing.[19,20,25,82,84-86] The size distributions include virus-containing small particles that can be distributed readily as aerosols. In one study, the virus was detected in the exhaled breath of COVID-19 patients (16.7 percent, n = 30) more often than on surfaces (5.4 percent, n = 242) or in air samples (and 3.8 percent, n = 26).[87] The single positive air sample was from an unventilated toilet room.

A third line of indirect evidence comes from the modeling of particle dispersion in indoor air, e.g., computational fluid dynamic (CFD) simulations of particle residence times using size distribution data from imaging and air sampling studies. These models demonstrate that the sustained suspension in air of SARS-CoV-2 makes long-range airborne transmission of disease plausible.[4,8,9,69,88-96]

However, there is still dispute in the scientific community about the occurrence and extent of airborne transmission. For instance, an outbreak among three families at separate tables in a restaurant in China has been cited as evidence both for and against airborne transmission.[69,97] Also, transmission did not occur on a 15-hour flight from Guangzhou to Toronto; however, the two infected persons had mild symptoms and wore masks.[98] An initial examination of transmission aboard a cruise ship concluded that the central air conditioning system did not play a role in the spread of the disease because long-range transmission did not occur, and the observed spread could be explained by passenger close contact and fomite transmission within staterooms after a quarantine was imposed.[99] A second analysis concluded that airborne transmission through the ventilation system could explain spread that occurred during the quarantine period because symptomatic infection rates were similar in cabins with and without confirmed cases, the latter included single-occupancy cabins (note: only symptomatic persons were tested during the quarantine period).[100] However, these conclusions are not relevant to central ventilation systems generally because, as a more detailed study of this outbreak pointed out, “cruise ships represent unique built environments with high ventilation rates (VRs) and no air recirculation.”[9] This particular ship provided 100 percent outdoor air, no recirculation, and a very high VR of 9–12 air changes per hour (ACH). This later study, reported in a not yet peer-reviewed modeling paper on the same outbreak, estimated the median contributions of short-range, long-range, and fomite transmission, over multiple models, to be 36 percent, 41 percent, and 21 percent, respectively.[9]

Many have cited the chamber studies discussed above[59,60] as evidence that SARS-CoV-2 can remain suspended in air and infectious for long periods. While replication-competent virus was recovered for up to 3 and 16 hours, the rotating drum used to keep the virus suspended produces conditions unlike typical air movement in buildings. Also, the nebulizer used generates small particles that may not represent the respiratory droplets that humans release, and the chamber temperature and humidity conditions may differ from those generally found indoors.[33,101-103]

Another argument made against airborne transmission is that COVID-19 apparently produces fewer secondary cases in close contacts, even among household members, than other diseases known to be airborne.[5,104,105] The basic reproduction number (R_0) is the average number of other persons that one disease case is likely to infect, in a population with no immunity (from previous infection) and no interventions (social distancing or mask wearing).[106] R_0 is determined by tracing close contacts of cases, and estimates for SARS-CoV-2 range from <1–7, lower than for known airborne infectious agents such as the measles and chickenpox viruses, with R_0 of 9–18 and 2–68, respectively (Appendix 2). However, the current coronavirus's transmissibility is similar to that of SARS-CoV, for which there is evidence of airborne transmission, even though the estimated R_0 for SARS-CoV is only <1–6 (Appendix 2).

To date, few field studies have used culture or other assays to assess viral viability in air,[55,107,108] although studies have documented viable SARS-CoV-2 on contaminated surfaces.[55,60,109] In one of these studies, three viable human respiratory viruses were recovered, but not SARS-CoV-2.[107] Only two of these studies have shown evidence that SARS-CoV-2 was capable of replication.[55,108] In the first study, the large variability in sampling results suggested air concentrations too low to be accurately quantified.[55] In the second, there was a clear progression of virus-induced cytopathic effects in cell culture, the recovered virus could be serially propagated, and the isolated viruses matched that in a newly admitted, symptomatic patient.[108] In addition to issues with detection limits,[110] some air sampling methods and conditions may damage the virus, rendering it nonviable.[51,53,55,101,108,111]

Although viral RNA has been detected in exhaled breath,[72] one study reported that viable SARS-CoV-2 was not detected even when an air sampler was just 10 cm from the chin of a patient with a high viral load when breathing, speaking, and coughing.[111] However, the authors noted that this failure may be explained by the protective design of the patient isolation room.[111] In another case, virus was detected on the surface of a patient's bathroom exhaust air louvre, possibly due to toilet flushing, and in one corridor air sample, but not from four samples of the patient's exhaled air.[54] In this study, surface and air samples from room and rooftop ventilation equipment were also negative. As evidence against airborne transmission, two studies have cited the absence of infection of unmasked susceptible patients or healthcare workers although exposed to a coughing, initially unmasked COVID-19 patient with a high viral load[112] or when susceptible healthcare workers did not use contact or droplet precautions.[113]

While at present the evidence for airborne transmission may be considered incomplete and inconsistent, some have called for equivalent, direct confirmatory evidence that the assumed routes of droplet and fomite transmission are in fact the sole or primary exposure routes outside medical and similar settings.[114] These scientists have asked why a much higher level of evidence is required to demonstrate airborne transmission,[114] which can be reduced, even if not entirely prevented, with appropriate building engineering controls.[41] Given the evidence that persons in crowded and poorly ventilated spaces are at increased risk of exposure to respiratory aerosols,[5,21,69-71] proper ventilation and filtration to prevent or at least reduce airborne transmission should be considered for schools.

Ventilation rates in California schools

Heating, ventilating, and air-conditioning (HVAC) systems can affect airborne contaminant concentrations (and thus indoor exposures) in several ways, including the amount of “clean” *outdoor air* provided to occupied spaces (referred to as the ventilation rate, or VR) and the efficiency of any particle filters in the HVAC system. The more outdoor air that is brought into a building (i.e., the higher the VR), the more indoor air is exhausted from the building. This reduces the indoor concentration of contaminants that are produced indoors, including any small airborne virus-containing or bacterium-containing particles emitted by infected occupants when they breath, talk, cough, or sneeze, as well as air concentrations of any disinfectants or other chemicals used indoors or emitted from building products and furniture.

The VR in a classroom is related to the configuration of the building and ventilation system. California school classrooms include a wide variety of building and ventilation types. “Relocatable” classrooms are prefabricated buildings holding one or more classrooms, usually ventilated by “unit” ventilator systems in each room (approximately 30 percent of California’s K-12 public school classrooms in 2004).[115] Other classrooms are in “site-built” (or “permanent”) school buildings, which can have unit ventilator in each classroom or central ventilation systems for multiple classrooms and other parts of the buildings. Any of these mechanical systems may or may not include conditioning of the air (cooling as well as heating). Classrooms with no mechanical ventilation have “natural” ventilation only, through openable windows and doors. The type of classroom (relocatable vs. permanent) may affect the ventilation method and HVAC equipment commonly chosen. For example, a study of California schools with recently retrofitted HVAC equipment reported that relocatable classrooms predominately used wall-mounted HVAC systems, and permanent classrooms predominately used rooftop units.[116] Another study found that, compared to permanent classrooms, relocatables more often are equipped with packaged HVAC systems with heat pumps, and have wall air handling units, automatic supply fan operation, and windows that open.[115] A deeper understanding of these different features in each type of classroom is important for identifying the most effective and energy-efficient measures for increasing VR.

Particle filters in HVAC systems remove particles from the air supplied by the HVAC system, including both the “fresh” outdoor air and any air recirculated from indoors. The more efficient a filter, the higher the proportion of particles removed. For any filter, the proportion of particles removed varies by particle size, with both larger and smaller particles being the easiest to remove, and the hardest particles to remove being those with intermediate diameter of around 0.3. For example, a filter rated with a Minimum Efficiency Reporting Value (MERV) 14 or higher will on average remove 75 percent or more of particles in the 0.3–1.0 µm size range based on ASHRAE 52.2.[117] For a MERV 13 filter, which is the target minimum filtration level recommended in ASHRAE guidance for reopening schools[41] and the lowest MERV rating for which ASHRAE 52.2 reports removal efficiencies for particles of 0.3–1.0 µm, an average removal of ≥65 percent of 0.3–1.0 µm particles may reasonably be assumed. This assumes that the filter is properly installed and maintained, i.e., with no air bypassing the filter and regular filter replacement. In comparison, a MERV 8 filter is minimally effective at removing particles in the 0.3–1.0 µm size range. Thus, because both higher outdoor air VRs and more efficient filtration of recirculated air in buildings reduce the concentration of indoor-generated small airborne particles, each would lower any long-range transmission of SARS-CoV-2 indoors by these airborne particles. For classrooms without mechanical HVAC systems, i.e., those dependent entirely on openable windows and doors for ventilation, window fans may be used to increase the delivery of the outdoor air to the occupied space (but if used, should be configured not to increase air movement near the occupants). With natural ventilation, filtration is still possible if portable air cleaners are used within the room to remove particles in the air. Portable air cleaners can also be used in rooms with HVAC systems to further increase particle removal.

The California Building Standard Codes (Cal. Mechan. Code [CMC], Title 24, Part 4–, and Cal. Energy Code [CEC], Part 6) require all occupied buildings, including educational facilities, to have ventilation systems designed and installed that are capable of providing at least the code-specified minimum amount of outdoor air ventilation.[118] In addition, the California Education Code requires school districts to maintain schools in good repair, including providing HVAC systems that are functional, supplying an adequate (not specified) amount of air to all classrooms, and maintaining interior temperatures within acceptable ranges.[119] The California Code of Regulations (Title 8, §§ 5142-5143) also include ventilation provisions that apply to schools and other public workplaces; these provisions are applicable for the protection of workers only, not students.[120,121] The regulations require that HVAC systems be maintained and operated to provide at least the quantity of outdoor air required by the State Building Standards Code in effect at the time the building permit was issued. They also require that HVAC systems be operated continuously during working hours, with stated exceptions, and require the regular replacement or cleaning of filters to prevent significant reductions in airflow.

However, while the *types* of ventilation typically used in California schools are known, little is known about the actual *numbers* of each specific ventilation type in current California schools, due to the lack of any state-wide assessment of school facilities.[122] For the same reason, even less is known about the operation and conditions of these systems.[122] According to a recent nationwide survey, 41 percent of public school districts in six states, including California, needed updating or replacement of HVAC systems in at least half of their schools; HVAC systems were the leading building system or feature of concern.[122] Nationwide, inadequate school funding poses challenges for correcting these problems.

Currently, little to no information is available on how classroom VRs and filtration influence the risk of acquiring COVID-19 in schools generally, and how adequately the current VRs and filtration in California classrooms are protecting students from airborne transmission. However, several existing studies have documented that the ventilation in California classrooms is usually inadequate, with most classrooms not providing even the minimum 7 L/s-person VR specified in California building codes.[116,118,123,124] For air-conditioned California elementary school classrooms, 25 percent had VRs less than 2-L/s-person and 5 percent less than 1.4 L-s/person.[124] This study of VRs and illness absence in California elementary schools suggested that increasing classroom VRs above the State standard might not only substantially decrease illness absence (−1.6 percent for each additional 1 L/s-person of VR), but also could produce economic benefits far exceeding the cost of providing the increased ventilation. Specifically, the study estimated that increasing classroom VRs from their current low level to the State VR standard would decrease illness absence by 3.4 percent and would increase attendance-linked State funding by $33 million annually, while increasing energy costs by only $4 million.[124] Despite these and related findings on low VRS in schools, efforts to increase VRs in California classrooms have had limited success.[125] The new challenge of reducing SARS-CoV-2 transmission in schools may bring increased attention to this important ongoing problem and new motivation to improve ventilation and filtration in schools. Improvements in these systems would also reduce all indoor particle concentrations and improve indoor air quality in classrooms in general.

Model description and input parameters

This paper introduces a model to provide rough initial estimates of the relationships of classroom VRs and filtration to the component of occupant infection probability due to assumed long-range airborne transmission of small aerosols. Our objectives are to illustrate the importance of providing adequate ventilation and filtration (in addition to social distancing, wearing masks, and intensified cleaning and disinfection) for safe school operation when reopening during the ongoing COVID-19 pandemic and to provide initial guidance for making decisions about these systems. In order to estimate the relative risks[126] of airborne transmission for classroom with different conditions, we constructed a simple interactive model in a spreadsheet. The model estimates the probability of infection (Appendix 3), based on a commonly used equation and the best available knowledge about the characteristics of California classrooms and of respiratory particles containing SARS-CoV-2. We then compared the relative rather than absolute risks for different scenarios, as this reduces the uncertainty related to specific assumptions about the rate of infectious respiratory emissions from infected persons[127] and focuses on the relative reductions in infection risk from the various ventilation and air filtration scenarios. It should be noted that this model is not meant to address the *overall* probability of infection because it does not account for very close-range transmission by infectious particles (whether large droplets or small aerosols), nor for transmission through fomites. These other two transmission modes should *not* be influenced by ventilation and filtration. Further limitations are discussed at the end of this section.

Wells-Riley equation and modification

One widely used method for modeling the risk of airborne transmission in enclosed environments is the Wells–Riley equation.[128] The model (Equation 1) is based on the concept of a "quantum of infection," whereby the rate of generation of infectious airborne particles (or *quanta*) is used to model the likelihood of a susceptible individual in a steady state, well-mixed, indoor environment being exposed to infectious particles and subsequently succumbing to infection.[129]

$$P_{infection} = \frac{N_c}{N_S} = 1 - e^{-\frac{Iqpt}{Q}} \quad (1)$$

where
$P_{infection}$ = the probability of infection
N_C = number of infected cases
N_S = number of susceptible individuals
I = number of infectious individuals
p = pulmonary ventilation rate of a person (m^3/h)
q = quanta generation rate produced by one infector (quanta/h)
t = exposure time (h)
Q = outdoor air ventilation rate (assuming clean outdoor air) (m^3/h).

Equation 1 only accounts for the role of outdoor air ventilation (Q). However, the reduced indoor concentration of airborne particles by HVAC filters and portable air cleaners may be considered as additional "equivalent" ventilation. To account explicitly for the potential risk reduction by filtration, we adopted a modified form of the Wells–Riley equation similar to Stephens[129] (Equation 2).

$$P_{infection} = \frac{N_c}{N_S} = 1 - exp\left[\frac{-Iqpt}{V(\lambda_{ventilation} + \lambda_{infiltration} + k_{filtration} + k_{deposition})}\right] \quad (2)$$

where
V = room volume (m^3)
$\lambda_{ventilation}$ = outdoor air change rate (i.e., infectious particle removal rate due to ventilation, assuming clean outdoor air (Q/V, h^{-1})
$\lambda_{infiltration}$ = air infiltration rate, i.e., infectious particle removal rate due to infiltration from the building envelope, assuming clean outdoor air (h^{-1})
$k_{filtration}$ = infectious particle removal rate due to filtration, i.e., HVAC filter or portable air cleaner (h^{-1})
$k_{deposition}$ = infectious particle removal rate due to deposition on surfaces (h^{-1}).

For a filter installed in a central HVAC system, the filtration removal rate ($k_{filtration}$) depends on the rate of airflow through the HVAC filter (Q_{filter}), the system operational time fraction (f_{HVAC}), and the removal efficiency of the filter (η_{filter}) (Equation 3a).

$$k_{filtration} = f_{HVAC} \frac{Q_{filter}\eta_{filter}}{V} \quad \text{(3a–for HVAC filter)}$$

where
f_{HVAC} = fractional HVAC operation time (%)
Q_{filter} = airflow rate through filter (m^3/h)
η_{filter} = removal efficiency of HVAC filter for infectious particles (%).

If a portable (in-room) cleaner with a High-Efficiency Particle Air (HEPA) filter is used, an equivalent filtration removal rate can be calculated from the Clean Air Delivery Rate (CADR) of the air cleaner[130] (Equation 3b).

$$k_{filtration} = \frac{CADR}{V} \quad \text{(3b–for portable air cleaner)}$$

where
$CADR$ = clean air delivery rate of a portable air cleaner for infectious particles (m^3/h).

Both the removal efficiency of an HVAC filter (η_{filter}) and the CADR of a portable air cleaner are particle-size dependent. Estimation of these parameters requires detailed knowledge of the device's removal efficiency for indoor particles in general as well as the size distribution of virus-containing particles.

In addition to remaining airborne, infectious particles may also deposit onto and re-suspend from indoor surfaces. Particle deposition and resuspension are dynamic processes that may be influenced by many factors, such as particle size and density, room characteristics, surface characteristics and areas, and human activity level. As an initial, "zero-order," estimation, we used the measured particle deposition loss rate data for residences that are summarized by Dillon et al.[131]

Model implementation

We implemented the model described above in interactive spreadsheets, including one simplified version with reduced user inputs, one sheet with default values for additional hidden parameters, and a supplementary sheet with a simplified MERV table (Appendix 3). The sheet with simplified user inputs requires information for basic parameters (e.g., floor area, number of occupants, and time spent in room, and simplified choices of VR, MERV rating of HVAC filter, and CADR of portable air cleaner), thus is usable by anyone with general knowledge about a school classroom. The default values in the second spreadsheet can also be modified if users have more detailed knowledge of building operations and airborne transmission, including occupant breathing rate for different age groups and activity levels, quanta generation rate and size distribution of infectious particles, fractional operation time of the HVAC system, total supply airflow rate and the outdoor air fraction, and user-defined filter removal efficiency. Another sheet contains default removal efficiencies of MERV-rated filters that are automatically linked to the filter MERV rating a user enters in the simplified version. Additionally, we included a spreadsheet for a reference case (defined in the following section "Analysis and results of classroom scenarios") so that the RRs of infection for other ventilation and filtration conditions can be calculated. Again, although the model estimates absolute risk of infection for specific classroom conditions, we focused on the RRs from comparing different conditions, because the current uncertainty about inputs such as rate of quanta generation makes estimates of absolute infection risk very uncertain.

Determination of default model input parameters

- Room height (*H*)
  We used a ceiling height of 3.0 m, which is typical for a classroom, as a default.

- Pulmonary ventilation rate (*p*)
  Table 1 shows the range of eight-hour breathing rate estimates from the California Office of Environmental Health Hazard Assessment.[132] [132] We used a value of 0.5 m^3/h (or 4.0 m^3/8-h, the average of the mean 8-h breathing rates for 2 to <16 years of age for sedentary & passive and light intensity activities) as a default.

Table 1. Eight-hour breathing rate (m^3/8-h) point estimates for males and females combined[132]

	0 to <2 years	2 to <9 years	2 to <16 years	16 to <30 years	16–70 years
Sedentary & Passive Activities[a] (MET< 1.5) Mean	1.86	2.24	***2.37***	2.33	2.53
95th Percentile	2.69	2.99	3.20	3.23	3.34
Light Intensity Activities[b] (1.5 < METs ≤ 3.0) Mean	4.61	5.44	***5.66***	5.72	6.03
95th Percentile	6.51	7.10	7.52	7.75	7.80
Moderate Intensity Activities[c] (3.0 < METs ≤ 6.0) Mean	8.50	10.20	10.84	12.52	12.94
95th Percentile	12.36	13.47	14.52	18.08	18.07

[a] Resting

[b] Activities within a classroom

[c] Activities during recess and some physical education classes

- Quanta generation rate (*q*)
  Very limited data are available for SARS-CoV-2 and the estimates vary widely. Buonanno et al. identified three emission rates: (i) low, <1 quantum/h; (ii)

intermediate, ≤100 quanta/h;[133] and high, >100 quanta/h.[134] A study of healthcare workers attending COVI-19 patients estimated a transmission rate of 0.225 quanta/h.[135] Another analysis using data from two outbreaks estimated four emission rates of 0.36, 2.4, 4.9, and 31 quanta/h for oral breathing at rest, oral breathing during heavy activity, speaking during light activity, and singing or speaking loudly during light activity, respectively.[136] Dai and Zhao estimated a generation rate of 14–48 quanta/h.[137] Miller et al. modeled a super spreader outbreak among a rehearsing choral group and estimated a mean quanta emission rate of 970.[138] Quanta generation rate varies with the type of vocalization, being higher for singing and coughing than for speaking.[139] Here, we assumed that individuals with persistent cough would not be present in the classroom and thus used a value representative of speaking (i.e., 1 quantum/h). Appendix 2 provides a more complete summary of quanta generation rates for common aerosol transmissible diseases.

WHO and CDC have recognized the role of mask use as a source control measure and its effect in preventing transmission from infected individuals to others. We considered a reduction of the quanta generation rate in the model to account for the effect of cloth mask wearing, using an assumed reduction of 50 percent.[140] We also conservatively assumed 0 percent inhalation protection provided by cloth mask wearing.

- Fractional operation time of HVAC system (f_{HVAC})
  We used 100 percent as a default, assuming that the HVAC system operates and provides ventilation and filtration continuously while the room is occupied.

- Outdoor air ventilation rate ($\lambda_{ventilation}$)
  Title 24—in both Part 4 (CMC) and Part 6 (CEC)—requires that buildings with no mechanical supply of outdoor air have windows with a total openable area of at least 4 percent of the floor area.[118] While Title 24 permits openable windows for outdoor air ventilation as an alternative to a mechanical supply of outdoor air, openable windows do not ensure that adequate outdoor air is provided to the space, as the amount of outdoor air entering through windows depends on the outdoor wind speed and the indoor-outdoor temperature difference. In addition, windows are often closed when the outdoor temperature is too cold or hot or the level of outdoor noise is too great, precluding any outdoor air from entering through the windows.

  As an alternative to openable windows, both the CMC and CEC require a mechanical supply of outdoor air. Both list code-required mechanical outdoor air VRs for a total of 14 educational facility space types, including classrooms, science laboratories, art classrooms, wood/metal shops, and music/theater/dance rooms. However, the code-required mechanical outdoor air VRs per the CMC and CEC differ. The CEC-required outdoor air VRs are greater than the CMC requirements for 8 of 14 educational spaces, with 5 of them having a ventilation requirement that is equal or greater by 10 percent.

The interactive spreadsheet allows the user simply to enter a VR per person (in units of L/s-person) or per floor area (in units of L/s-m^2) that is either calculated based on the above code requirements or obtained from actual measurements. We provide five example calculations in the following section "Analysis and results of classroom scenarios."

This model is for classrooms with a mechanical supply of outdoor air and cannot be used for classrooms with no mechanical supply of outdoor air but only openable windows, as the VRs in these classrooms are highly variable depending on local weather conditions.

- Air infiltration rate ($\lambda_{infiltration}$)
  Infiltration refers to air leakage through unintentional openings in the exterior envelope of a building, driven by wind, indoor-outdoor temperature difference and equipment operation.[141] Little to no data are available for the air infiltration rates in classrooms with no mechanical ventilation and all windows closed. Here we assumed an infiltration rate of 0.2 ACH, which is close to the median infiltration rate reported for occupied homes with no mechanical ventilation and windows closed in a California new home study.[142] We also assumed that the mechanical systems are "balanced," and that this small amount of infiltration is simply additive to the mechanical-ventilated outdoor air.

- Airflow rate through a filter (Q_{filter})
  Equation 2 assumes that the air entering the filter is the recirculated air, with the average indoor concentration of infectious particles. Depending on the ventilation system type as well as the thermal load of the classroom, the total supply airflow rate, and the fraction of recirculated air in the supply air may vary. We assumed a constant air volume system with a total supply airflow rate equivalent to 6 ACH (i.e., 5.0 L/s-m^2 or 16.5 L/s-person for the hypothetical classroom defined in this paper) as a default. The recirculated airflow rate was then calculated as the difference between the total supply air and outdoor airflow rates.

- Removal efficiency of a HVAC filter for infectious particles (η_{filter})
  Commercial HVAC filters often have a MERV rating. These MERV ratings are established based on size-resolved removal efficiencies for 0.3–10 μm particles measured in a laboratory setting according to ASHRAE Standard 52.2.[117] A table of filter MERV ratings and associated removal efficiencies is available in ASHRAE Standard 52.2 (Appendix Table J-2). However, it does not report removal efficiencies for the particle size ranges of 0.3–1 μm and 1–3 μm for low MERV-rated filters. Meanwhile, Dillon and Sextro summarized the single-pass filtration efficiency distributions for 0.1–μm, 0.3–μm, 1–μm, 3 μm, and 10–μm particles for a range of filters (i.e., MERV 0, 5, 7–8, 11–12, and 14–15), considering efficiency variation both (a) within similarly rated filters and (b) due to filter loading over the filter lifetime.[143]

Table 2 summarizes the removal efficiencies of MERV-rated filters that we assumed for particles in three size ranges—0.3–1, 1–3, and 3–10 µm. To be conservative, we used the lower bound of the minimum composite average particle size removal efficiencies specified in ASHRAE 52.2 Table J-2 (i.e., apply to MERV 14–16 filters for 0.3–1 µm particles, MERV 10–16 filters for 1–3 µm particles, and MERV 5–16 filters for 3–10 µm particles). We also assumed a filtration efficiency of 65 percent for MERV 13 for 0.3–1 µm particles, 40 percent for MERV 9 for 1–3 µm particles, and 10 percent for MERV 1–4 filters for 3–10 µm particles. For low MERV-rating filters that do not have removal efficiencies specified in ASHRAE 52.2 Table J-2 (i.e., MERV 1–12 filters for 0.3–1 µm particles, and MERV 1–8 filters for 1–3 µm particles), we used the 50th percentile of the cumulative filtration efficiency distributions ($P_{50\%}$) from Dillon and Sextro.[143] For filters of MERV 1–12, we used the average of $P_{50\%}$ for 0.3 and 1 µm for particles in the size range of 0.3–1 µm. For filters of MERV 1–8, we used the average of $P_{50\%}$ for 1 and 3 µm for particles of 1–3 µm. If $P_{50\%}$ was not given for a specific MERV rating filter (i.e., MERV 1–4, 6, 9 and 10), we used the value for the closest lower MERV-rating filter. To make a conservative estimate, we further divided these $P_{50\%}$ values by a factor of three.

Table 2. Assumed removal efficiencies of various MERV filters for particles in three size ranges

HVAC filter MERV rating	Assumed removal efficiency (%) 0.3–1.0 µm	Assumed removal efficiency (%) 1.0–3.0 µm	Assumed removal efficiency (%) 3.0–10.0 µm
1	0	0	10
2	0	0	10
3	0	0	10
4	0	0	10
5	2	8	20
6	2	8	35
7	15	28	50
8	15	28	70
9	15	40	85
10	15	50	85
11	19	65	85
12	19	80	90
13	65	90	90
14	75	90	90
15	85	90	90
16	95	95	95

As for the size distribution of virus-containing particles in room air, very limited data are available for SARS-CoV-2. Stephens, largely based on work with influenza A from Lindsley et al.,[144] assumed a particle size distribution of infectious particles: 15 percent, 25 percent, and 60 percent in 0.3–1, 1–3, and 3–10 µm size ranges, respectively. Based on recent air sampling results for SARS-CoV-2,[53,58] we assumed the following slightly different proportions:

  - 20 percent of infectious particles in the 0.3–1 µm size range
  - 30 percent in the 1–3 µm size range
  - 50 percent in the 3–10 µm size range.

The viral load in respiratory secretions, e.g., sputum, saliva, and fluid accumulated in the lungs because of pneumonia, likely varies at different stages of infection. However, knowledge of viral load is not needed when the fractional distribution of respiratory particles can be estimated, assuming the virus is distributed uniformly throughout respiratory secretions and, therefore, throughout exhaled particles.

The spreadsheet calculates a size-weighted average filtration efficiency for infectious particles based on the MERV rating of the filter that a user enters.

- Clean Air Delivery Rate (CADR) of portable air cleaners for infectious particles
  The CADR of a portable air cleaner indicates the volume of filtered air directly delivered to the room. A portable air cleaner, as certified by the Association of Home Appliance Manufacturers (AHAM), often lists three CADR numbers—one for tobacco smoke (0.09–1.0 µm), one for dust (0.5–3 µm), and one for pollen (5–11 µm).[145] With the very limited available data for the size distribution of SARS-CoV-2 containing particles in room air, we simply assumed the following and directly utilized the CADR numbers for tobacco smoke, dust, and pollen when estimating the effect of using a portable air cleaner:
  - 20 percent of infectious particles in the 0.09–1.0 µm tobacco smoke size range
  - 30 percent in the 0.5–3 µm dust size range
  - 50 percent in the 5–11 µm pollen size range.

  The spreadsheet assumes that the portable air cleaner operates continuously and calculates a size-weighted average filtration efficiency for infectious particles based on the CADR numbers for the three size fractions that a user enters.

- Infectious particle removal rate due to surface deposition ($k_{deposition}$)
  We assumed the same particle size bins used for HVAC filter MERV ratings for simplicity. We used the 50th percentile of the cumulative frequency distributions of particle deposition loss rates ($P_{50\%}$) from Dillon et al.[131] For particles in the size range of 0.3–1 µm, we used the average of $P_{50\%}$ for 0.3 and 1 µm. For particles of 1–3 µm, we used the average of $P_{50\%}$ for 1 and 3 µm. For particles of 3–10 µm, we used the average of $P_{50\%}$ for 3 and 10 µm. To make a conservative estimate, we further divided them by a factor of three. The $k_{deposition}$ determined was 0.14, 0.29 and 0.91 h^{-1} for infectious particles in the size range of 0.3–1, 1–3, and 3–10 µm, respectively, which led to a size-weighted removal rate of 0.57

h^{-1} with the assumed size distribution (i.e., 20 percent, 30 percent, and 50 percent for infectious particles of 0.3–1, 1–3, and 3–10 μm, respectively).

Model limitations

It is important to note the following limitations to be aware of when using the model:

- The model assumes that the indoor air has reached steady state with continuous room occupation and is well-mixed (i.e., infectious airborne particles are evenly distributed in the occupied space).
- The model assumes the same default quanta generation rate for all infected persons and a default pulmonary ventilation rate of 0.5 m^3/h for all occupants. Actual values may differ due to differences in activity level and the effect of age on COVID-19 transmission and susceptibility.
- The model does not consider additional limiting factors that may be common in practical applications. For instance, filter bypass can result from improper filter fitting, design, or installation within HVAC units. Filter ratings also are based on ideal modeled conditions and not necessarily real-world conditions. These factors all can reduce the actual benefits of filtration.
- Outdoor and filtration airflow rates may be less than expected due to deferred HVAC maintenance or incorrect operation, resulting in problems such as closed outdoor air dampers, obstructed outdoor air inlet screens, dirty filters that are past their service life and are restricting airflow , fan controls not set for continuous operation during classroom hours (e.g., thermostat fan switches set for “auto” or “off” and not for “on”), improperly set HVAC start/stop time clocks, or out-of-calibration carbon dioxide (CO_2) sensors for demand-control ventilation (DCV) systems.
- The default model input parameters were based on current information about the possibility of airborne transmission of SARS-CoV-2. However, knowledge of the dominant transmission routes, quanta generation rates, and the size-distribution of infectious particles is rapidly evolving.

Analysis and results of classroom scenarios

Defining the reference case

We defined a hypothetical classroom environment (see Table 3 for basic user input parameters), and a reference case that operates at the code-required minimum VR and uses a MERV 8 filter. We used the larger of the Title 24 CMC and CEC code-required minimum outdoor air VRs for classrooms (age ≥9 years): the CEC code requirement for the greater of 7 L/s-person or 1.93 L/s-m^2.[118] Thus, for the modeled 89.7-m^2 classroom with 27 occupants, this code-required minimum VR is 7 L/s-occupant.

Table 3. Basic input parameters used for a hypothetical classroom environment

Parameter	User input value	Units
Room floor area[a]	89.3	m^2
Room occupancy[a]	27	person
Exposure time[b]	5	h
Number of infected individuals	1	person
Total number of non-susceptible occupants, e.g., current infection or immune (previous recovery or vaccination)	1	person

[a] The floor area and occupancy of a school classroom defined in a *Standard Method for the Testing and Evaluation of Volatile Organic Chemical Emissions from Indoor Sources Using Environment Chambers* were used.[146] It was based on the dimensions of a typical relocatable classroom.

[b] Assume a total school time of 7 h (i.e., 8 a.m.–3 p.m.) with approximately 70 percent of the time in a classroom.

A focus on relative risk (RR)

There are wide ranges and large uncertainties of quanta generation rates reported in the literature, so we first conducted a sensitivity analysis to better understand the impact of this parameter on the modeling results. Because we assumed only asymptomatic infected individuals, we considered a quanta generation range of 0.1–100 quanta/h. Results (Figure 2) indicate that for the exposure scenarios considered, the predicted probability of infection increases nearly linearly with an increase in quanta generation rate. In Figure 2, we also plotted “inhaled quanta” as the second x-axis, which is the combination of all the variables in the exponential term ($Iqpt/Q$) in Equations (1) and (2). Although the probability of infection would gradually increase non-linearly and eventually begin to plateau (i.e., approach 100 percent) with the increase of “inhaled quanta,” the “inhaled quanta” for the classroom scenarios we modeled in this paper are predominantly in the lower range (i.e., < 0.2), in which the probability of infection increases approximately linearly with the increase in “inhaled quanta.”

The quanta-generation rate of SARS-CoV-2 from infected individuals has still not been determined and estimates have varied widely given the outbreaks that have been studied (Appendix 2). To reduce the importance of the specific default quanta generation rate used in the models (1 quantum/h) on the interpretation of modeling results, we report the *relative risks*[126] of infection for various ventilation and filtration conditions, compared to the reference case.

Besides the quanta generation rate, the assumed infectious particle size distribution in indoor air is also a key model parameter that strongly influences the absolute risk of infection but has large uncertainty. However, Azimi and Stephens have modeled a hypothetical office environment and have demonstrated that this uncertainty could be largely cancelled out in RR estimates.[127] They showed that, in modeling infection risk from aerosols, changing assumed values for infectious particle size distribution or quantum-emission rate greatly influenced absolute risks but had small effects on RRs.

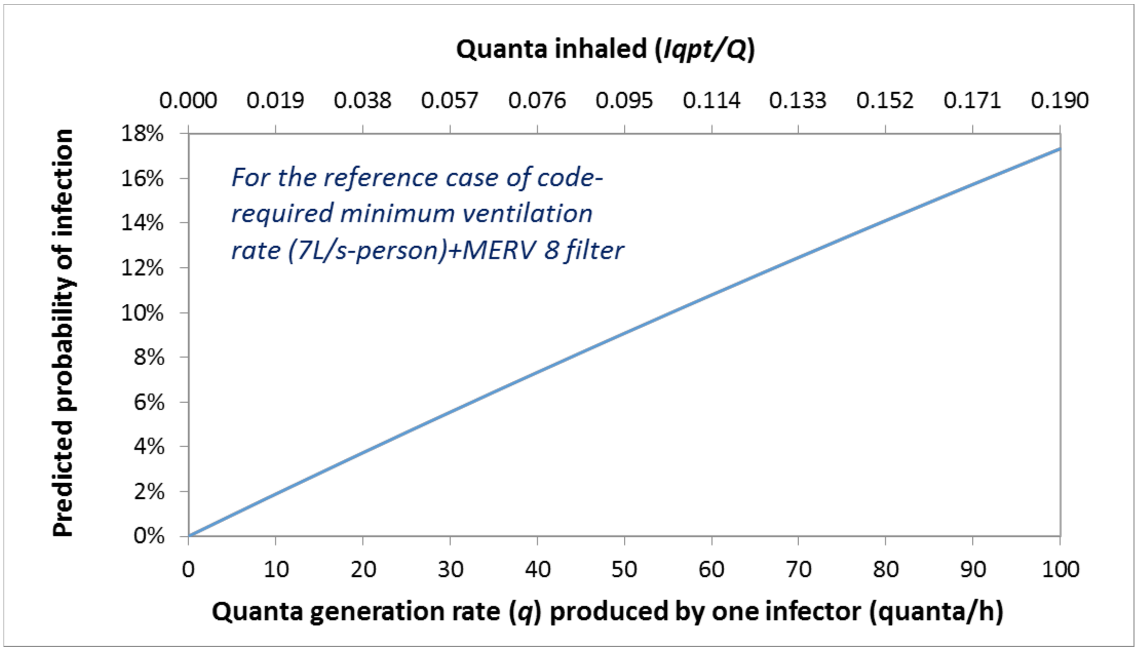


Figure 2. Risk of SARS-CoV-2 infection in a hypothetical classroom, based on input parameters defined in Table 3 and other default values defined in this paper for a reference case (code-required minimum ventilation rate (VR = 7 L/s-person) and a MERV 8 filter).

Risk reduction from intervention strategies

We analyzed four series of scenarios as initial estimates of the potential effects of ventilation, additional filtration, additional portable air cleaner use, and mask-requirement policies in reducing SARS-CoV-2 transmission indoors (Table 4).

Table 4. Classroom scenario analysis for different ventilation, filtration, and mask-wearing conditions. Scenario 1: Poor ventilation (current median for air-conditioned classrooms, 2.8 L/s-person,[124] 40% of Title 24 code requirement). Scenario 2: Somewhat under-ventilated (current median for classrooms with recently retrofitted HVAC equipment, 4.8 L/s-person,[116] approximately 70% of Title 24 code requirement). Scenario 3: Meets Title 24 code requirement of 7 L/s-person. Scenario 4: Well above Title 24 minimum code requirement, 10.5 L/s-person, 150% of Title 24 code requirement

Scenario case number	Enhanced filtration: Upgrade to MERV 13 filter	Enhanced filtration: With additional portable air cleaner(s)[a]	Teacher & students wear masks[b]	Relative risk of infection, compared to reference case[c]
1a	No	No	No	120%
1b	No	No	**Yes**	60%
1c	**Yes**	No	No	82%
1d	**Yes**	No	**Yes**	41%
1e	No	**Yes**	No	60%
1f	No	**Yes**	**Yes**	30%
2a	No	No	No	110%
2b	No	No	**Yes**	55%
2c	**Yes**	No	No	80%
2d	**Yes**	No	**Yes**	40%
2e	No	**Yes**	No	58%
2f	No	**Yes**	**Yes**	29%
3a[c]	***No***	***No***	***No***	***100%***
3b	No	No	**Yes**	50%
3c	**Yes**	No	No	79%
3d	**Yes**	No	**Yes**	39%
3e	No	**Yes**	No	55%
3f	No	**Yes**	**Yes**	27%
4a	No	No	No	88%
4b	No	No	**Yes**	44%
4c	**Yes**	No	No	76%
4d	**Yes**	No	**Yes**	38%
4e	No	**Yes**	No	51%
4f	No	**Yes**	**Yes**	25%

[a] AHAM recommends choosing a portable air cleaner with a tobacco smoke CADR (in units of ft^3/min or CFM) at least 2/3 of the room area (in units of ft^2). The suggested CADR for the classroom defined in Table 3 is 1087 m^3/h (or 640 ft^3/min), which was used in the scenario analysis.

[b] A 50% reduction in quanta generation rate was assumed if teacher and students wear masks.

[c] Case 3a is the reference (i.e., with code-required minimum VR and a MERV 8 filter).

In addition to the code-required minimum VR scenario, we also modeled three other VR scenarios (two with less and one with more than the code VR). In scenario 1, 2.8 L/s-person is the median VR reported in Mendell et al. for California classrooms with AC units (based on 3rd–5th grade classrooms in three California school districts)[124] and 40 percent of the Title 24, Part 6, CEC code-required minimum. In scenario 2, 4.8 L/s-person is the median VR from Chan et al. for California classrooms with recently retrofitted HVAC equipment[116] and approximately 70 percent of the code-required minimum. In scenario 3, 7 L/s-person is the current code-required minimum;[118] and in scenario 4, 10.5 L/s-person is 150 percent of the code-required minimum. Each ventilation scenario uses a MERV 8 filter (a) as a baseline filtration level.

For enhanced HVAC filtration, MERV 13 filters were used (c and d); these offer both reasonable removal efficiency for the hardest to remove particle sizes, as well as practicality in terms of cost and pressure drop. Use of MERV 13 or better filters where possible also is recommended in ASHRAE's school reopening guidance.[41,147] For enhanced particle filtration, a CADR of 1087 m^3/h (or 640 ft^3/min) was assumed if using portable air cleaner(s) (e and f). This CADR number is based on the floor area of the hypothetical classroom and AHAM's 2/3 Rule for choosing a portable air cleaner. For the model calculations in this paper, we have assumed a CADR of 1087 m^3/h for each of the particle size test ranges: tobacco smoke (0.09–1.0 μm), dust (0.5–3 μm), and pollen (5–11 μm). We note that having the same CADR for all three particle size ranges is only applicable to portable air cleaners with HEPA filters. For air cleaners with less efficient, non-HEPA filters, the CADR will not be the same for the three particle size ranges (smoke is less than dust removal, and dust is less than pollen removal) and the specific CADRs can be input into the model. These assumed values are mainly for illustration purposes.

Figure 3 shows the results of analyses under the specific assumptions and conditions defined for this hypothetical classroom, which are also reported in the "Relative risk of infection" column in Table 4. A poorly ventilated classroom (1a) could increase the relative probability of infection by 20 percent compared to a classroom with ventilation that meets the minimum code requirement (3a). Wearing a mask (with an assumed 50 percent reduction in quanta generation rate) could lower the relative probability by approximately half for each ventilation scenario (b vs. a). With the additional upgrade of the HVAC filter from MERV 8 to MERV 13 (4d, 3d, 2d and 1d), the relative probability of infection from long-range, small particles could reduce to 38–41 percent of that for the reference case. With the use of portable air cleaners (with AHAM-recommended CADR) in addition to mechanical ventilation with MERV 8 filter (4f, 3f, 2f and 1f), the relative infection probability could reduce to 25–30 percent of that for the reference case. It should be noted that more than one portable air cleaner may be needed to reach the desired CADR, following AHAM's 2/3 rule,[130] because most commercially available portable air cleaners have CADRs in the range of 170–680 m^3/h (100–400 ft^3/min).

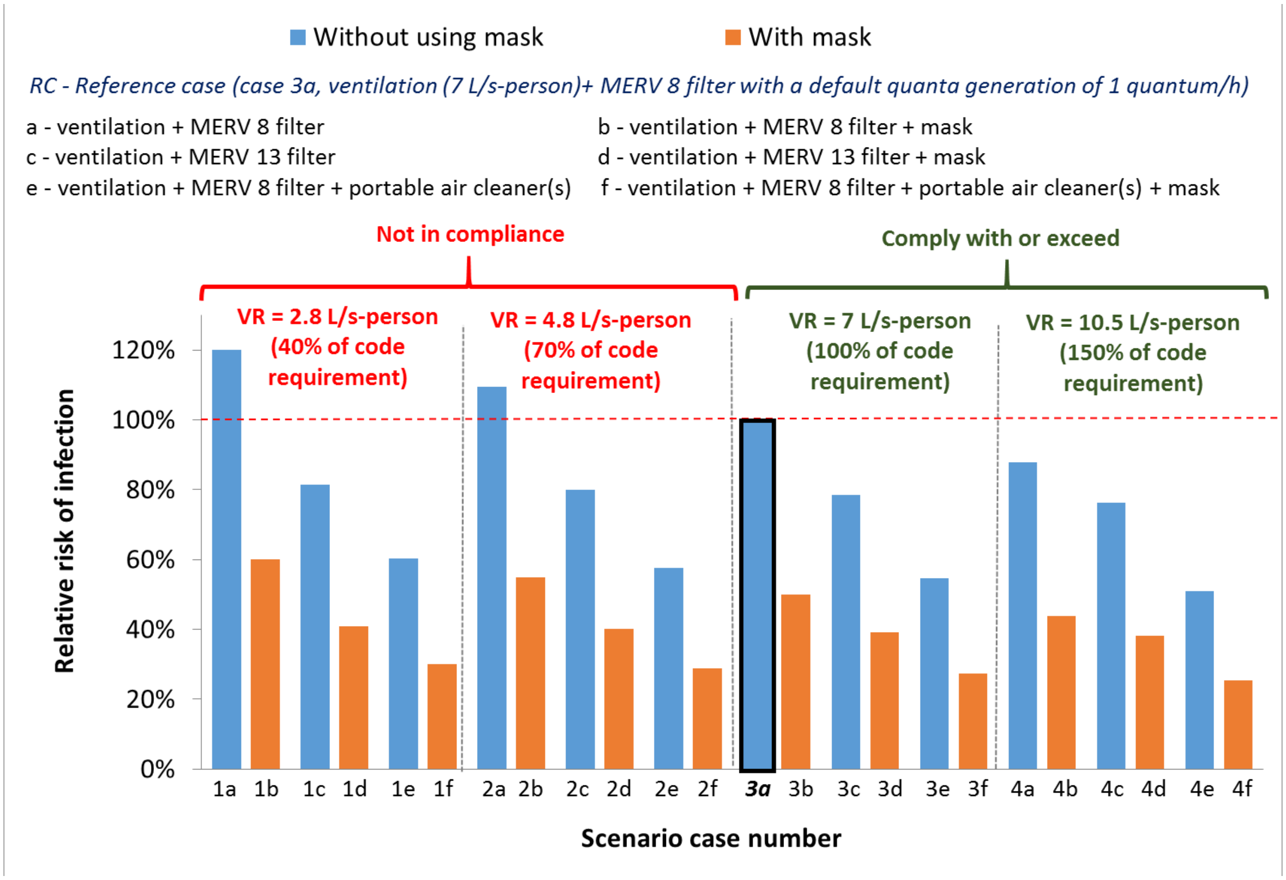


Figure 3. Relative risks of SARS-CoV-2 infection in a hypothetical classroom, compared to the reference case (3a), based on input parameters defined in Tables 3 and 4 and other default values defined in this paper for four ventilation rates: two below (scenarios 1 and 2) and two in compliance with (scenarios 3 and 4) California Title 24 ventilation requirements.

Under current model assumptions, mask use is equally or more effective than either of the enhanced filtration strategies in isolation for all modeled ventilation scenarios. It must be noted that this comparison does not consider close-range transmission between occupants, for which masks are the best preventive strategy and HVAC systems will provide little exposure reduction.

A scenario with no classroom ventilation

In addition to the above four ventilation scenarios, we also modeled an extreme “no ventilation” scenario which may occur under the following situations:

- Classrooms have no mechanical ventilation, just openable windows, and the windows are closed (e.g., due to rain, uncomfortable outdoor temperature, outdoor noise, or wildfire smoke).
- Classrooms have a mechanical ventilation system, but the system is unintentionally off because of operation clock error or fan controls are set for

"auto" and not "on," thus operating only when heating or cooling is needed; or intentionally off, such as when a teacher turns off a noisy system in a relocatable classroom so that students can hear better.
- Classrooms have a mechanical ventilation system operating, but the outdoor air damper is unintentionally closed due to damper control failure, or intentionally closed to exclude wildfire smoke.

For this scenario, we considered only 0.2 ACH air infiltration and modeled eight hypothetical cases (E-I to E-VIII) to demonstrate the impact of mask wearing and different filtration strategies (MERV 8 filter, MERV 13 filter, or AHAM-sized portable air cleaner) under this situation. We included the cases of using MERV 8 (E-III and E-IV) and MERV 13 filters (E-V and E-VI) because classrooms with a mechanical HVAC system operating, even if the outdoor air damper is closed, will still benefit from an HVAC filter that removes infectious particles from recirculated air. For these cases (E-III to E-VI), we assumed a total supply airflow rate equivalent to 6 ACH (same as specified before) and 100 percent recirculated air.

Figure 4 shows the results of this analysis. Under the specific assumptions and conditions defined for the no ventilation/air cleaning scenario (E1), the RR of infection from long-range, small aerosols could increase to more than six times as high as that for the reference case (E-I vs. 3a). Wearing a mask (with an assumed 50 percent reduction in quanta generation rate) could lower the RR of infection by approximately half (E-II vs. E-I). In combination with mask-wearing, use of a MERV 8 or MERV 13 filter (i.e., in a classroom where the HVAC system operates continuously with 100 percent recirculated air) or AHAM-sized portable air cleaner(s) (i.e., in classroom with closed windows and no or a non-operating mechanical ventilation system) could further reduce the RR of infection (i.e., compared to the reference case) to 69 percent (E-IV), 42 percent (E-VI), and 51 percent (E-VIII), respectively. In our model, results show a significant reduction of infection probability even for the use of a MERV 8 filter, because we assumed only 20 percent of infectious particles are in the 0.3–1 μm size range. These results may change with evolving knowledge on the size distribution of virus-containing particles.

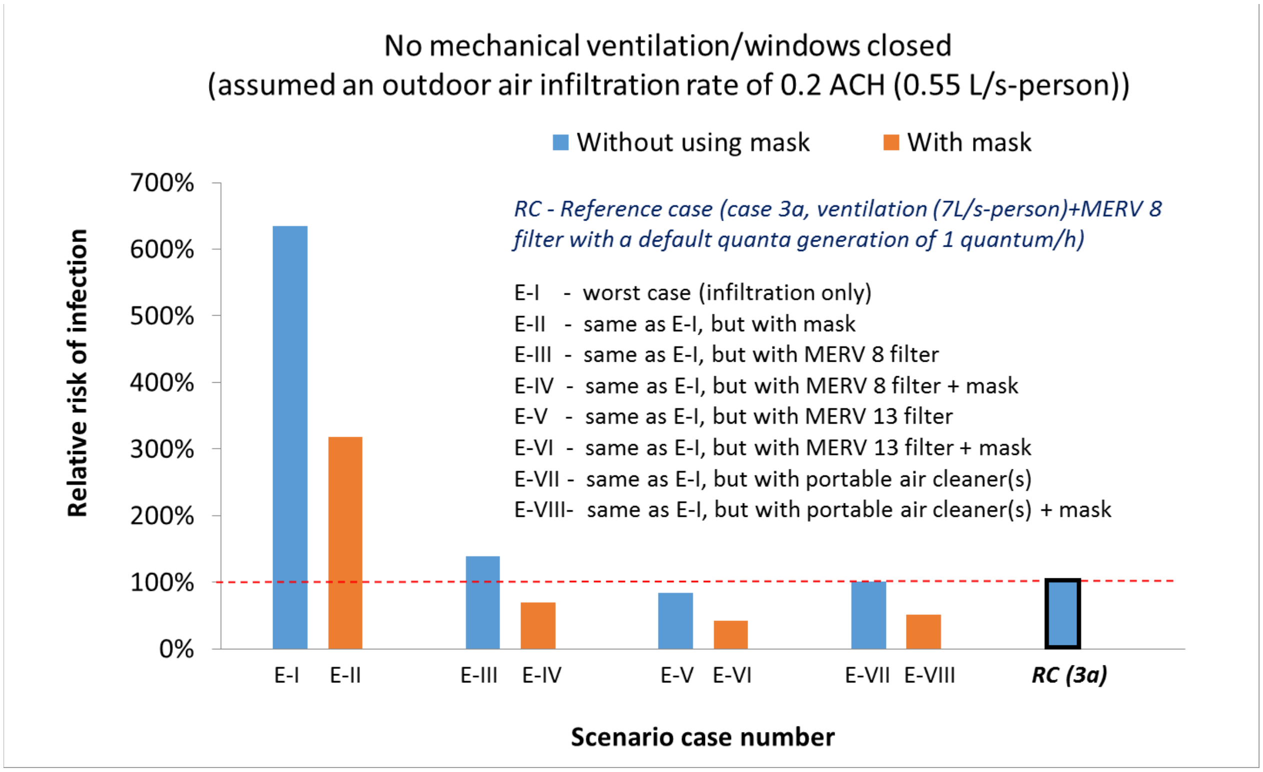
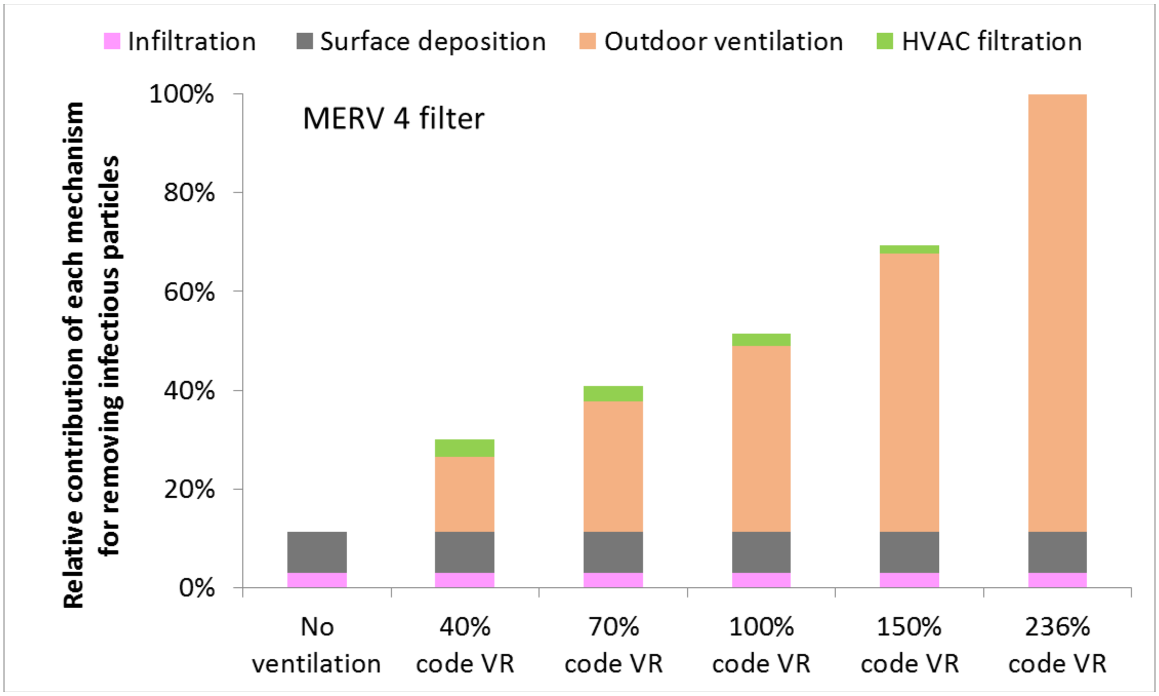


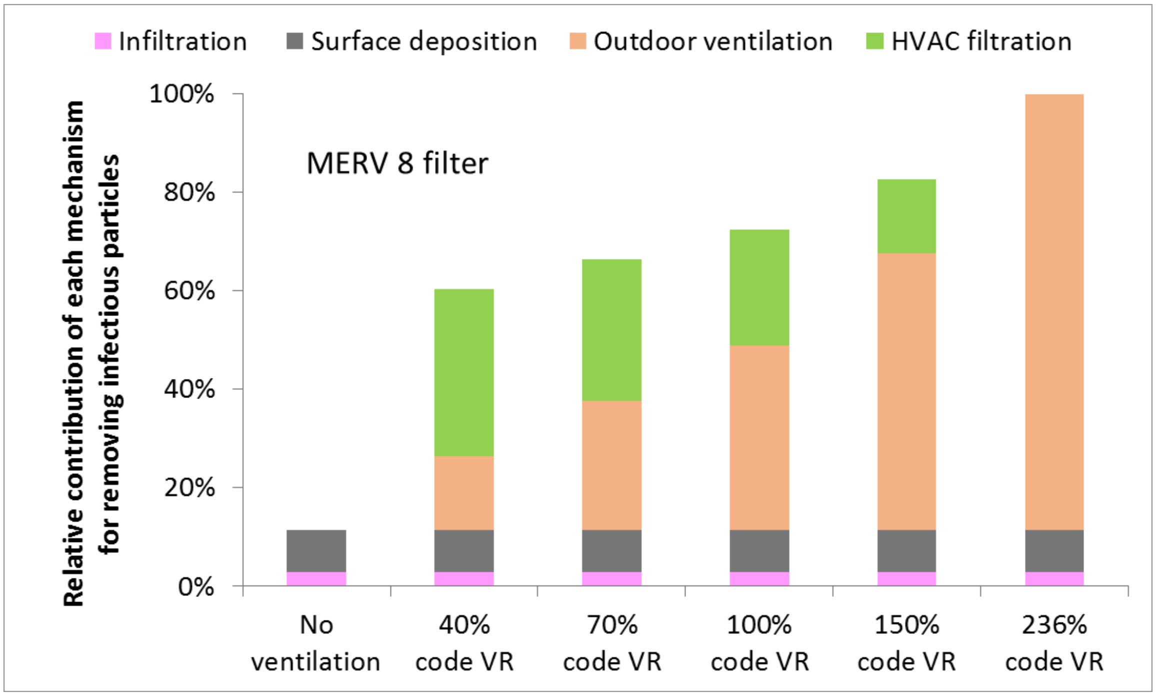
Figure 4. Relative risk of SARS-CoV-2 infection in a hypothetical classroom with "no ventilation," compared to a reference case (RC 3a) and based on input parameters in Tables 3 and 4 and other default values defined in this paper: no filtration (E-I and E-II), MERV 8 filter (E-III and E-IV), MERV 13 filter (E-V and E-VI), and one or more portable air cleaners with a total of 1087 m^3/h CADR (E-VII and E-VIII).

Contribution of each mechanism to total infectious particle removal

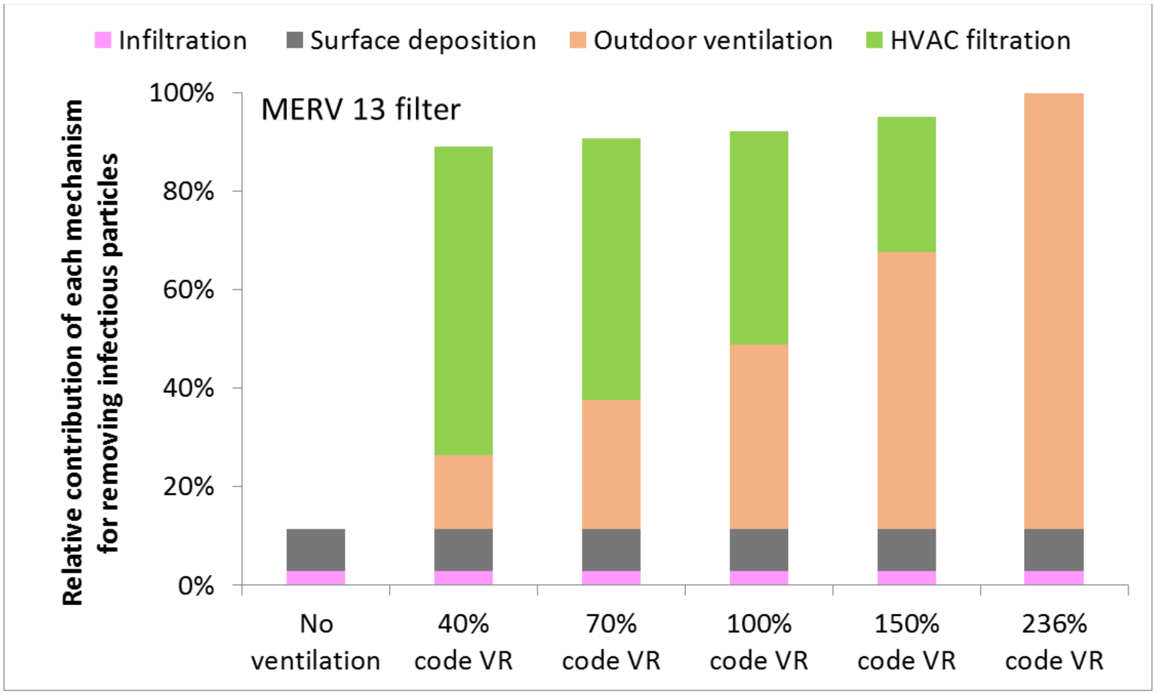
Figures 5a to 5c show the relative contributions of each mechanism for removing SARS-CoV-2 virus-containing particles with increased levels of HVAC filtration (i.e., MERV 4 vs. MERV 8 and MERV 13) under various VRs. We included a MERV 4 filter in the comparison because some classrooms may have a filter less efficient even than MERV 8 (the default filtration level in the reference case). We defined the maximum possible infectious particle removal rate as 100 percent, achievable by the provision of 236 percent of the code-required VR (i.e., 100 percent outdoor air).


Infiltration
Surface deposition
Outdoor ventilation
HVAC filtration
MERV 4 filter
Relative contribution of each mechanism for removing infectious particles
100%
80%
60%
40%
20%
0%
No ventilation
40% code VR
70% code VR
100% code VR
150% code VR
236% code VR

(a)


Infiltration
Surface deposition
Outdoor ventilation
HVAC filtration
MERV 8 filter
Relative contribution of each mechanism for removing infectious particles
100%
80%
60%
40%
20%
0%
No ventilation
40% code VR
70% code VR
100% code VR
150% code VR
236% code VR

(b)



(c)

Figure 5. Relative contributions of each mechanism for removing SARS-CoV-2 virus-containing particles with increased levels of HVAC filtration in a hypothetical classroom under various ventilation rates (VR), based on input parameters defined in Tables 3 and 4 and other default values defined in this paper, with the maximum removal rate achievable under 236% of the code-required VR (100% outdoor air) defined as 100%: (a) MERV 4 filter; (b) MERV 8 filter, and (c) MERV 13 filter.

Results illustrate that the total infectious particle removal (thus RR reduction) from increasing VRs depends on the efficiency of the HVAC filters: increasing VRs lead to greater risk reductions for systems with low efficiency filters than for those with high efficiency filters. For example, increasing VR from 40 percent of the code-required VR to 100 percent outdoor air enhanced infectious particle removal by a factor of 3.3 (i.e., from 30 percent to 100 percent) when a MERV 4 filter is installed, whereas for a MERV 13 filter removal changed only by a factor of 1.1 (i.e., from 89 percent to 100 percent).

Figures 5a to 5c also clearly show the increased contribution of filtration to the total infectious particle removal as filter efficiency increases, especially under poor ventilation conditions. For example, for the cases with 40 percent of the code-required minimum VR, the estimated contribution of filtration to the total infectious particle removal for the hypothetical classroom defined in this paper was 4 percent, 34 percent, and 63 percent of the maximum possible removal rate for MERV 4, MERV 8, and MERV 13 filters, respectively.

Again, we note that all these results are rough estimates of infection probability due to assumed long-range, airborne viral transmission, using simplified hypothetical scenarios. The *proportional contributions* of long-range airborne transmission vs. close-range droplet and surface transmission to total infection risk is an important yet challenging question beyond the scope of this work.

Discussion

Here we present an illustrative model of how changing ventilation rate (VR), air filtration, and mask-wearing practices, each alone or in combination with the others, can alter the estimated relative probability of infection from long-range, small aerosols, in conditions that represent California classrooms. Broadly, the results demonstrate that any of these interventions, compared to none, reduces the estimated probability of infection by long-range, small aerosols. Other researchers have discussed a similar concept of integrating indoor air quality[96] control strategies to reduce the risk from asymptomatic SARS-CoV-2 infections in classrooms[79] and to reduce viral aerosols indoors more generally.[127]

Ventilation and filtration–combined effects and relative contributions

The model results demonstrate that ventilation can play an important role in reducing long-range, airborne viral transmission. Failure to increase the current VRs in California classrooms, often substantially below the Title 24 minimum code requirement,[116,124] is estimated to result in a 10–20 percent increased probability of infection from small aerosols (1a and 2a in Figure 3), relative to the reference compliance case. The extreme case of “no ventilation” could increase the probability of infection by over 500 percent (E-I in Figure 4). This benefit is recognized in some guidelines, which recommend maximizing outdoor air ventilation for HVAC systems with fixed total air supply.[43]

The model also shows that effective air cleaning/filtration, installed and operated properly, can substantially reduce the probability of airborne viral transmission. Guidelines from multiple other groups emphasize the importance of using adequately efficient filters such as MERV 13 or higher, properly installed and maintained, to most effectively remove infectious agents from recirculated HVAC air.[14,15,41,43,45,106,125,147,148] A different recommendation comes from one European source: because of skepticism that the filtration generally used would be adequate to ensure safe recirculated air, they recommend 100 percent outside air.[148] Because provision of 100 percent outdoor air is not practical for many U.S. HVAC systems, effective filtration of recirculated air is essential. Proper selection, installation, and maintenance of HVAC filters are all essential to achieving the desired particle filtration benefit. The higher the MERV rating of installed filters, the safer, within the feasibility limits of system compatibility and cost. The ASHRAE guidance for school reopening recommends installation of MERV 13 or better filters, where possible, for the best current balance between effectiveness and feasibility.[41]

Although the combined improvement of ventilation and filtration can always reduce long-range airborne transmission, the transmission reduction from each of three strategies–increasing ventilation, improving HVAC filtration, and adding in-room particle filtration–depends on the values of the others (as well as on other model assumptions; e.g., size distribution of virus-containing particles, filter removal efficiency, and recirculated airflow rate).

In our results, more efficient HVAC filters reduce risk more when VRs are lower, because (assuming fixed total air flow) recirculated airflow rates are then higher and recirculated air is filtered repeatedly. Thus, in the simulated scenarios, the contribution of a given HVAC filter to overall risk reduction gradually decreases as VR increases. At a given VR, risk reduction from increasing MERV 8 to MERV 13 is only marginal (10 to 40 percent), because even a MERV 8 filter is efficient at removing the particle sizes that the current model specifies as most likely to contain virus. If instead, an infectious particle size distribution with viruses primarily in smaller particles is assumed, model results would show a larger benefit from upgrading to a MERV 13 filter

As for the choice between upgrading the HVAC filter and adding portable air cleaners, for many of the ventilation scenarios modeled in this paper, the use of AHAM-sized portable air cleaner(s) in addition to standard MERV 8 HVAC filters reduced the relative infection probability approximately 20 percent more than upgrading to a MERV 13 filter. However, it should be noted that multiple portable air cleaners probably would be needed in each classroom to meet AHAM's 2/3 rule.[130] In addition, the relative impacts of HVAC filtration can be greater if the HVAC system provides a higher recirculating airflow rate than assumed in our modeled scenarios, in which case the overall HVAC filter particle removal rate would increase and may make it more protective than portable air cleaners.

Practical considerations for ventilation and filtration

VRs below code requirements[116,124] have implications for the transmission of viruses and other infectious agents more broadly, and these results suggest that disease transmission occurring through small airborne particles might be reduced if California classrooms consistently met code requirements during occupancy. As part of a larger focus on improving VRs in schools, several sources have recommended installation of carbon dioxide (CO_2) sensors to verify that proper ventilation is maintained throughout the school year.[125] Continuous measurement of CO_2 is useful as it provides a real time, direct measure of the accumulation of occupant-emitted bioeffluents, as well as an indication of the amount of outdoor air that the ventilation system delivers per person.

Title 24–2019 Building Energy Efficiency Standards requires use of MERV 13 filters or greater for all new systems and constructions.[118] Therefore, upgrading filters to MERV 13 may be a long-term strategy for particle filtration for classrooms with mechanical ventilation systems, and should be considered before adding portable air cleaner(s). However, portable air cleaners may play an important role if there is no mechanical ventilation (e.g., classrooms with only openable windows) or when outdoor air pollution, such as wildfire smoke, is high.[149] With wildfires predicted to recur regularly in California's future, schools would benefit from preparing alternatives to outdoor air ventilation, such as air filtration, for these situations. Still, caution should be used when selecting air cleaning/filtration products. Some types of air cleaning devices, although commercially available and marketed as effective and safe for use indoors in response to the COVID-19 outbreak, have unproven efficacy, and some (i.e., ozone generators and ionization devices) may even produce harmful pollutants.[150,151] CARB strongly advises against the use of ozone generators in occupied spaces and provides a list of potentially hazardous ozone generators sold as "air purifiers." CARB also provides a list of approved air cleaning devices, certified for electrical safety and low (usually near-zero) ozone emissions.[150,151] When considering air filtration devices, it is best to select only devices that have MERV or CADR ratings.[150]

Only limited cost-benefit analysis has been done for the various intervention strategies included in these scenarios.[127,152] It would be useful to further research the ease of implementation and relative costs of these strategies in order for school districts to identify the most economical way to achieve the same risk reduction and other IAQ benefits.

Mask use

In our model, we treated mask use only as a strategy for contaminant source control (not as personal protective equipment, PPE), and assumed that mask reduced infectious particle emissions by 50 percent. Thus, without changing anything about a classroom, infection probability was reduced by half if teachers and students followed this recommendation. Our estimation is conservative because more effective face masks could further decrease this probability of infection.[82,140,153] Moreover, masks may also provide a personal protective benefit by filtering out some of the indoor airborne aerosols before they are inhaled, a benefit which has not been included in our model. For each assumed VR, the lowest probability of infection was observed when *some form of enhanced air filtration and masks were both used*. It should be noted that these estimates do not include additional risks from any close-range exposure to small and large respiratory droplets, currently considered a primary transmission route for SARS-CoV-2. For such close-range exposure, face masks can play an even more important role in reducing the probability of infection—more effectively than ventilation or filtration, which remove only long-range, small aerosols. In addition, face masks interrupt the transmission of viral fomites from surfaces to hands and then to the nose or mouth. Overall, our analysis supports the most recent California school reopening guideline, requiring face coverings for students in 3rd grade through high school and for all teachers and staff,[154] as well as advice from CDC.[155]

Further modeling efforts

There are other recently released modeling tools. The U.S. National Institute for Standards and Technology (NIST) has released a web application (*Fate and Transport of Indoor Microbiological Aerosols [FaTIMA]*).[141] It allows more input parameters and supports more complex dynamic behavior analysis of indoor microbiological aerosols associated with ventilation, filtration, deposition, and inactivation mechanisms. Results are presented as particle concentrations, not probability of infection. Additionally, a "SARS-CoV-2_*Airborne_Transmission_Estimator*" has been posted online, including a calculation spreadsheet for classrooms, and the benefit of mask wearing.[156] However, the estimation does not consider particle size and uses a lumped virus particle loss rate for all additional control measures without explicitly specifying its linkage to the MERV rating of an HVAC filter or the CADR of portable air cleaners.

The model described in this paper can also be adjusted to include virus deactivation via other technologies. It has recently been highlighted how vulnerable the SARS-CoV-2 virus is to ultraviolet radiation.[157-159] The use of ultraviolet germicidal irradiation (UVGI) as a potential air disinfection strategy, either within a room as upper air irradiation or within an HVAC system to treat recirculated air, is an active area of research, and UVGI application for SARS-CoV-2 reduction warrants further evaluation.[6,29,160] See Appendix 4 for estimates of irradiance requirements for SARS-CoV-2 and further discussion of UV applications.

Comparing results from these various models and further improving the model presented in this paper would allow confirmation and more accurate estimation of relative infection risk for various scenarios, and more broadly, greater understanding of how managing buildings and the behavior of people in school classrooms can affect that risk.

Conclusions

New research and reports on the spread and control of COVID-19, both in general and for school environments in particular, are being published continuously and our understanding of its transmission and effective control measures are growing. Here, we have taken an existing model of aerosol disease transmission and adapted it for the SARS-CoV-2 virus, using currently available information. Although simplified in its approach, the model highlights the potential impact from different classroom interventions (e.g., face masks, ventilation, and air cleaning) as a tool for prioritizing strategies, providing insights relevant to COVID-19 as well as to other airborne contaminants in California classrooms and elsewhere.

Our results demonstrate that classroom interventions, including ensuring HVAC system operation to meet the Title 24 code-required minimum ventilation rate (i.e., through testing and adjusting ventilation system equipment and continuous CO_2 monitoring) and providing enhanced particle filtration (i.e., through HVAC systems or AHAM-sized portable air cleaners), have the potential to reduce the probability of respiratory infections that could occur through long-range, small aerosols. Further planned activities with other California agencies and field HVAC experts include promoting such interventions and conducting post-reopening surveys on school operation and maintenances.

In this paper, we also briefly demonstrate the substantially decreased infection risk if classroom occupants wear masks to reduce infectious emissions. However, these estimates do not account for the multiple other benefits masks provide, which together could be as large or larger: reducing close-range exposure to small and large respiratory droplets, reducing deposition of droplets onto surfaces, preventing wearers from touching their noses and mouths, and also providing a personal protective benefit by filtering out some indoor airborne particles before they are inhaled. It is beyond the scope of this paper to quantify all of the advantages and disadvantages of mask wearing in school environments. As a general guiding principle, source control (such as excluding symptomatic persons from schools, covering coughs, and wearing masks during respiratory infections) should always be considered first to minimize disease transmission.

Finally, this paper mainly addresses airborne viral transmission, for which ventilation and filtration play important roles in reducing infection risk. For SARS-CoV-2 specifically, we acknowledge the great uncertainty of whether and how significantly long-range airborne transmission contributes to overall infection risk, and we support the use of other appropriate control/prevention strategies (e.g., social distancing, wearing masks, and intensified cleaning and disinfection) that have been widely addressed in other published guidance documents on reducing disease transmission during the COVID-19 (or SARS-CoV-2) pandemic.

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