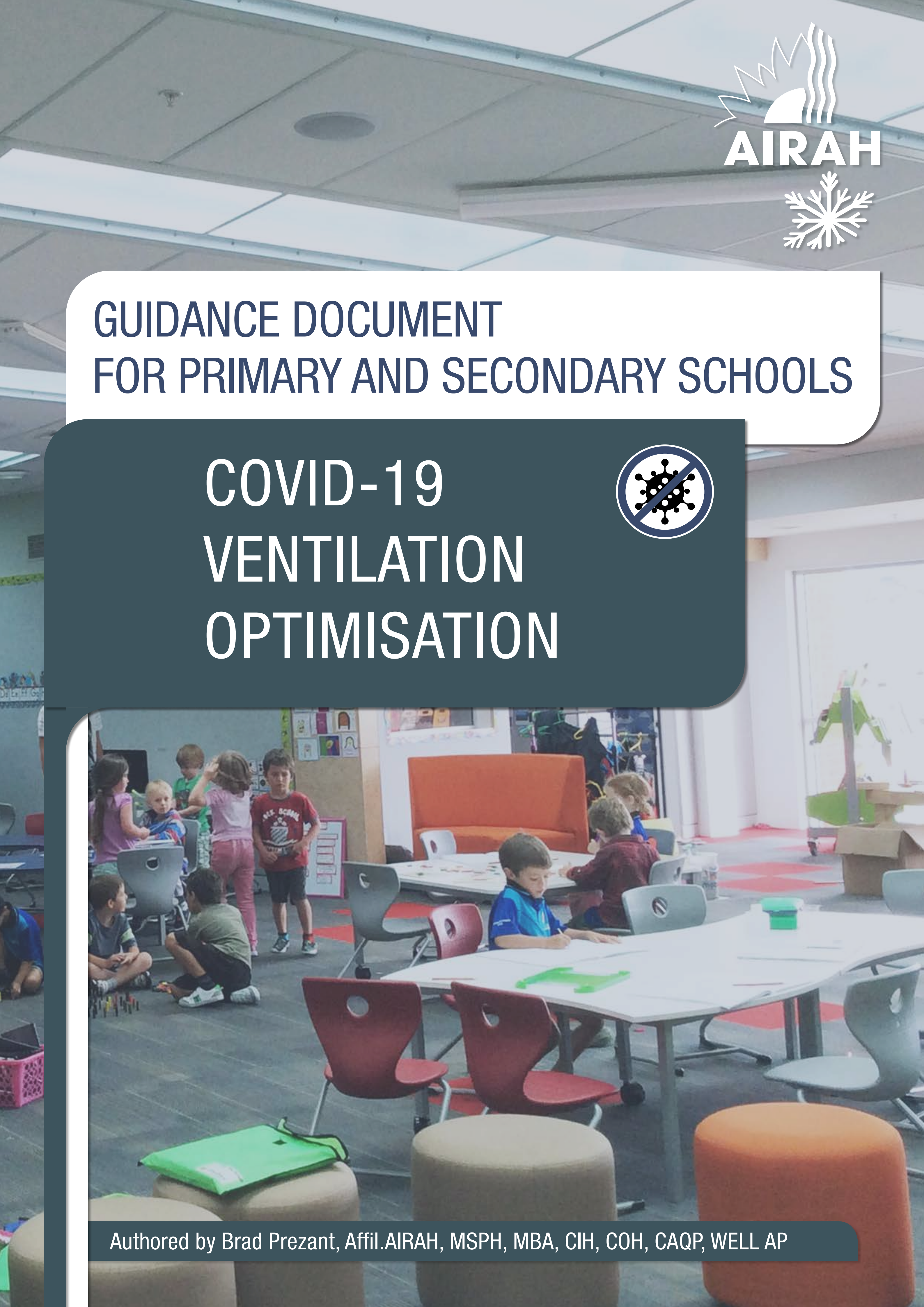

AIRAH

GUIDANCE DOCUMENT FOR PRIMARY AND SECONDARY SCHOOLS

COVID-19 VENTILATION OPTIMISATION

Authored by Brad Prezant, Affil.AIRAH, MSPH, MBA, CIH, COH, CAQP, WELL AP

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Cover photo: Brad Prezant

Introduction

Schools are re-opening throughout Australia. School administrators and teachers are concerned about the safety of children and staff. There are many more questions about the best way to protect children from COVID-19 infection at school than there are answers.

School administrators are being bombarded by vendors selling a myriad of products, some of which may improve the health of occupants, and some of which may increase the risk of infection. Many of the solutions offered are expensive.

This document, written from an evidence-based public health perspective, is intended to address the many questions that school administrators have been and will be considering in order to provide appropriate guidance for creating a school setting where the focus can be on education, and not the building itself. It is intended as a resource both for schools, and for mechanical engineering designers and maintenance engineers.

Review and revision

Users of this guidance document are encouraged to make known their experience in using it, and to notify AIRAH of any additional information they can provide or to which reference can be made.

Acknowledgements

This COVID-19 Ventilation Optimisation guide is authored
by Brad Prezant, Affil.AIRAH, MSPH, MBA, CIH, COH, CAQP, WELL AP
Principal Consultant at Prezant Environmental: prezantenvironmental.com.au

AIRAH also acknowledges the review and input of Clive Broadbent, L.AIRAH,
Kate Cole, BSc, MEEM, MSc Occupational Hygiene Practice, MAIOH, COH, CF,
Brett Fairweather, M.AIRAH, John Penny, M.AIRAH,
Adj. Professor Dino L. Pisaniello, FAIOH, FAIHS, FRACI,
Dustin J. Poppendick PhD (Environmental Engineer,
National Institute of Standards and Technology – NIST USA),
Associate Professor Robyn Schofield, and Jeremy Stamkos, M.AIRAH.

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Other COVID-19 resources

This document can be found among other resources and frequently asked questions at www.airah.org.au/coronavirus

Last updated November 17, 2021

Executive summary

Space, time, and activity create infection risk indoors. A layered approach to risk reduction is most effective, with social distancing and masks a first step to addressing "near-field" airborne exposures, and ventilation addressing "far-field" exposures.

Classroom ventilation systems range from operable windows, to wall- or ceiling-mounted heat pumps, and include ducted HVAC systems. Unfortunately, most classrooms, as presently designed and operated, do not provide adequate ventilation to minimise these "far-field" airborne exposures.

Ensuring ventilation in classrooms achieves 4 ACH to 6 ACH (air changes per hour), or is as close to that as is feasible, is one important way to minimise COVID-19 transmission indoors. Equally important is understanding the pattern of flow within the space, with cross-ventilation providing the greatest removal efficiency of exhaled air.

A first step for any school is to ensure that the existing ventilation system is performing as originally intended, and if not, returning it to its original operation. This can be accomplished through a tabletop assessment and/or a site assessment.

It is helpful to characterise the existing system's ventilation performance prior to choosing an intervention strategy in order to benchmark existing conditions, and then develop a plan moving forward based on the resources available. Any chosen intervention can then be evaluated against that benchmark as to its predicted or actual effectiveness. Easy-to-use web-based infection risk calculators can help model the infection risk that a particular room presents, once the air exchange is known.

Simple changes in the existing ventilation of the rooms can often be made to achieve infection reduction goals. Additional options for modifying or augmenting the existing ventilation system can also be considered. Some modifications require behavioural changes – occupants are important stakeholders and may need to be included in the assessment and planning.

A variety of technologies are discussed in this document to assist in understanding and choosing the best ones for any particular room or school. There is no one solution; each room and school should consider a variety of approaches in order to select the most effective. Initial capital cost, required maintenance, ongoing energy expense, and other benefits from improved indoor air quality are all part of the equation.

Background

Airborne transmission is now recognised as the dominant pathway for transmitting COVID-19. Recent coverage in the popular media has focused the public's attention on indoor "ventilation" and how it can be assessed and managed to reduce SARS-CoV-2 airborne transmission:

"… many Victorian classrooms – the site for several recent outbreaks – have air quality that is 2 ½ times worse than recommended." [1]

Building stakeholders occupying primary and second schools and childcare centres include employees, students, and parents of students. Each of the groups has recently been bombarded with news accounts similar to these.

Building owners and facility managers are not experts in infection control. Whereas hospitals may have been designed for infection control, childcare facilities and schools have never been designed for this purpose. However, assessing and optimising any building to minimise infection risk is an attainable goal.

This document is intended to identify factors in typical Australian facilities that relate to transmission of COVID-19, in order to form a framework for understanding and choosing appropriate interventions that will:

- Reduce the risk of respiratory infections (including but not limited to COVID-19);
- Optimise resource allocation for maximum benefit;
- Address stakeholder concerns;
- Minimise liability;
- Create a more healthful building environment for occupants beyond avoiding infection.

While the impetus to address these issues may be the current pandemic, there are enormous benefits to be gained from improving school ventilation, which would extend well beyond this present compelling need.[2]

1 Ventilation 'revolution' needed to speed up Australia's path out of lockdown, *The Age*, August 22, 2021.

2 *The Lancet* COVID-19 Commission Task Force, April 2021

Informed approach to intervention

Although Australia spans a wide variety of climate zones and each facility will differ in design and layout, there are a number of common elements such that many considerations will be applicable to a high percentage of buildings used for this purpose.

Each building, however, also has unique aspects of design, operation, maintenance, and use, and the "toolbox" of feasible interventions will need to be intelligently applied for optimal benefit and efficiency. A "layered approach" will typically be required, with several mitigation measures selectively applied to the different buildings based on an understanding of the existing conditions and an analysis of the costs and benefits of the various potential interventions.

A 20-year-old vehicle being brought in for repair might need cleaned spark plugs, a replacement alternator, a head gasket, or just a change in engine timing. Or all of the above. Or just some of the above. There is no simple "one solution fits all" approach likely to represent an efficient use of resources with optimal results for all school buildings.

Existing building characteristics

Many newer buildings are slab-on-grade structures, while older buildings may be on stumps or of similar construction with a traditional beam and bearer support structure.

Many modern schools are heated and/or cooled with wall-mounted or ceiling-mounted split system refrigerant-based "heat pumps/air conditioners", with evaporators indoors and condensers (in cooling mode) located outdoors. Older schools may have unit ventilators along perimeter walls; such a system often includes at least a small percentage of outdoor air intake. Central ducted HVAC systems are also commonly used for larger schools.

Each ventilation, heating, and cooling design presents challenge and opportunity for providing ventilation and minimising infection.

Toilets, sinks, and/or showers, when incorporated, require by code that there be ceiling exhaust in the design. These can influence airflow.

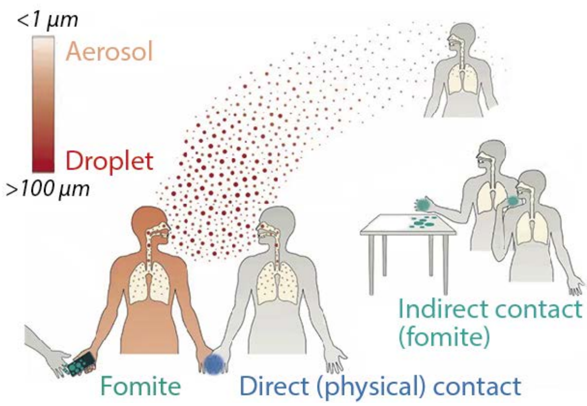
UNDERSTANDING AIRBORNE TRANSMISSION

Space

There are three airborne transmission "scenarios of interest". One is when people are within 1.5 metres of each other, or "near-field". Near-field includes direct touching, deposition of large droplets on the skin or eyes from talking, sneezing, or coughing, and the inhalation of immediately exhaled air from a person close by.

A second transmission mechanism that took 18 months to be fully recognised, particularly in Australia, with many consequential infections, such as hotel quarantine escapes. This "far-field" transmission scenario is particularly important with the delta variant, and likely explains many infections. "Far-field" is more than 1.5 metres, and is similar to cigarettte smoke diffusing thoughout a room. A third transmission mechanism is when air moves from room to room within the same building or even between buildings. This is less common but exists.

Ultimately, risk is a function of how close one is to the source of infection. Research suggests that being close to the person exhaling, in their "near field" of within 1.5 metres, or farther away but directly in line with a cough or sneeze, can result in exposures to infective material five times higher than if you are in the "far-field".[3]



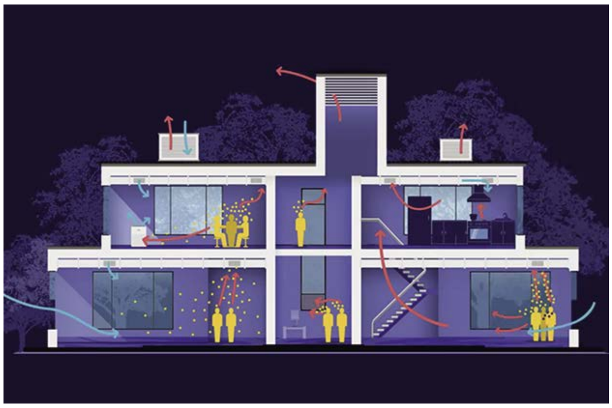


Image: Brad Prezant © Prezant Environmental

3 Table 7.3, *Assessment of Risks of SARS-CoV-2 Transmission During Air Travel and Non-Pharmaceutical Interventions to Reduce Risk, Phase Two Report: Curb-to-Curb Travel Through Airports* (Faculty and Scientists at the Harvard T.H. Chan School of Public Health), https://cdn1.sph.harvard.edu/wp-content/uploads/sites/2443/2021/02/Harvard-APHI-Phase-Two-Report.pdf

Concentration in air

Close to the source, for "near-field" exposures, the concentration of exhaled infective material in the air is highest. After being diluted and mixed with the surrounding room air the concentration decreases – but the potential for infection is still present. The small exhaled particles hang around in the air and gently follow room air currents, mixing and diluting within the room air, behaving similarly to the way smoke would behave. Just as one might smell smoke anywhere in a large room if a smoker is present, one is exposed to infective material anywhere in the room once an infected person is present, exhaling, and this mixing occurs. This is what is meant by "far-field". When air moves from room to room, dilution of infective material may or may not occur, such that simply being separated by a wall may or may not be protective.

Dose = Concentration × Time

For each of these scenarios of interest, a critical factor is time of exposure. While the exact mechanisms of transmission are not fully understood, based on current knowledge it is predicted that longer exposures to low concentration of airborne infective material are the equivalent of higher exposures for shorter periods of time. Thus the risk of infection for a susceptible person is the product of airborne concentration and time spent breathing that air.

Activity = Source strength, which determines airborne concentration

Activity determines the strength of emission by an infected person, with higher activity (breathing) levels or higher vocalisations (such as occur with shouting or singing) related to higher emissions. Higher emissions result in higher airborne concentrations. Activity also affects breathing rate in a susceptible person, and therefore impacts dose, as a person breathing twice as hard due to a higher activity level will cycle two times more infective material into their lungs and have double the dose. It is for this reason that numerous outbreaks of COVID-19 occurred in gyms where both infected and susceptible persons are at high activity levels for moderate periods of time.

How space, time, and activity interact to create infection risk

When an infected person enters an indoor space, their normal breathing expels both large and small particles of respiratory fluid containing infective SARS-CoV-2 virus. The large particles settle out due to gravity, but the small particles shrink in size as they dehydrate and remain airborne for a long period of time, sometimes hours, carried on room air currents throughout the space. These particles likely remain infectious for an extended period, and as small particles, have the potential to enter the deepest portions of the lungs and cause infection.

Over many minutes and hours of exhalation, these particles accumulate within the space, and an increase in concentration of infective material spread throughout the room occurs, assuming the person continues to be present and exhaling. There is wide variation among different persons in the amount of exhaled particles.

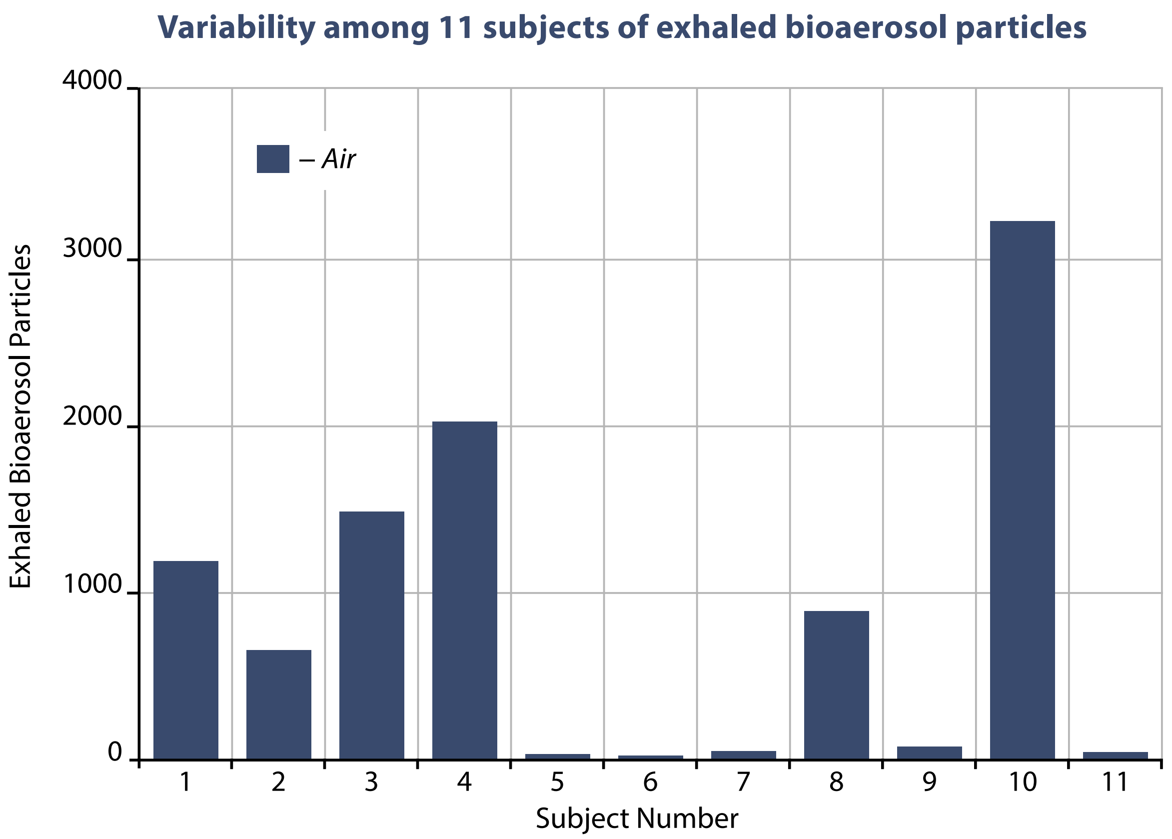


Chart: Edwards DA, Man JC, Brand P, Katstra JP, Sommerer K, Stone HA, Nardell E, Scheuch G. Inhaling to mitigate exhaled bioaerosols. Proc Natl Acad Sci U S A. 2004 Dec 14;101(50):17383-8. doi: 10.1073/pnas.0408159101. Epub 2004 Dec 6. PMID: 15583121; PMCID: PMC536048.

Dilution of room air, and a reduction in concentration of these particles will occur from air entering the space, either through infiltration through the building envelope, operable windows or doors, or an active HVAC system capable of bringing in outdoor air and mixing it into the delivered air.

Based on how many air changes per hour (ACH) are occurring in a room, assuming the infected person continues their occupancy (doesn't leave and keeps exhaling), buildup in concentration of airborne infective particles can increase for many hours, taking as long as 6 hours to reach a maximum value if ACH are low, i.e., at 0.5 ACH.

With higher ventilation rates, for example, 3 ACH, this maximum value will be reached in 1 hour, and the ultimate maximum concentration reached would be lower than if there is less air exchange (lower ACH) of infective particles.

If the infected person leaves the room, the decrease in airborne concentration can also take a long time, with continued exposure for anyone present. The decrease is quicker with more air changes, and slower with fewer air changes.

Given two rooms with an infected person present and equal air exchange, if the room is very large in volume (length x width, times ceiling height), the exhaled infective material will reach a lower maximum concentration than if the room is very small in volume, because the same amount of exhaled material is divided between a larger volume. A small room concentrates the infected material in a smaller area, with higher concentrations reached. In general, therefore, higher ceilings are protective.

If a susceptible person is present in the room the entire time, sharing the air with the infected person but always more than 1.5 metres away, this susceptible person is exposed to infective material for the duration of time both persons occupy the room. If they both leave, and a new susceptible person immediately enters, this person as well will be exposed, as the concentration of infective material will remain airborne, decreasing slowly with time, as a function of the ventilation rate in ACH.

Strategies for minimising exposure and infection risk

All strategies for mitigating exposure and infection risk will utilise the principles outlined above, and all interventions potentially considered should be able to be assessed as to how they are impacted by these criteria.

Existing mitigation measures

Occupancy restrictions, social distancing, and mask wearing are critical public health elements in minimising the public health impact of SARS-CoV-2, and have been extensively recommended throughout Australia. Each of these can impact both "near-field" and "far-field" exposures:

- Restricting occupancy reduces the likelihood of a randomly infected person to be present simply because there are fewer people. Restricting occupancy also reduces the number of persons who could potentially be infected if an infected person is present (one person infecting 1, 2, 3, 4, or more susceptible persons). But when one infected person is present, the risk of any individual present becoming infected is the same whether there is only one person in the room with the infected person or many persons in the room with the infected person.
- Minimising indoor time is extremely effective, as "far-field" transmission outdoors in wind and sunlight has not been documented. Transmission outdoors is only likely to occur in the "near field", with two persons facing and close to one another, or in dense crowds. Holding classes outdoors in favourable weather when feasible, or taking multiple breaks outdoors during the day, is a highly effective mitigation measure.
- Social distancing both indoors and outdoors reduces near-field exposures and ultimately dose, and is extremely effective in minimising transmission.
- Mask wearing is also extremely important as it reduces both the exhalation of infective material by approximately 30%[4] (and up to 99% depending on the type of mask worn), and reduces the inhalation of infective material by approximately 30% (and up to 99% depending on the type of mask worn). The ultimate dose is therefore reduced by the product of the two, such that with 30% efficiency masks (70% penetration), the inhalation of infectious particles is $0.7 \times 0.7 = 0.49$, or one-half of the exposure if neither person were wearing a mask.

4 Jin Pan et al. *Inward and outward effectiveness of cloth masks, a surgical mask, and a face shield*, (2020)

Layered approach

All mitigation measures – social distancing, mask-wearing, and minimising contact time should be implemented when feasible, with ventilation providing an additional layer of mitigation. This has been described as the "swiss cheese" approach, with each layer providing additional protection:

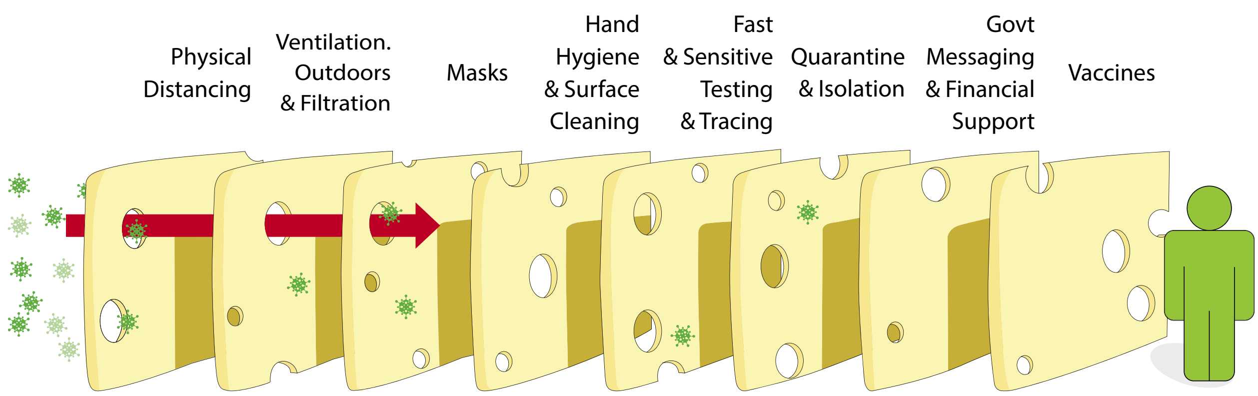


Image: Brad Prezant © Prezant Environmental. Adapted from Ian Mackay, *Virology Down Under*, virologydownunder.com

BUILDING VENTILATION SYSTEMS

Types of systems

Building ventilation systems range from very simple, i.e., operable windows but no mechanical equipment, to very complex with mechanical heating, cooling, and ventilation (HVAC) systems and accompanying sensors capable of both delivering and assessing quantity, composition, and delivery rates of a mixture of both building return and outdoor filtered and conditioned air.

Image: Brad Prezant © Prezant Environmental

Image: www.apave.fr/actualite/groupes-froids-comment-etre-en-conformite?hcb=1

Also included in building ventilation systems are those components not intended to heat or cool, such as toilet or kitchen exhausts, or passive or wind-driven roof vents that supplement the natural thermal stack effect and move air upwards and out of the structure.

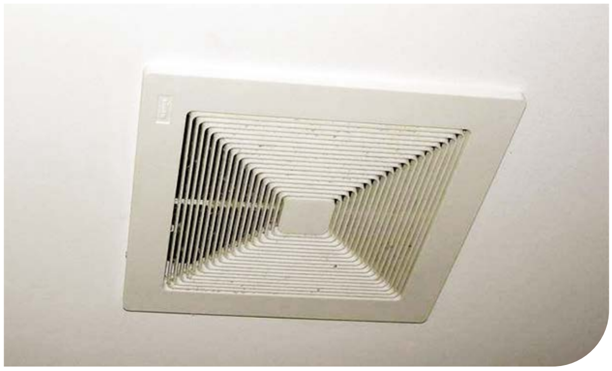


Image: Brad Prezant © Prezant Environmental

Building ventilation systems determine the ACH within the indoor space by exhausting indoor air to the outdoors and replacing it with air from the outdoors. Higher exhaust and intake rates created by fans and dedicated exhaust/intake ducting create higher ACH.

Building ventilation systems impact "far-field" exposures by controlling the time it takes to reach maximum airborne concentration of infective material being exhaled by an infected person, and the magnitude of concentration of infective material in the air. They have little impact on "near-field" exposures; other mitigation measures are required to address these exposures.

At one extreme, building ventilation systems can create a pattern of flow that is linear, such as what exists in a clean room or operating room, with air moving only in one direction, passing clean air over contaminated zones and then exhausting that contaminated air.

At the other extreme, building ventilation systems can create a pattern of flow described as complete mixing, or turbulent mixing, with dilution of generated contaminants (including infective particles) spread throughout the room somewhat uniformly, such as what might exist in a room with an operating overhead fan. While this may be ideal for creating temperature uniformity, for infection control it has the potential to expose everyone in the room to exhaled viruses.

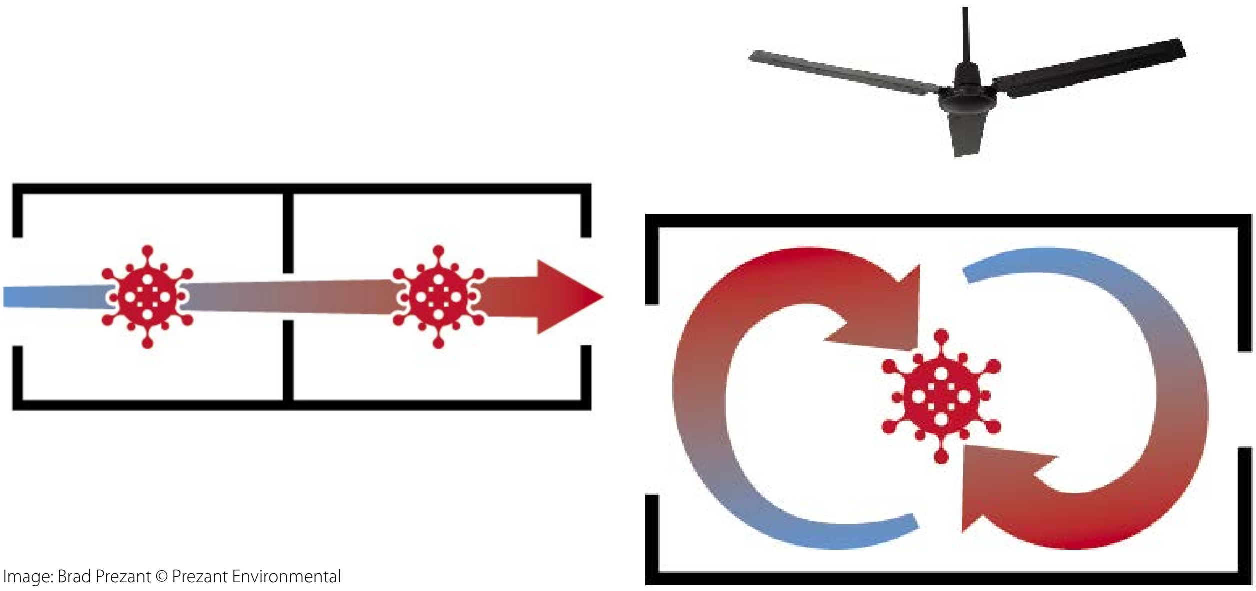


Image: Brad Prezant © Prezant Environmental

Unit ventilators or ceiling or wall-mounted refrigerant-based evaporators, i.e., "heat pumps", or "split systems" might recirculate air in a consistent pattern in one portion of the room, creating "hot spots" of recirculation in that part of the room relative to other portions of the room. These systems should be audited to ensure that the present discharge configuration is not creating high air velocities that enhance "unfiltered" distribution of airflows from one person to another.

Ceiling or wall-mounted refrigerant-based evaporators also have the potential to create stratification when in heating mode. During heating season, warm air from the evaporators will tend to hug the ceiling due to the physical principle of hot air rising, and resist mixing with the cooler air near the floor that has "sunk" from perimeter walls and window glazing. The air lower in the room becomes a stagnant zone, and infective material will concentrate at higher levels in that stagnant zone than if there were more turbulent mixing, thereby increasing the risk of infection in the lower "stagnant" region.

Heat pumps/refrigerant-based split systems do not exhaust air from the space or bring in outdoor air, thus they do not "ventilate", they only recirculate with thermostat-driven heating or cooling. Other components must be relied upon to ventilate these spaces, including natural ventilation.

ACH and flow pattern determine far-field infection risk

Both the overall air exchange measured in ACH, and the pattern of flow define the exposure potential and infection risk. Higher ACH reduce shared air and therefore infection risk, and flows which direct potentially contaminated exhaled air towards the exhaust rather than mix it into room air reduce exposure to shared air and infection risk.

Hospitals adjust air exchange to be in the range of 6 ACH to 12 ACH for infection control purposes. These values are not always practical to achieve in public buildings; some public health authorities have suggested 4-6 ACH,[5] without undesirable airflow characteristics. This could be achieved through a mix of outdoor air introduction and particle removal within the room. The two are additive, such that if the outdoor air ventilation is accommodating 2 ACH, and localised particle removal achieves 2 ACH to 4 ACH, a total of 4 ACH to 6 ACH will be reached.

All buildings have a pattern of flow that can be determined and assessed independently of the ACH. These patterns can possibly be optimised or manipulated in some manner to minimise infection risk, as shown below:

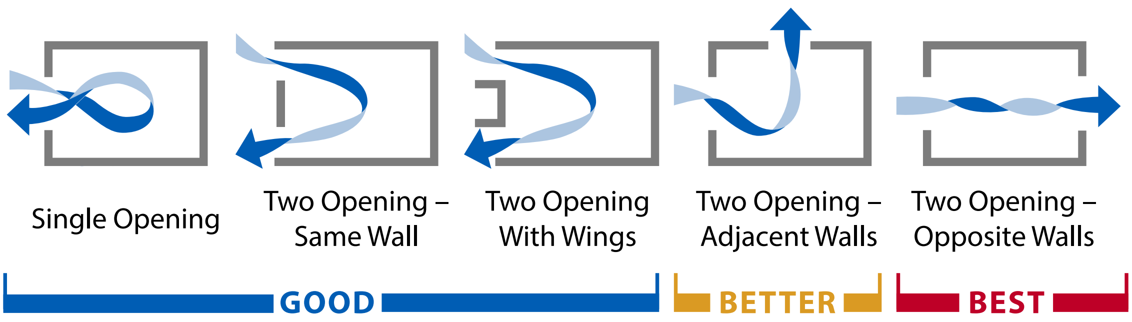


Image: Adapted by Brad Prezant from schools.fohealth.org

For a building with operable windows, 4 ACH to 6 ACH may be achieved under the correct conditions with windows and/or doors open. With windows closed this level of air change will not be approached, and a reasonable estimate absent specific building knowledge is that air changes in schools and childcare centres may be around 1 ACH, and possibly significantly lower. This can vary significantly with wind and temperature differences.

5 *5-step guide to checking ventilation rates in classrooms*, Joseph Allen, Jack Spengler, Emily Jones, Jose Cedeno-Laurent, Harvard Healthy Buildings program, www.ForHealth.org

For a mechanically ventilated building, a fixed amount of ACH may be designed into the system, or the HVAC system may automatically adjust the ACH based on outdoor air conditions and thermostat settings. For these systems, the minimisation of energy use while still maintaining thermal comfort may be the sole criterion determining the ACH.

Introduction of outdoor air can have unintended consequences

For either a building with operable windows or mechanical ventilation, adjusting the system to deliver the 4 ACH to 6 ACH might be ideal for minimising infection risk, but it is critically important to understand that the building as a whole may not have been designed to manage the additional moisture introduced by a large quantity of outdoor air entering. The building may or may not be able to accommodate the introduction of this moisture without causing potentially grievous damage to the building components. It is therefore imperative that prior to modifying the ACH, consideration be given to the impact of this moisture within this larger context of building performance. Introduction of outdoor air may also impact energy costs.

While it is generally advantageous to ventilate at the greatest possible number of ACH for infection control, that assumption presupposes that the outdoor air is of good quality. If a building is located in a particularly polluted location, such as immediately adjacent to a highway, or outdoor air is compromised by excessive fine particulate due to frequent controlled burns and bushfires, increasing the amount of outdoor air may not be at all desirable, or may at least be considered as a trade-off.

Provision of outdoor air by design

Classrooms in general are required to introduce outdoor air by design, either through natural ventilation or mechanical ventilation.

On initial construction, building codes will define the required outdoor air ventilation to be designed into an active HVAC system, in litres per second per person, and differ for the type of occupancy based upon *AS 1668.2–2012 The use of ventilation and air conditioning in buildings Part 2: Mechanical ventilation in buildings*. For classrooms the appropriate value is 12 L/second/person.

There is no information on carbon dioxide in the Australian standard, though in New Zealand, a benchmark of 1,000ppm CO_2 is set, and in the U.S., 700ppm above ambient, or around 1,125ppm CO_2.

AS 1668.4–2012 The use of Ventilation and air conditioning in buildings Part 4: Natural ventilation of Buildings will be applicable in the absence of a built-up HVAC type system, and may represent the large majority of facilities. The provisions for natural ventilation define the percentage area of openable windows and doors as a function of floor surface area as an alternative to provide mechanical outdoor air ventilation. Wind-driven roof-mounted aluminium ventilators present on the roof may be integrated into the design considerations for natural ventilation, as they will augment the natural stack effect of the building and move air upwards and outwards. Of course, their functionality in practice is somewhat dependent on wind speed and building-specific factors.

Assessment of ventilation systems

Toilets are required by building codes to have exhaust but these may be linked to lighting operation, presence detection, or controlled by a clock, and may not be operating at all times. For infection control purposes, these exhausts should operate on a continuous basis so as to ventilate the toilet area and also to increase overall ventilation in the building.

As part of a recommendation for an initial audit of the existing ventilation control systems to verify intended design, installation and operation, simple tests can be done to demonstrate that the toilet exhausts are functioning, as shown below:

Images: Brad Prezant © Prezant Environmental

On the left, is a small vane anemometer that can be used to estimate the actual flow and compare with design specifications. On the right is the even simpler "toilet tissue test" that doesn't require a calibrated instrument but would at least identify exhausts that are present, and either very poorly functioning or not functioning at all.

Toilets may have both mechanical exhaust ventilation and operable windows. Opening the windows in toilets could be counter-productive, as it would disrupt the exhaust flow and potentially direct contaminated aerosolised toilet air inward to other occupied areas (see section below on additional transmission mechanisms). For this reason, they should be kept closed unless airflows are assessed. Passive exhaust ventilation in toilets may not always function as intended, that is air could flow inward in reverse direction to the intended outward flow. Consideration to incorporating active fan ventilation in such systems would benefit infection control.

Kitchen exhaust systems may be set to operate continuously to contribute to increased ventilation and ACH in the building, and thereby enhance infection control.

It is highly unlikely that naturally ventilated buildings are delivering either 10–12L/s/person of outdoor ventilation air or keeping CO_2 levels below those cited above, excepting when a high percentage of openable doors and windows are open.

When windows and doors are closed in naturally ventilated buildings, the ACH achieved may be between 0.5 ACH and 1.0 ACH, or lower, depending on the construction details, the frequency of door opening and closing, the functionality of toilet and any other building exhausts, and the degree of infiltration through the building envelope.

When windows and doors are open, air exchange rates are often unpredictable and highly variable, from 2.0 ACH to 20-plus ACH, influenced by outdoor wind conditions as well as the area, configuration, and location of the openings.

Measuring ACH

Ventilation, in ACH, can be estimated for buildings with active mechanical systems by inferring from the design drawings (engineering estimates), or measuring the actual as-built, installed and maintained airflows (commissioning and/or re-commissioning).

Tracer gases are the most accurate method to provide a realistic, in-use measure of ACH. Blower door tests can also be a less precise, but useful estimate of ACH.

For buildings with openable windows, ventilation ACH can also be estimated using exhaled carbon dioxide (CO_2), as infiltration through windows or doors cannot be directly measured using instrumentation as one might do for diffusers and outdoor air intakes in buildings with mechanical HVAC systems.

There are important caveats to using carbon dioxide because CO_2 values measure both ventilation and occupancy, and we only want to measure ventilation – the values obtained can therefore be misleading.

When using CO_2 in either naturally ventilated or mechanically ventilated buildings to estimate ACH, ***there must be the typical maximum numbers of occupants present for several hours prior to measuring CO_2***.

Alternatively, CO_2 can be artificially increased in an unoccupied building using dry ice or compressed gas to build up a concentration of several thousand ppm, and the curve from the tracer decay analysed to determine the air changes per hour.

Inappropriate interpretation of CO_2 levels can falsely indicate the room is better ventilated than it actually is.

This error is particularly common when a single measurement is taken, rather than using continuous reading instruments tracked over time. In particular, if CO_2 were measured as part of a short (1–2 hour) audit of a room or building, and the room is not a typical "full" occupancy, it is very possible that a misleading value for CO_2 might be obtained.

High CO_2 measured values indoors, however, typically do indicate that the space is poorly ventilated and that condition is identified by the use of CO_2. In Australia, the NCC (National Construction Code) IAQ Verification Method (originally designed as an indicator for body odour) recommends a maximum concentration of CO_2 of 850ppm averaged over 8 hours, which represents 400–450ppm greater than outdoor air. This is defined as an adequately ventilated building from an occupant "odour amenity" point of view, not an infection control point of view. A recent 2020 AIRAH publication recommends an orange light indicator at 800ppm and a red light indicator at 1,000ppm "in order to promote as much ventilation as possible."[6]

850ppm CO_2 is probably a reasonable level of CO_2 to aspire to in an educational setting. Many if not most schools in Australia likely do not have sufficient ventilation.

For buildings depending on natural ventilation (openable windows, doors, and/or sliders), opening these continuously either partially or wholly, intermittently on schedule, or after occupancy and prior to re-occupancy, may create thermal discomfort but can contribute significantly to reducing airborne infection risk. Doing this when outdoor conditions are mild would of course be highly effective without thermal consequence, and cracking the windows even during adverse outdoor air temperature periods may minimally impact thermal comfort.

Periodic opening of doors and windows requires behavioural modification by staff, and may be difficult to achieve. CO_2 monitors in classrooms could demonstrate the impact of the operable

6 *AIRAH Guidance for School Buildings COVID19*, https://www.airah.org.au/Content_Files/Resources/2020_AIRAH_COVID-19_Guidance_for_School_Buildings.pdf

windows in reducing CO_2 and indicate when the outdoor air has completely refreshed the indoor air, i.e., when the concentration of CO_2 indoors approximates the concentration outdoors. Doors and windows would remain open no longer than necessary using this approach. Additionally, occupants would gain a perception of control of infection risk, which could increase satisfaction and reduce anxiety regarding the building and the risk of infection.

One should anticipate an energy cost penalty if the mechanical systems had to re-heat or re-cool the outdoor air.

Heat recovery ventilation

Heat recovery ventilation (HRV) can be a useful strategy for increasing air exchange (in ACH) with minimal energy penalty. HRVs bring in outdoor air and remove room air, transferring the heat (or cool) from the exhaust air to the incoming air with high efficiency. This effectively dilutes contaminants present indoors, including infectious particles generated by occupants as well as volatile organic compounds associated with building materials, people, or activities.

This provides an advantage over portable particle air cleaners, as the overall air quality will be improved, provided outdoor air is of high quality.

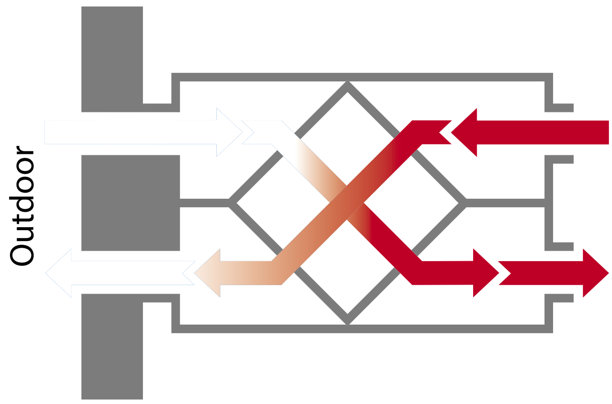


Image: Brad Prezant © Prezant Environmental

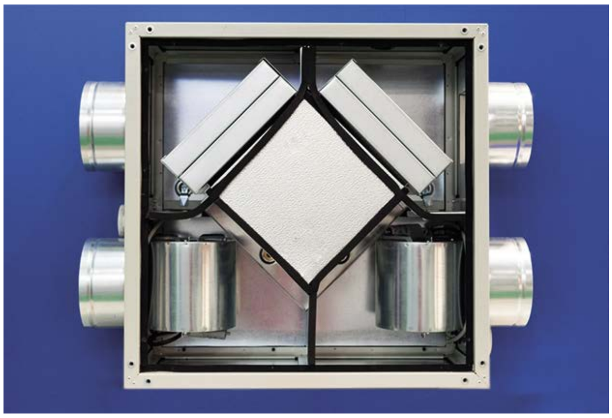


Image: www.ny-engineers.com/blog/ventilation-efficiency-measures

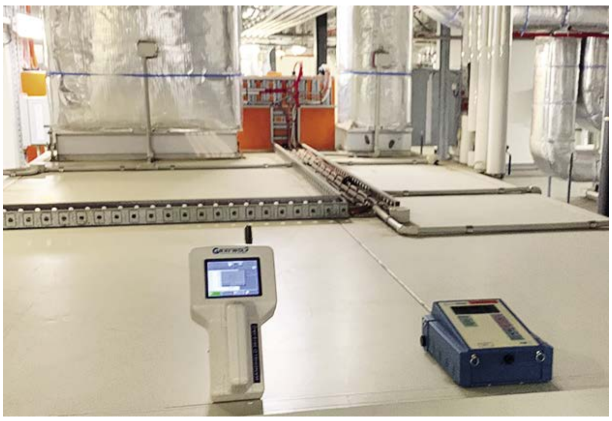
Heat recovery ventilators introduce outdoor moisture, and as discussed elsewhere, introduction of moisture could impact overall building integrity. This needs professional assessment prior to implementation. HRVs can be combined with dehumidification in certain climates – this can be a very desirable strategy for creating comfortable and healthful indoor environments and is gaining in popularity, particularly when existing systems do not effectively dehumidify.

Many HRV systems are ducted, requiring complex installation including provision of electrical service to the HRV fan location, and will therefore incur considerable initial cost. Maintenance of HRVs is important to prevent build-up of dusts and/or moisture within the units, which could lead to problems of mould growth.

Indoor particulate monitoring

Particulate monitoring, including size-selective particulate monitoring, can easily be accomplished using portable instrumentation. But because such monitoring is not specific to respiratory aerosols, and respiratory aerosols represent only a small fraction of total particulate of all sizes that might be airborne, any infectious signal is overwhelmed.

Past experience in child care and school settings is that the relatively high density of occupation combined with the active nature of kids, creates ongoing disruption of the settled dusts within an activity room. This dust consists of outdoor soil and outdoor biological material, but also will be enriched with products used indoors as part of the learning experience such as art materials. Various contaminants are brought indoors by the kids on their clothing and shoes, such as pet hair and other allergens.



Images: Brad Prezant © Prezant Environmental

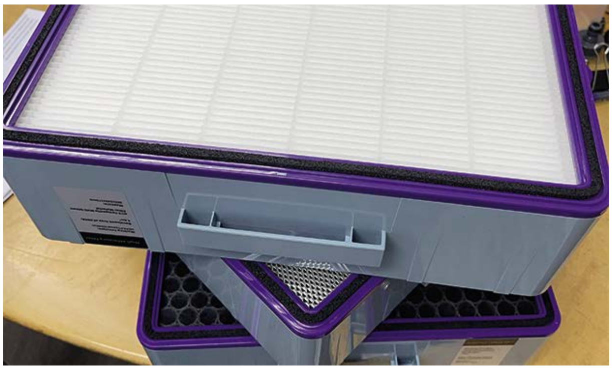
Particulate monitoring may serve as a surrogate measure of air removal and replacement in a before/after type of scenario when operating an air cleaning device or turning "on" ventilation that removes room air and introduces outdoor air, and could be useful to determine the effectiveness of the device or ventilation. Particulate monitoring might also be useful to check functionality of a HEPA-type air cleaner on a periodic basis, as these units can fail due to breakdown of the seal between the unit and the filtration device and cease to remove fine particulate, or malfunction and allow leakage in some other manner.

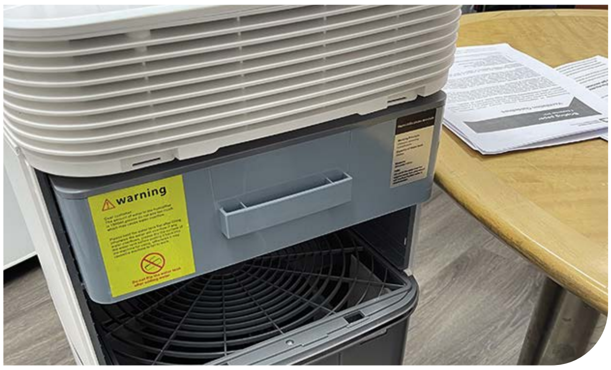
Filtration and filter change schedule

For an HVAC system that cycles occupied space return air through an HVAC unit containing a filter, higher filtration efficiency will remove a greater proportion of fine particulate associated with disease transmission. All filtration systems remove a percentage of particles, so even lower efficiency filtration provides some removal of fine particulate associated with infectious aerosols.

Ideally, to achieve a high degree of removal efficiency, MERV-13 rated filters would be in place in such systems, but many systems have not been designed for the pressure drop associated with higher efficiency filtration, and original system design criteria may have specified filters with lower capture efficiency. While HEPA systems remove up to 99.97% of all particles, lesser-rated filters can have high removal efficiencies, exceeding 90%.

Frames to support filters may not provide sufficient support or clearance for higher efficiency filters. Prior to upgrading filtration from the original manufacturer specified efficiency or type, an engineering assessment should be undertaken to ensure that other aspects of system operation are not adversely impacted, particularly a reduction in total flow from the additional resistance associated with higher efficiency filters.





Images: Brad Prezant © Prezant Environmental

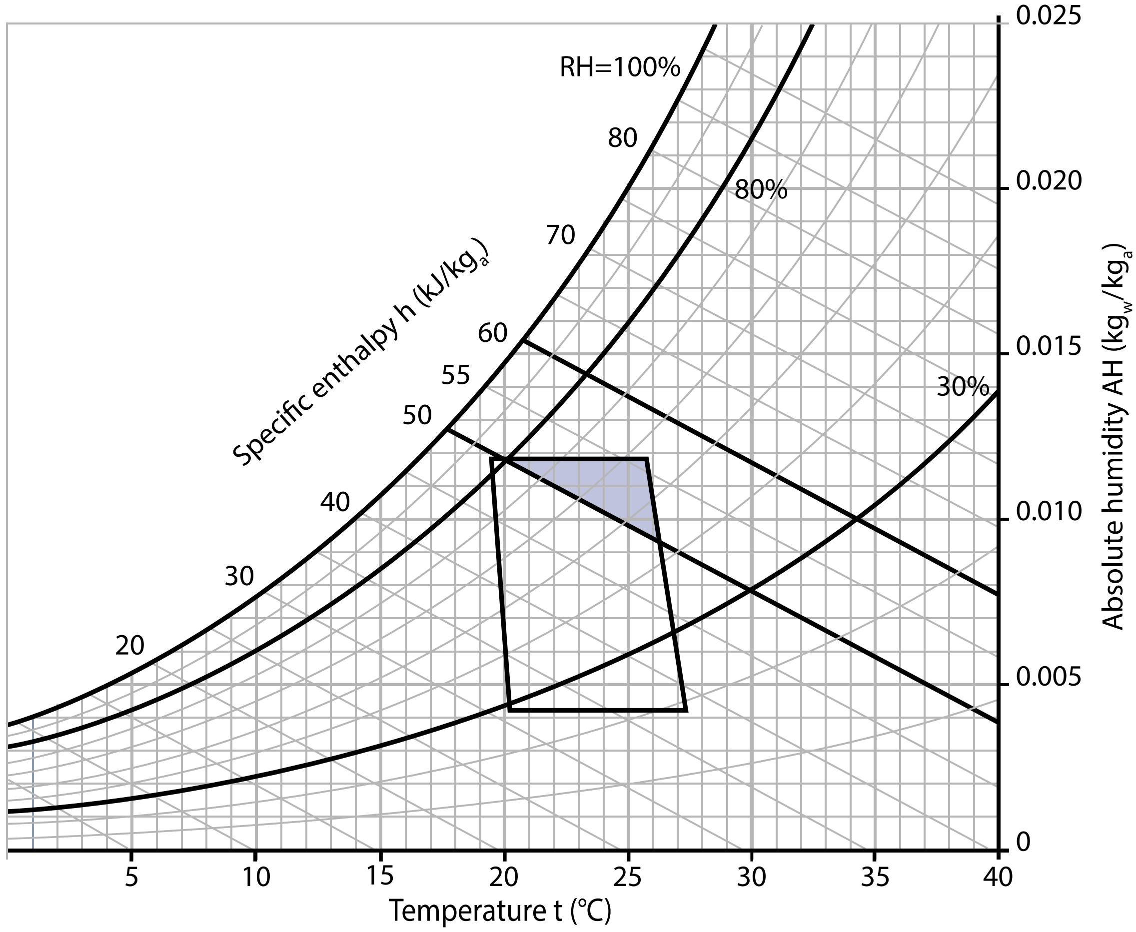
It is desireable to ensure that filters are present, properly in place, and not overloaded or clogged so they are functioning as intended. There is no value, however, in increasing the existing scheduled interval for replacing outdoor air filters, as this additional expense will not create additional value in infection control. For filters on internal fans such as those on wall or ceiling-mounted split systems evaporators, there is no evidence to suggest that impacted particles will be shed from these filters during use, so similarly, the existing replacement interval should be followed to ensure proper airflow unimpeded by pressure drop resulting from an overloaded filter. The scheduled replacement interval should therefore not be advanced for the purposes of infection control.

When changing out filters, particularly if there is reason to suspect that an infected person may have been present in the space, precautions including gloves and respiratory protection, and gentle handling as the filter is placed in an enclosed sealed bag would be appropriate for the safety of maintenance personnel.

Managing temperature and humidity

There is some information suggesting that SARS-CoV-2 survives poorly and inactivates faster in warmer and more humid environments. The drawing below indicates in the grey shaded area where these unfavourable conditions of survival fall within thermal comfort recommendations (the larger rectangle represents the comfort zone).

This SARS-CoV-2 "quicker deactivation" zone that is still within the range of thermal comfort is approximately 21–26°C, with humidity levels of 45% RH to 80% RH (the grey coloured triangle below).



In more tropical climatic zones, maintaining a high temperature and humidity might be feasible, but it would be difficult in cooler climatic zones to maintain levels in excess of 50% RH, absent humidification. These high levels of humidity would not be recommended due to consequential moisture management issues.

Quantitatively, it is difficult to estimate the contribution that maintaining these values would contribute to reducing infection risk, and how much better 26°C and 80% RH would be than 21°C and 45% RH, or any values in between, but this could be considered as one element of a comprehensive approach. Minimally, openable windows on cool dry days can be regulated such that indoor temperatures do not drop to the (undesirable) lower left corner of the comfort zone pictured above, 20°C and 30% RH, the cool and dry corner of the comfort zone.

Air cleaning technology

The particles of condensed respiratory fluids that contain the infective SARS-CoV-2, flu virus, and/or other pathogens are within the size range that can be filtered by pleated paper filters. High efficiency particle-arresting (HEPA) filters will effectively remove 99% + of these particles and consequently reduce the airborne concentration and infection risk.

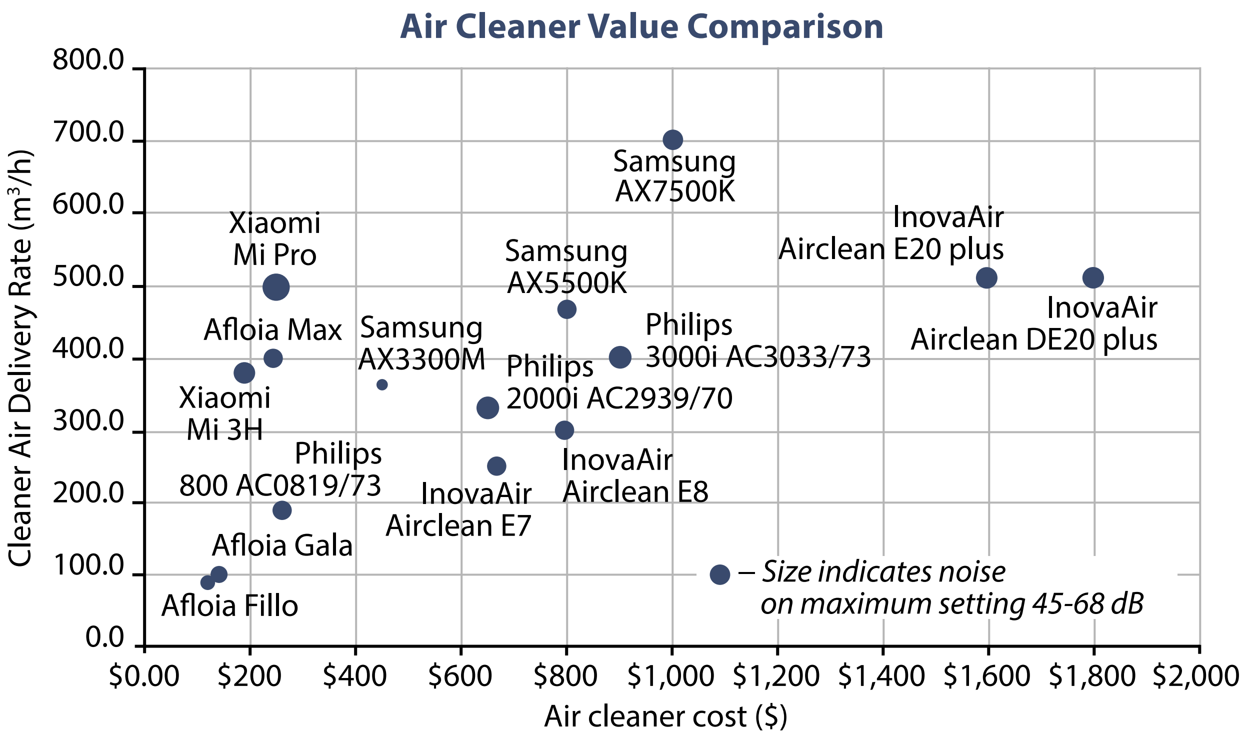
Put simply, they work quite effectively to reduce infection risk, but do not provide the same additional benefits that increasing the ACH by exhausting room air and introducing outdoor air provide, as they do not remove the gases and vapours present in the air.

Absent their ability to remove gases and vapours, however, and specific to removing respiratory aerosol carrying SARS-CoV-2, air filtration and outdoor air ventilation are complementary and can be manipulated to have an additive effect in reducing exposure to infective particles. If it is not feasible to improve ventilation, air cleaning technology can achieve the same goal of reduced infection risk. If air cleaning is not feasible, ventilation can be improved. Improve both and the infection risk reduction benefits are increased in an additive manner.

HEPA filters can be incorporated into an existing HVAC system when the equipment permits (which is not typically the case), or such systems can be modified to accept higher efficiency filtration than what they were originally equipped with (not always feasible, but often possible), or HEPA filtration can be accomplished via stand-alone ceiling-mounted or portable devices.

All HEPA devices will load with particulate as their hours of operation increase. The volume of air passing through will decrease with the added resistance resulting from loading. Filtration efficiency, however, will remain the same or improve with use. It is not advantageous to replace filters on an accelerated schedule, but it is important to replace them when they become "loaded" with use and the resistance increases to the point where volumetric flow is reduced. Pre-filters can prolong the life of HEPA filters.

An important criterion when considering air filtration devices is noise. If the unit is noisy, it will be turned off. Choosing a product based upon its volumetric throughput with minimal noise is therefore essential. Fortunately, there are resources that suggest the sweet spot for both capacity (Clean Air Delivery Rate or CADR) and noise. Below is a chart produced by researchers at the University of Melbourne indicating some air cleaners commercially available in Australia, the CADR, cost, and the noise on maximum setting as a function of the size of the dot:[7]



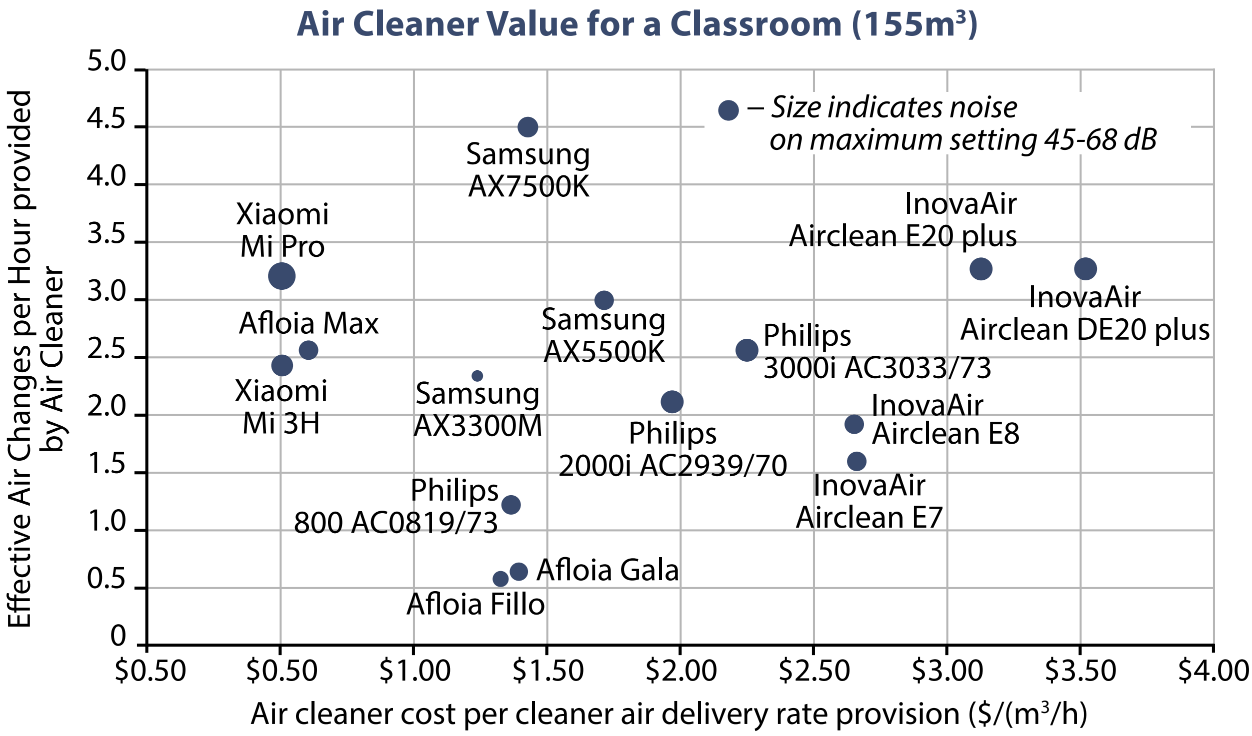
Source: https://sgeas.unimelb.edu.au/engage/guide-to-air-cleaner-purchasing

Recent research suggests that many portable air cleaners recirculate the cleaned air back through the intakes, reducing their efficiency. This may reduce the CADR by as much as 25%.[8]

7 Accessed at https://sgeas.unimelb.edu.au/engage/guide-to-air-cleaner-purchasing

8 *Viruses have arrived in society, Correct design and evaluation of mobile air cleaners to prevent false safety* (draft paper), Fahmi Yigit, November 2021.

For use in a room of 155m³, or a footprint of 65m², with a 2.4 metre ceiling, the following ACH can be achieved by the products illustrated above:



Source: https://sgeas.unimelb.edu.au/engage/guide-to-air-cleaner-purchasing

Multiple portable air cleaners might be required to reach the intended air change per hour goal.

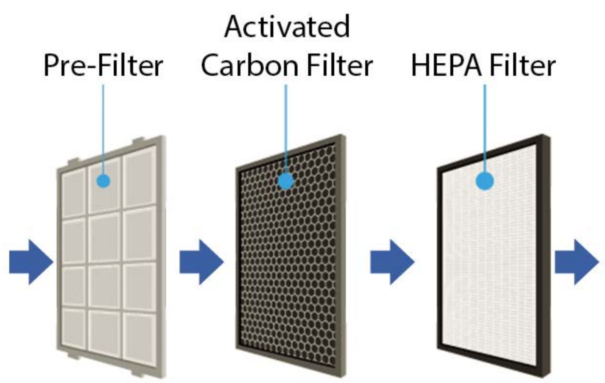
For planning and budgeting, if portable air cleaners were to be utilised throughout a school, one could compare alternative scenarios for both initial and ongoing costs for these units with comparable initial and ongoing costs to achieve higher ACH through the existing or a modified HVAC system.

Placement of air cleaners can be optimised to minimise far-field transmission. As a general guide, the air cleaner should be placed as close as possible to the source of emissions. If the students are clustered in one area, it would be far more effective to place all of the air cleaners in their immediate vicinity or "downwind" from the group if the patterns of flow are discernible, rather than distributing them in a static manner, for example, in each corner of the room. This would be true even if the students dispersed to other parts of the room after gathering, as the air cleaners located close to the source will reduce the ambient level of infective particulate everywhere. This approach would suggest an easy method of moving them, which, given they are trailing a power lead that could create a trip hazard, may not be easy to achieve. If they are to be located "permanently" in the room, at least a preliminary analysis of airflows can be assessed such that they aren't placed directly adjacent to an openable window or another source of fresh air, but likely to be close to a source of exhaled air.

Another reasonable option for the use of air cleaners would be in occupied separate offices and/or reception areas, where a single air cleaner would create 4 ACH to 6 ACH due to the smaller room footprint. This would reduce the exposures of the admin person working in these locations.

Carbon filtration

Carbon filtration is not a practical or desirable filtration technology for infection control. Carbon filtration selectively removes some but not all non-polar dissolved chemicals in the air, but has no impact on small respirable particles that can enter the lung and carry infection.



Images: Brad Prezant © Prezant Environmental

Most portable devices using carbon filtration have a small amount of active surface area carbon filtration, which quickly becomes saturated with humidity and/or absorbed contaminants, rendering the devices ineffective and requiring rapid replacement of the media, creating unnecessary expense with no benefit. They may also slightly increase the pressure drop within any fan-driven system, and are therefore detrimental to ideal functioning of the air delivery system by reducing overall volume throughput.

If portable air filtration systems are utilised that contain both HEPA filters and activated carbon filters, it is recommended that the activated carbon filters either be removed (if that would not adversely impact operation), or not replaced when they reach saturation and/or the end of their service life, provided that does not impact airflow.

Air disinfection

Ozonation, photochemical oxidation (PCO), and ionisation technologies (positive, negative, and bipolar) have all been suggested as air cleaning technologies to deactivate SARS-CoV-2 and reduce airborne transmission of COVID-19. A typical product using these technologies would be a free-standing device, though systems intended to be incorporated into HVAC systems exist. Many of these technologies have not been independently and/or verifiably demonstrated to be effective as deployed in a typical room volume, despite manufacturer claims to the contrary.[9]

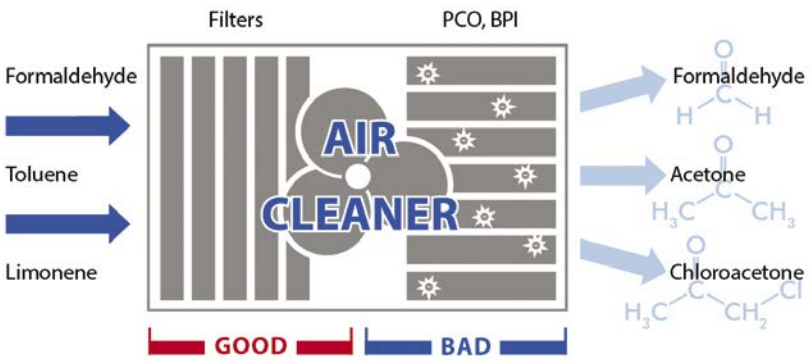


Image: Brad Prezant © Prezant Environmental – based on Ye 2021 & Chen 2005

These technologies are based on chemical or light energies that are non-selective – they oxidise both the target organisms (with the goal of de-activating them) but also oxidise any airborne volatile and semi-volatile chemicals dissolved in the air at low concentrations. Some of these airborne volatile and semi-volatile chemicals are from outdoor air as pollutants, but most are generated indoors from building materials, furnishings, clothing, occupants, and classroom items such as water-based markers, paper, or other art supplies. Breakdown products resulting from the oxidation of these compounds from disinfection technologies can be more irritating than the original chemicals, or in other ways adversely impact human health.

Some disinfection technologies produce ozone, either intentionally or as a by-product. Ozone very effectively rips apart both pathogens as well as everything chemical in the air. Even at low levels of generation, this would augment typical outdoor ozone levels infiltrating indoors. For ionisation systems, the ions produced are proportional to the amount of ozone generated, thus more effective air cleaners may generate more ozone.

9 *Open Letter to address the use of Electronic Air Cleaning Equipment in Buildings*, Dr Marwa Zaatari and Dr Marcel Harmon, https://medium.com/open-letter-to-address-the-use-of-electronic-air/no-to-ionizers-plasma-uvpco-bc1570b2fb9b

All ozone is bad in occupied spaces, even low levels of infiltrating outdoor ozone. Ozone is an EPA-recognised air pollutant in all jurisdictions, with adverse effects on human health. Increasing ozone levels indoors via an introduced technology is not protective of human health, and generation of even minute quantities should be avoided.

Upper room GUV

One exception as regards disinfection technology is upper room GUV (germicidal ultra-violet radiation). It uses shortwave UV-C spectrum wavelength (usually 254nm) to penetrate the cell wall (for bacteria), disrupt DNA or RNA (for viruses), and inactivate micro-organisms (for both bacteria and viruses). This technology has been deployed in hospitals for many years, and while its effectiveness for SARS-CoV-2 has not been demonstrated, initial studies suggest it is effective, with 71% to 100% efficiency in some studies.[10] With any UV radiation, the intensity of irradiance and the time the air spends being irradiated are important to reach critical levels necessary to inactivate any micro-organism. Any system employing such technology needs to demonstrate that these factors are aligned to achieve the intended goal.

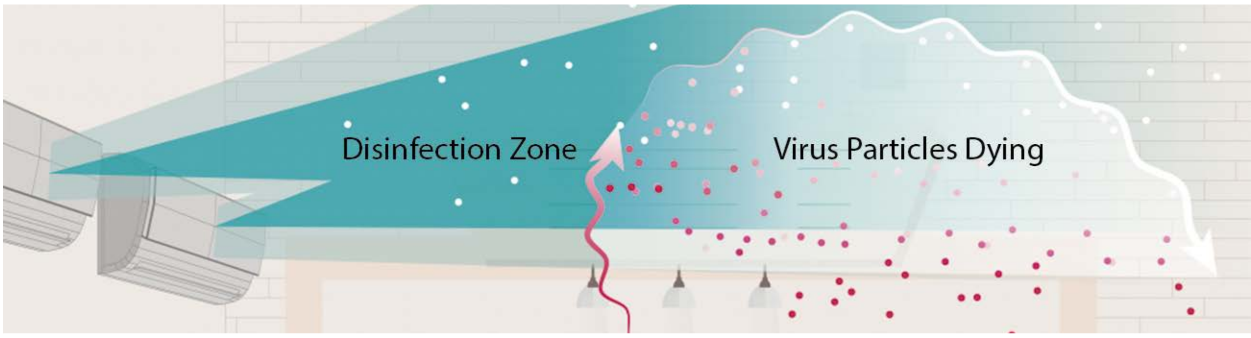


Image: https://www.alfaauv.com/blog/the-use-of-upper-room-uvgi-system-for-air-disinfection-during-covid-19-pandemic/

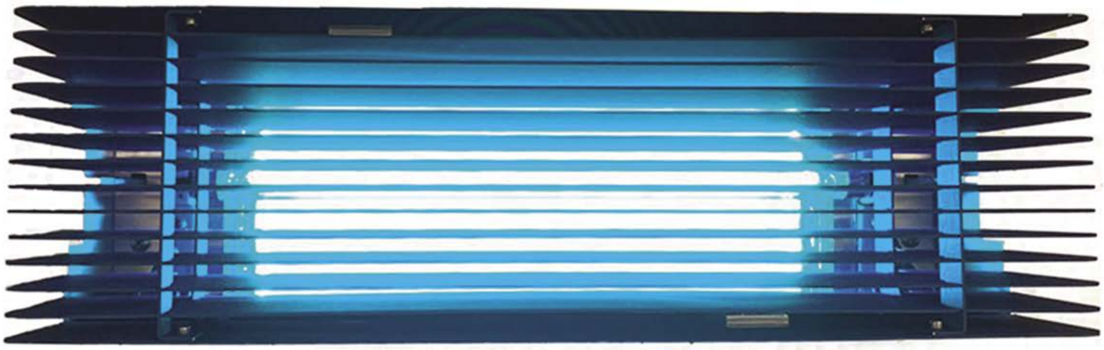


Image: https://uvresources.com/powerful-upper-room-germicidal-uv-c-fixture-kills-airborne-viruses-and-bacteria/

10 Berry, G., et. all, A review of methods to reduce the probability of the airborne spread of COVID-19 in ventilation systems and enclosed spaces *Environmental Research* 203(2022)11765

As typically deployed, upper room GUV is limited to the ceiling portion of the room, and impacts far-field airborne pathogens as they move via normal air currents through the upper portion of the room. A system typically contains reflectors that direct the light upwards and prevent exposure to occupants below. Upper room GUV would only be applicable in a reasonably high-ceilinged room where the irradiation is directed away from occupants, as the UV-C creates significant safety concerns for the skin and particularly for the cornea of the eye.

Professional installation and commissioning of upper room GUV systems including purpose-built fixtures with minimal reflection below, and measurement of irradiance in occupied areas is required, as certain ceilings can reflect UV. Supplemental mechanical air mixing such as low velocity ceiling fans is sometimes utilised to move air vertically in order to permit air to spend as much time as possible in the irradiated zone (germicidal effectiveness is a function of intensity of irradiance and time).

In poorly ventilated spaces, upper room GUV might be extremely effective in reducing far-field (but not near-field) exposure to viable SARS-CoV-2, as viruses are easier to kill than other pathogens as they have no cell wall. Upper room GUV has been shown to be quite effective in reducing transmission of airborne tuberculosis (TB) by up to 80% in studies (TB is likely harder to kill than SARS-CoV-2).

When utilised, cleaning of air that is the equivalent of 6 ACH to 12 ACH of air exchange can be achieved by properly designed systems. Annual re-lamping, maintaining lamp surfaces with periodic cleaning, and dedicated specialised fixture costs as part of the initial investment make this a significant investment, but with a service life of 15 years, upper room GUV is likely to be more cost effective than mechanical ventilation or room air cleaners to achieve the same infection control goals as increased ACH. It should be noted that upper room GUV doesn't have the ancillary benefits that filtration or ventilation have at removing other particles and gases. There is little data on formation of chemical species from UV-C as utilised in upper room GUV at present, and this is of some concern.

Some new promising research suggests that UV radiation in the 222nm band may be ideal for inactivation of SARS-CoV-2. This is a band with minimal penetration into human skin, and a better alternative to 254nm UV.

Unlike other mitigation measures, upper room GUV is quite visible to occupants, and may have psychological benefits to stakeholders that other non-visible mitigation measures cannot provide.

Other UV-C devices

Upper room GUV is a better choice than placement of uVGI inside ventilation ducting, as the air is passing through the irradiated zone quickly inside a duct, whereas it passes slowly in upper room GUV. With UV lamps within ducting, a long linear path of irradiance must therefore compensate for the short exposure time; efficiency of deactivation is greater in upper room GUV due to longer contact time.

UV-C decontamination in healthcare settings of surfaces using portable trolleys emitting high levels of UV-C in unoccupied rooms has been deployed, but would not be recommended for surface disinfection or airborne disinfection outside of hospitals.

Use of other wavelengths of UV (200nm – 222nm) that might be effective in inactivating SARS-CoV-2 with fewer risks to human health are being explored, but lack validation at present, and are therefore not a current option to consider. Some of these technologies, however, show promise.

UV-C irradiation of cooling coils to minimise growth with bacteria and fungi has been successfully utilised and is a recommended component of WELL Building guidance for new building construction. This technology is unlikely to impact airborne concentration of infective virus as the time of exposure as the air passing through the coils is very small, and not likely to reach critical values necessary to deactivate the virus.

Fumigation

Fumigation or fogging, such as with hydrogen peroxide vapour or using other chlorine-based systems, is not recommended because it creates significant safety risks.

It is only effective on surfaces, and the primary route of transmission is airborne. Also, fumigation creates chemical by-products that can be a concern.

Its use should only be considered following known presence of an infected person in the space, and then only with experienced guidance in an unoccupied building.

Use of internal partitions or other methods to modify airflow

Various devices intended to reduce near-field exposures have been suggested and/or implemented in school environments. As one example, millions of dollars have been spent on plastic barriers in school districts throughout the U.S.

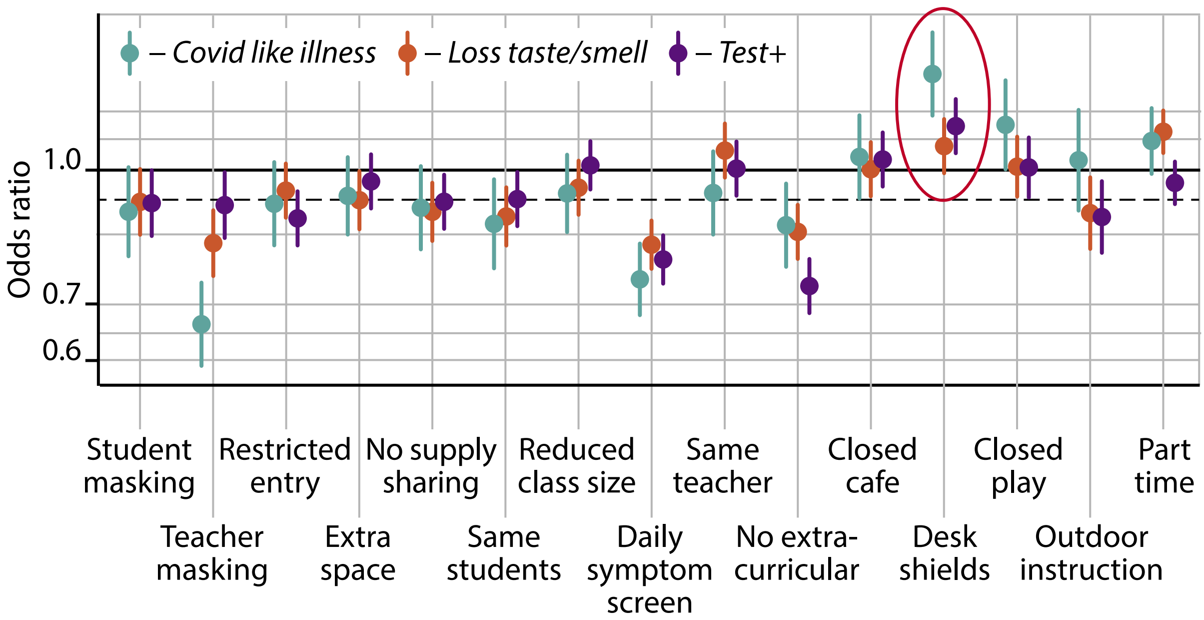


Image based on https://www.mdpi.com/2071-1050/13/12/6875/pdf

A recent study examined various school interventions, including the use of plastic barriers such as desk shields.[11] Plastic barrier desk shields were the only intervention noted to increase risk, not decrease risk. This was hypothesised to be due to a decrease in the effectiveness of ventilation efficiency.

Such an approach is not recommended without detailed engineering and/or occupational hygiene analysis of the likely effectiveness.

11 Lessler J. et al., Household COVID-19 risk and in-person schooling; *Science* 10.1126/science.abh2939 (2021).

Other transmission mechanisms – Surfaces

At the beginning of the pandemic, significant resources were invested in cleaning surfaces. Particularly for outdoor surfaces, normal sunlight UV will rapidly degrade SARS-CoV-2. Indoors, several research studies have suggested that touching surfaces is a minor means of transmitting COVID-19, and that resources devoted to repeated cleaning might be more productively used to reduce airborne transmission.

Some materials can inhibit survival of viruses such as SARS-CoV-2, including copper surfaces, and some cleaning products claim to leave a residue with antimicrobial properties.

If an infected child is sharing an indoor space with other susceptible persons, particularly in a child care setting, for several hours, it is unclear how shared touching of surfaces absent a microbial surface can be effectively prevented. The evidence base to justify enhanced cleaning to prevent infection is weak – normal cleaning is sufficient. "Deep cleaning" of all surfaces – as was done before the accumulation of evidence suggesting a minor role of touching as a transmission mechanism – is likely neither necessary nor cost-effective.

Other transmission mechanisms – Sewage

In 2003, SARS-CoV-1 is suspected to have been transmitted via faecal contact, either faecal-oral or potentially from aerosolisation resulting from flushing of toilets. Stool samples have been shown to contain SARS-CoV-2 virus, and the potential for transmission via this route should be considered.

Aerosolisation from toilets is best controlled by flushing toilets with a closed lid. This is best accomplished by mechanical means, as depending on behavioural controls is unreliable. Ensure that intended toilet exhaust ventilation is present and operating according to its intended volumetric flow. Of additional concern is the potential for dried-out drains and U-traps in floors causing aerosol transmission through the sewage system. This is best addressed through maintenance procedures that specify an appropriate interval for watering traps, typically at least every three weeks, according to REHVA (Federation of European Heating, Ventilation and Air Conditioning Associations).

Sunlight

SARS-CoV-2 decays rapidly in sunlight, and the outdoors provides rapid dissipation of exhaled air. Moving activities outdoors in good weather can dramatically lower airborne exposure and risk of transmission.

To the extent surfaces could transmit COVID-19, SARS-CoV-2 will deactivate rapidly on sun-bathed surfaces.

While the class is outside, ventilate, turn portable air cleaners to maximum setting, operate exhaust fans, and do anything else that can maximise air exchange during this period. Ideally, all infective material could be removed during these unoccupied periods, such that when the class returns, there is no residual infective material present.

Operating schedule

Most ventilation systems shut off at the end of the day, and during weekends. Natural infiltration will achieve sufficient air exchanges over an 8-hour period that no additional operation of the ventilation system should be required to reduce any airborne contagion to less than 1% of its previous maximum concentration. If a shorter time period exists between the end of occupancy and the beginning of re-occupancy, flushing of the building would be appropriate to achieve several air changes prior to re-occupancy, with consequent reduction of airborne particulate.

BUILDING A STRATEGY FOR YOUR FACILITY

Using risk of infection modelling

It is useful to have a tool to understand the existing risk of infection present in any given building. This serves two purposes. First, it gives a baseline for any building such that the toolbox of interventions can be assessed, and when this assessment is repeated after the interventions, the effectiveness of the effort can be measured and its cost/benefit and cost-effectiveness determined.

Second, it enables the buildings/rooms to be rank ordered in terms of infection risk present and, assuming not all locations will be simultaneously addressed, permit those in greatest need of improvement to be prioritised.

There are a number of infection risk models that incorporate building characteristics, ventilation design, time of occupancy, and activity to determine the risk of transmission of SARS-CoV-2 (expressed as a % risk of infection for an occupant). Most of these models consider only far-field exposure – the Harvard model considers both near-field and far-field.[12] They can also incorporate and determine the reduction of risk obtained with the use of air cleaning technologies, such as upper room GUV or portable air cleaners, and in the case of the latter, determine the appropriate capacity and number of units required to achieve a defined goal.

From these models, a risk of infection can be quantitatively assessed both prior to intervention and following intervention. This can assist in determining the likely benefits and justify associated expense.

An iterative approach to site assessment

Desktop assessment

An iterative approach begins with a "desktop" assessment of the structure and function of the existing building configuration and intended design for ventilation. From this assessment, conducted off-site, the operation and capabilities of the system can at least be inferred, as can be described in the cases below.

12 https://covid-19.forhealth.org/covid-19-transmission-calculator/

A building with a roof-mounted "cupola" (thermal chimney) may provide an opportunity to exhaust air from this central roof location, creating an airflow pattern through doors and windows in the perimeter walls toward the centre of the building. While that may not have been the original design, this modification may achieve a better pattern of flow for minimising shared exhaled air and reduce infection potential.

A building with an opposing shed-style roof with clerestory windows along the ridgeline might be able to be modified to exhaust air and provide both greater ventilation and more linear flow within the classrooms. Such an interior ceiling would present a much greater volume of air in the rooms, which will result in lower concentrations of airborne infective particulate assuming uniform mixing throughout the full height of the space.

Smaller volume rooms may provide additional challenge but could be amendable to either ceiling-mounted air cleaning or upper room GUV. Larger rectangular rooms with large ratios of width to length and depending on natural ventilation might have a potential to create a linear flow from one end to the other via fan assistance in openable windows.

Many buildings have been modified from their original heating, ventilating and/or air conditioning design, either intentionally or unintentionally. Returning the system to its original functionality could be the lowest-hanging fruit to accomplish the intended goals with minimum effort.

A small minority of schools have a built-up HVAC system (a central system with central fan and distribution ducts). For these systems, the controls logic, also referred to as the building management system (BMS) provides a powerful tool to manage many factors that could influence the amount and distribution of air. Very often the operational and ventilation strategy can be understood, and changes made to the operating characteristics of this system, via internet remote access. In this manner, one could understand and potentially optimise for air exchange without changing out any equipment or even being on-site. Other types of systems may require a site visit.

Demand control ventilation varies total supply airflow based on occupancy in order to save energy when rooms are minimally, or not at all occupied. Because these systems reduce the volume of air delivered to save energy during these low occupancy periods, the overall air exchange (ACH) in the room is reduced during these low occupancy periods. Unfortunately, the risk of infection is therefore increased for anyone who happens to be in the room when these systems modulate down the volume of delivered air. This is because exhaled air from the infected person accumulates to a higher concentration during reduced supply volume periods, and therefore the exposure to a susceptible person in the room increases, and the risk of infection for that person then increases.

If a demand control system were operated at full capacity, regardless of occupancy, we would be maximising airflow and minimising infection, whether there is one susceptible person present or many susceptible persons present. The system should therefore be operated at maximum flow at all times: demand control ventilation is not ideal for infection control.

Site assessment

A site assessment can range from a simple walk-through with verification of the presence of intended design elements to a more thorough assessment of function, including simple or more complex measurements.

It is not unusual in a commercial building to have "structure but a lack of function", i.e., the HVAC equipment is present but it is not operating as intended. When this is the case, the site assessment audit may permit systems to be returned to the intended design condition, which can often be an excellent first start.

If the target ACH or other health-based targets of the school have been articulated, simple modifications determined to be achievable from the site assessment may be implemented with minimal time and expense.

Building occupants are important stakeholders and involving them in the process can be an important component of the site assessment. These include occupant perceptions of indoor air quality, temperature, lack of ventilation. When occupants understand which zone is covered by what thermostat, or gain control of windows or similar, actual or perceived air quality issues can be resolved.

All potential interventions can be modelled using the "risk of infection" models described above, with existing conditions identified, and possible interventions quantitatively estimated, yielding reasonable expectations for what can be achieved by a suite of interventions, along with the expected costs associated with each potential benefit.

Most importantly, the site assessment provides the school with a logical decision-making approach to evaluate, compare, prioritise, and implement interventions effectively as is economically feasible given the school's specific requirements and resources.

Next steps

Following either a desktop assessment conducted remotely, and/or a more intensive site assessment and investigation, existing conditions can be identified and a plan to further assess the ventilation of the system may then be considered.

The site assessment provides the school with the starting point for ventilation modifications: a benchmark to assess the impact of any changes that might be accomplished. With the proposed target criteria defined, such as 4–6 ACH, a logical decision-making approach to evaluate, compare, prioritise, and implement interventions can then be formed. This plan can determine if the best way to achieve the goal is via modification of the existing system, augmentation with portable air cleaners or other localised air cleaning technology, or a combination of the two approaches.

As one approach, a carbon dioxide (CO_2) monitor could be located in each room, or representative rooms, tracking levels of CO_2 over a 2- to 4-week period during normal operation, combined with a log of the occupancy loads during each daytime period (see discussion of interpreting CO_2 levels, above, as this data can require specialised expertise to interpret correctly).

Select CO_2 monitors upload the measured CO_2 levels to the internet, where they can be stored and remotely accessed.

A CO_2 monitor that continuously uploads data to a web portal, where it can be inspected and analyzed for trends. When combined with an understanding of the design of the ventilation system, this can assist in understanding air exchange. It also allows an expert to look at the data from afar, saving time and costs associated with site visits.

Image: John Penny.

Following assessment of these buildings, it may not be necessary to keep a CO_2 monitor present full-time in any given room, unless it is being used by the staff as described above to inform ventilation. This would permit the monitors to be moved from room to room, or for a multi-building campus, from building to building and reduce the capital costs associated with acquisition of the monitors. When they are being used, they can be deployed, but if they are not providing useful information to staff, they can be relocated.

A centralised monitoring and reporting system can be implemented for storing long-term measurement history from monitors throughout the school. Some of these CO_2 systems also can be integrated with the BMS if a more sophisticated HVAC system is present, and the values of CO_2 are used to change the operating conditions to maximise ventilation when CO_2 levels in excess of a given value are identified.

For any school, measurement of air changes per hour can be conducted in classrooms or other spaces using a tracer gas, such as SF6 or, if the building is unoccupied, CO_2.

Once the ACH are calculated for a room, with the room dimensions of height, length, and width, infection risk modelling can be conducted to determine the percentage likelihood of infection for any given time period using web-based infection risk calculators.

This likelihood of infection can be compared with the percentage likelihood of infection of a "typical" classroom of $81m^2$, with a ceiling height of 3 metres, and the recommended air change rate of 5 ACH (this works out to a risk of infection of between 0.4% and 2.0% for a student sitting at rest using the web-based risk models such as published by the University of Colorado or QUT).

Because the volume of a room has a very strong effect on the risk of infection, high ceilings are quite protective, and a large gymnasium or multipurpose room, for example, with only 1 ACH, will provide a lower risk of infection than a typical classroom with 5 ACH.

Using this approach, the numerous spaces in a school of different ceiling heights and ventilation rates can be ranked ordered by degree of risk of infection, and priorities determined for use and/or for intervention.