Australian Government
National Health and Medical Research Council

NHMRC

**National COVID-19 Health and Research Advisory Committee**[a]

**Date of advice: 30 March 2021**

# The role of airflow and ventilation in relation to SARS-CoV-2 transmission in quarantine arrangements.

## Question

What is the role of airflow and ventilation in relation to SARS-CoV-2 transmission in quarantine arrangements?

## Notes

The key findings represent expert interpretation of relevant evidence as at 19 March 2021. In order to provide timely advice, a full systematic review process was not undertaken.

This report was reviewed by Professor Jonathan Carapetis AM, member of the National COVID-19 Health and Research Advisory Committee (NCHRAC), Professor Robyn Schofield and Professor Jason Monty.

## Key points

The following is a summary of preliminary or published evidence and expert advice relevant to the topic. The evidence on this issue is emerging which is consistent with the recent nature of the COVID-19 pandemic.

**Transmission**

- SARS-COV-2 can be transmitted through airborne, droplet, direct physical contact and fomite/indirect contact transmission routes. While the relative contributions of these routes remains debated, the airborne route is strongly implicated in several indoor settings.
- The evidence review covered several types of studies and settings including hospitals, cruise ships, schools and public transport. None of the papers specifically examined airflow or ventilation in hotels; however, the findings are applicable to the hotel quarantine setting.
- An early release of an article in *Emerging Infectious Disease*, hypothesises that suspended aerosol particles were the probable mode of transmission during managed

[a]NHMRC is providing secretariat and project support for the Committee, which was established to provide advice to the Commonwealth Chief Medical Officer on Australia's health response to the COVID-19 pandemic. The Committee is not established under the NHMRC Act and does not advise the NHMRC CEO.

isolation and quarantine in New Zealand. This event presents similarities to those seen in hotel quarantine in WA, NSW, QLD, VIC and SA.

**Heating and Ventilation and Air Conditioning (HVAC) systems**

- HVAC systems in hotels are designed for personal comfort, energy efficiency and economy function. Infection prevention and control measures are generally not considered in their design or set up.

- The evidence reviewed supported the use of engineering controls on HVAC systems to assist in reducing the risk of airborne transmission in indoors, such as:
  - Ventilation rate: the outdoor air exchange rate should be increased as far as practically allowed by the operation of the HVAC unit.
  - Air temperature and relative humidity: optimal levels for disease control are considered to be 20-25$^{0}$C and 40-60%.
  - Filtration: Increase air filtration rate and upgrade the system's particulate filters to as high as possible without impairing system function. This is particularly beneficial when increasing outdoor air delivery options are limited.
  - Airflow: rebalance or adjust HVAC systems to increase total airflow to occupied spaces. Evaluate air movement and direction by considering repositioning supply louvers, exhaust air grilles, and/or altering damper settings.
  - Servicing: ensure HVAC system is functioning as designed and for the occupancy level for each space. Operation should also meet Australia Standards.
- Additional measures that can be used to complement HVAC system operation:
  - The use of portable air cleaners, especially High Efficiency Particulate Air (HEPA) filters, have been shown to be effective in reducing risk of exposure to airborne particles in indoor settings.
  - Ultra Violet Germicidal irradiation (UVGI) has been used to inactivate SARS-CoV-2, usually when there is a limited ability to improve ventilation or filtration.

**Airflow**

- An Individual building assessment by a qualified expert is the best way to understand the multitude of factors that affect indoor airflow and ventilation. This assessment will assist in identifying what measures could be implemented to reduce the potential risk of airborne transmission.

- Optimise airflow so it travels form clean to potentially-contaminated reduces the risk of staff, and other occupants, being exposed to airborne infectious material.

- The literature advises that the recirculation of air via fans and split system is to be avoided as it may increase the risk of airborne transmission.

**Natural Ventilation**

- The use of natural ventilation, i.e. opening a window/outside door, needs to be considered in terms of the impact it has on internal airflow. Outdoor air is beneficial in that it increases the volume of fresh air in the room thus reducing the risk of exposure to aerosols for the occupant. Conversely, outdoor air can increase room air pressure and/or temperature that promotes the spread of potentially infectious material into adjacent rooms or hallway, potentially exposing others.

## Background

Transmission of SARS-CoV-2 has occurred in Australia's hotel quarantine system. The Chief Medical Officer (CMO) asked NCHRAC to undertake a rapid search and review of evidence to explore the role of airflow or ventilation could contribute to the transmission of SARS-CoV-2 and if additional measures are required.

## Approach

A rapid review of the evidence was conducted to identify primary studies published since July 2020. The following identification strategies were used:

1. Literature search (Pubmed)
   a. Terms: covid AND airborne AND transmission AND ventilation
   b. Filters: Abstract, Free full text, in the last 5 years, English
   c. Inclusion criteria: published after June 2020, paper provides advice on airflow and/or ventilation interventions and their effects in relation to COVID-19.

The cut-off date for the publication of papers in the search (9 July 2020) was based on when the WHO updated its scientific information that airborne transmission was possible[b]. The search and screening criteria were deliberately wide to capture any articles related to airborne transmission of SARS-CoV-2 and ventilation. Twenty articles remained after the full text screen.

NCHRAC convened an expert roundtable on 18 February 2021 to inform this advice to the CMO and the Australian Health Protection Principal Committee (AHPPC) on the role of ventilation and airflow in the transmission of SARS-CoV-2. Four additional articles that were provided by experts (roundtable attendees) that met the inclusion criteria.

A summary of the included studies is at **Attachment A**.

Out of Scope for this advice:

- The minimum specifications for mechanical interventions such as air cleaners/filters and requirements for cleaning of ventilation systems
- The distinction between droplet and airborne transmission as there is a spectrum of particle size that can carry SARS-CoV-2. Hence the use of the term 'particle' in this paper.

## Summary of expert roundtable

Invited experts with a knowledge of airflow and ventilation, virology, fluid dynamics, aerosol science, occupational hygiene and engineering were asked to discuss the available evidence on:

- the role of mechanical versus natural ventilation in SARS-CoV-2 transmission

[b] https://www.who.int/news-room/commentaries/detail/transmission-of-sars-cov-2-implications-for-infection-prevention-precautions

- the impact of air flow and ventilation interventions on SARS-CoV-2 transmission, and whether personal behaviours (by persons quarantining or staff/contractors in quarantine hotels) affect air flow and impact SARS-CoV-2 transmission
- the application and relevance of available evidence to specific settings, including quarantine arrangements
- other factors related to airflow and ventilation, particularly in light of the transmissibility of new variants of SARS-CoV-2.

A summary of the roundtable discussion is at **Attachment B.**

## Summary of the evidence

The evidence includes literature reviews, primary research and modelling in the hospitals, cruise ships, schools and public transport setting. No paper was identified that specifically examined airflow and ventilation in hotels, however the concepts discussed regarding indoor airflow and the transmission of SARS-CoV-2 are applicable to this setting.

At the roundtable there was discussion on an outbreak of SAR-COV-2 in residential aged care facilities that was attributed to an inadequate HVAC system that recirculated unfiltered indoor air.[1] The early release of an article in Emerging Infectious Disease, traced suspended airborne particles as the probable mode of transmission during managed isolation and quarantine in New Zealand.[2] These case studies suggest that airflow and ventilation may contribute to the transmission of SARS-CoV-2. As such additional precautions should be implemented to reduce the risk of exposure, particularly in situations where air change rates are low or limited. [3,4]

The relative contribution of SAR-CoV-2 transmission via airborne, droplet, direct physical contact and fomite/indirect contact routes has not been quantified. A number of articles attempted to quantify the viral load and dispersal of SARS-CoV-2 in droplets and aerosols produced by infected patients when breathing, talking and other vocal activities.[5,6,7] Associate Professor Robyn Schofield presented evidence at the roundtable on respiratory particle size and the potential for the transmission of SARS-CoV-2. Particles <100 micron (µm) in size can remain suspended in the air for a period of time and be inhaled because typical room air velocities exceed the terminal settling velocities of the particles.[8] Particles that evaporate to their nuclei (approximately 0.3 µm in size) can remain viable or stable for longer periods of time.[9,10] The evidence revealed that respiratory particles can remain suspended for hours and undergo complex movements and thermodynamic transformations (e.g. dehydration and evaporation) on emission depending on air flow, temperature and humidity.[11] This means ventilation can have both positive and negative impact on reducing exposure to infection airborne material.

Understanding the airflow and ventilation requirements of a building is complex and is influenced by its design, functions, HVAC system capability and operation, as well as environmental factors.[12] HVAC systems can create pressure differentials that affect the flow of air between rooms and into adjoining common areas (for example, corridors, lifts, stairwells, kitchens and offices).[13] When the air pressure in a room is lower than the air pressure outside the room, air will be drawn in from adjacent spaces, along with potentially infectious airborne pathogens. Conversely, opening an external door or window alters the air pressure and temperature in the room, causing air, and possibly infectious material, to flow out from the room and potentially exposing others.

At the roundtable, the benefit of a comprehensive assessment of a building's ventilation system by an occupational hygienist or HVAC engineer was discussed to be an appropriate way to understand how to airborne exposure can be minimised as air flows from the supply to the exhaust.

The evidence review identified a number of measures that can potentially reduce the risk of airborne transmission of SARS-CoV-2 by modifying airflow and ventilation in the hotel quarantine setting:

- Air should flow from clean to potentially contaminated spaces. This can be achieved through the manipulation of HVAC controls ie the positioning of supply and exhaust vents or by use of natural ventilation.[c]
- Ventilation rates should be maximised as much as possible and appropriate for the occupancy rate.[14]
- Recirculation of indoor air should be avoided/limited and the outdoor air exchange rates maximised.[15,16] The current Australian standard for building ventilation (AS 1668.2) guarantees some fresh air in a space however this may not be sufficient.[d]
- Additional controls to influence air flow include:
    - Displacement ventilation (outside air supplied at low speed from diffusers near floor level and extracted above the occupied zone, near or on the ceiling).[17,18]
    - The use of seals on door and windows to restrict air entry/escape or the installation of additional vents in hotel room doors to encourage air flow.
    - Installation of floor to ceiling screens to disturb airflow and limit exposure to air from contaminated spaces.[19] This can be used to protect staff from cumulative or interval exposures if they are located in a single location for a protracted period of time.
- Indoor temperature and relative humidity levels of 20-25°C and 40- 60% have demonstrated virus deactivation. Surrogate SARS-CoV-2 mRNA studies suggest that virus survival is affected by decreasing temperature and relative humidity.[5,6,7] There is fair evidence to suggest mucus membrane barriers and other immune system processes are impaired when the relative humidity is below 40%. Mid-range relative humidity, ie 40% and 60%, is also correlated with improved immunity against respiratory infections as well as providing unfavourable conditions for microorganisms.[e]
- In an enclosed space, the time to reduce the airborne viral concentration by 99% in a room occupied for a prolonged period by an infected person will be influenced on the number of air changes per hour of the ventilation system.[f]

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[c] https://www.cdc.gov/coronavirus/2019-ncov/community/ventilation.html

[d] https://www.standards.org.au/standards-catalogue/sa-snz/manufacturing/me-062/as--1668-dot-2-2012-archive

[e] ASHRAE Position Document on Infectious Aerosols, April 2020 https://www.ashrae.org/file%20library/about/position%20documents/pd_infectiousaerosols_2020.pdf

[f] https://www.cdc.gov/infectioncontrol/guidelines/environmental/appendix/air.html#tableb1

- Mechanical air filters, such as HEPA filters, are effective at removing airborne particles.[5,20] The placement and number required will be dependent on room size and an assessment of airflow and ventilation.[21] The use of portable air cleaners have been shown to be effective in indoor settings. An unpublished study in a clinical setting observed that commercially available portable air cleaners had an equivalent efficacy to physical barriers such as shields in reducing the circulation of potentially contaminated air flows, (discussed at the roundtable, Attachment B)
- Ultra violet germicidal irradiation (UVGI) has been shown to be effective at killing SARS-CoV-2 and is suggested for use in instances where ventilation cannot be improved.[22,23,24] Some modelling studied suggested that UV-C lamps can be used to create an upper room irradiation field in an occupied room.[9] However, the safety of this approach has not been demonstrated and this technology is currently unregulated in Australia. In addition, this technology requires specialist installation and higher cost compared to equivocally effective methods such as the use portable HEPA filters.
- Creation of a negative pressure environment could be created within a hotel room through the manipulation of the HVAC system. However, maintaining this state is challenging as a hotel is a dynamic environment where air pressure fluctuates with the movement of people through the building.
- Given SAR-CoV-2 modes of transmission there is the potential for the virus to settle on Personal Protective Equipment (PPE) and room surfaces. Aerosolised infectious particles may be produced on cleaning of surfaces (fomites) as well as during the removal of the PPE. So care needs to be taken in doffing areas and when cleaning rooms.[15]

Discussion at the roundtable suggested the layering of mitigation strategies, in accordance with the hierarchy of controls, to reduce the risk of exposure to airborne SARS-CoV-2. The hierarchy of controls ranks actions according to their effectiveness in limiting exposure to a hazard.[g] Based on the evidence gained from the literature review and the roundtable, Table 1 outlines a number of possible actions that can be considered.

Selection of the control relevant to a specific hotel should guide by the advice received through an individualised risk assessment of airflow.

[g] https://www.cdc.gov/niosh/topics/hierarchy/default.html

**Table 1.** Hierarchy of controls to manage the exposure to airborne SARS-CoV-2 in the hotel setting

| | Hierarchy of controls | Possible mitigations |
|---|---|---|
| **Effectiveness of control to prevent exposure** | **Elimination**<br>Measures that remove ability for airborne exposure | Remove the potential for hotel staff to be exposed, such as using CCTV to monitor hallways rather than have hotel security guards located on floors. |
| Most | **Engineering controls**<br>Measures that reduce airborne exposure without relying on human behaviour | • Modify HVAC controls that can reduce the risk of exposure include:<br>○ Ventilation rate: Introduce sufficient amounts of outdoor air.<br>○ Temperature: 20-25$^{0}$C is advised. The difference between indoor and outdoor air temperature can affect the efficiency of outdoor air intake rates as well as thermal comfort.<br>○ Relative humidity: between 40 and 60% for the purpose of disease mitigation this may be achievable through ventilation system. Alternate low cost options such as portable humidifiers or water bowls can be placed in rooms.<br>○ Airflow direction: isolate systems to limit air circulating between different areas in the building.<br>• Increase outdoor air exchange rate and limit the recirculation of unfiltered air, noting:<br>○ Outdoor air temperature can effect efficiency of mechanical ventilation system operation.<br>○ If a system monitors $CO_2$ consider the parameters in regard to filtering and intake of outside air as inactive environments usually have low $CO_2$ levels.<br>• Air cleaners or mechanical air filters, ie HEPA filters, be a part of the existing ventilation system and are effective at removing airborne infectious material. Otherwise portable air filtration units can be used in occupants' room and corridors.<br>• Physical Barrier Walls that offer floor to ceiling physical separation, such ZipWalls, can prevent airflow form potentially infected areas to clean areas, i.e. in front of areas staff occupy.<br>• The addition of air disinfection systems, such as (UVGI), can be considered for installation in exhaust vents prior to recirculation. However this requires specialised installation, other more cost effective methods, such as HEPA filtration, may be preferred.<br>• Disable an occupant's ability to turn system off or alter settings of the unit. This can assist with stabilising airflow but it needs to be balanced against personal comfort. |

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| | **Administrative controls**<br>Measures that people perform that reduces airborne exposure | • Regular cleaning of HVAC system, filters and purifiers should be done by an engineer or technician with appropriate training and awareness of infection prevention and control.<br>• Scheduling and coordination of activities of staff and occupants, this reduces the potential for incidental exposure to infectious airborne material due changes in air flow due to movement. For example hotel staff perform their duties near rooms when occupants' are restricted from leaving their rooms (ie open doors).<br>• Entry into a vacated room can be restricted for a set period of time to ensure a sufficient number of air exchanges have occurred thus lessening the concentration of potentially infectious material.<br>  ○ Based on a risk reduction of 99% of air clearance, the time required for clearance is dependant on the number of fresh-air exchanges per hour.<br>• Disable opening of external doors and windows, an individual facility assessment will need to determine what impact natural ventilation has on the risk of airborne transmission.<br>• Reinforce existing public health measures such as vaccination, physical distancing, frequent environmental cleaning of high touch surfaces, ensuring cleaning practices don't create aerosols.<br>• Cohorting – there may be benefit in grouping infected occupants to an area supplied by one ventilation system as a means of limiting potential exposure to others.<br>• Controlling of occupancy rates ensures that the facility has the ability to implement the appropriate engineering controls to operate their ventilation system properly and provide acceptable indoor air quality for the current occupancy level for each space. |
| **Least** | **PPE**<br>Physical barrier to protect from people for exposure | Use of gloves, gowns/protective clothing, eye protection and facemask as appropriate for the task. Face masks: N95 masks offer the best protection to aerosols and are effective at short (<2m) and long (>2m) range if worn appropriately. Surgical mask have shown to offer some protection at short range and if worn by the infected occupants assist in reducing exposure.[25,26] |

## Other considerations

- A better understanding of how transmission of SARS-CoV-2 has occurred in Australian hotel quarantine. The provision of outcomes from analyses of events by jurisdictions would assist in identifying contributing factors and assessing the risk and adequacy of mitigation measures currently in place.
- More information is required on superspreaders (individuals infected with SAR-CoV-2 that have high viral loads), whether they can be identified to reduce the exposure risk to those around them.
- Emerging technology for the sampling of room air for infective virus is undergoing testing/validation. This technology may be useful in the future hotel quarantine environment. NCHRAC provided advice in February 2021 on a range of emerging technologies for the detection of COVID-19 cases (see *NCHRAC Advice: New and novel methods for detection of COVID-19 cases*).
- NCHRAC is aware that the National COVID-19 Clinical Evidence Taskforce expert panel for infection prevention and control is currently assembling evidence looking at levels of ventilation, the efficacy of air purifiers and the impact of occupancy levels.

## Attachments

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| Attachment A: | Summary of literature |
| Attachment B: | Summary: Roundtable on role of airflow and/or ventilation in relation to SARS-CoV-2 transmission in quarantine arrangements |

## References

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Attachment A

**Summary of literature identified by the evidence review**

| Reference number, reference title | Source |
|---|---|
| Abstract | |
| Relevance and key points | |

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| Azimi, P., Keshavarz, Z., Cedeno Laurent, J. G., Stephens, B., & Allen, J. G. (2021). *Mechanistic transmission modeling of COVID-19 on the Diamond Princess cruise ship demonstrates the importance of aerosol transmission*. Proceedings of the National Academy of Sciences, 118(8), e2015482118. doi:10.1073/pnas.2015482118<br>3/2/2021 | PubMed search |
| "Several lines of existing evidence support the possibility of airborne transmission of coronavirus disease 2019 (COVID-19). However, quantitative information on the relative importance of transmission pathways of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) remains limited. To evaluate the relative importance of multiple transmission routes for SARS-CoV-2, we developed a modelling framework and leveraged detailed information available from the Diamond Princess cruise ship outbreak that occurred in early 2020. We modelled 21,600 scenarios to generate a matrix of solutions across a full range of assumptions for eight unknown or uncertain epidemic and mechanistic transmission factors. A total of 132 model iterations met acceptability criteria (R2 > 0.95 for modelled vs. reported cumulative daily cases and R2 > 0 for daily cases). Analyzing only these successful model iterations quantifies the likely contributions of each defined mode of transmission. Mean estimates of the contributions of short-range, long-range, and fomite transmission modes to infected cases across the entire simulation period were 35%, 35%, and 30%, respectively. Mean estimates of the contributions of larger respiratory droplets and smaller respiratory aerosols were 41% and 59%, respectively. Our results demonstrate that aerosol inhalation was likely the dominant contributor to COVID-19 transmission among the passengers, even considering a conservative assumption of high ventilation rates and no air recirculation conditions for the cruise ship. Moreover, close-range and long-range transmission likely contributed similarly to disease progression aboard the ship, with fomite transmission playing a smaller role. The passenger quarantine also affected the importance of each mode, demonstrating the impacts of the interventions." | |
| Study type – Case study of outbreak event.<br>Setting – The Diamond Princess cruise ship.<br>Mode of transmission – Modelling showed aerosol inhalation to be a significant transmission route during the Diamond Princess outbreak. Close-range transmission was defined as an area equivalent to a circle around the person with a radius of approximately 1.2m, and long-range was beyond that.<br>Model – The model could be applied to other indoor environments such as offices and schools. | |

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| Pease, L. F., Wang, N., Salsbury, T. I., Underhill, R. M., Flaherty, J. E., Vlachokostas, A., . . . James, D. P. (2021). *Investigation of potential aerosol transmission and infectivity of SARS-CoV-2 through central ventilation systems.* Building and Environment, 107633. doi: https://doi.org/10.1016/j.buildenv.2021.107633<br>29/1/2021. | PubMed search |
| "The COVID-19 pandemic has raised concern of viral spread within buildings. Although the near-field transmission and the infectious spread within individual rooms are well | |

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| studied, the impact of aerosolized spread of SARS-CoV-2 via air handling systems within buildings remains unexplored. This study evaluates the concentrations and probabilities of infection for both building interior and exterior exposure sources using a well-mixed model in a multi-room building served by a central air handling system (without packaged terminal air conditioning). In particular, we compare the influence of filtration, air change rates, and the fraction of outdoor air. When the air supplied to the rooms comprises both outdoor air and recirculated air, we find filtration lowers the concentration and probability of infection the most in both source and connected rooms. We find that increasing the air change rate removes virus from the source room faster but also increases the rate of exposure in connected rooms. Therefore, slower air change rates reduce infectivity in connected rooms at shorter durations. We further find that increasing the fraction of virus-free outdoor air is helpful, unless outdoor air is infective in which case pathogen exposure inside persists for hours after a short-term release. Increasing the outdoor air to 33% or the filter to MERV-13 decreases the infectivity in the connected rooms by 19% or 93% respectively, relative to a MERV-8 filter with 9% outdoor air based on 100 quanta/h of 5 µm droplets, a breathing rate of 0.48 m3/h, and the building dimensions and air handling system considered.” |
| <u>Study type</u> – Model of a multi-room building connected via a central air handling system.<br><u>Setting</u> – Virtual building.<br><u>HVAC controls</u> – Filtration of recirculated air was the found to be most effective in lowering the aerosol concentration and probability of infection via the HVAC system. Authors suggest outdoor air is the second most effective measure to reduce aerosol transmission but caution it can have impacts on energy use and thermal comfort. Authors suggest increasing air change rate should be considered with caution in case it increases the rate of aerosol spread through HVAC systems to connecting rooms.<br><u>Mode of transmission</u> – Potential spread through HVAC systems is supported by the model used. |

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| Passos, R. G., Silveira, M. B., & Abrahão, J. S. (2021). *Exploratory assessment of the occurrence of SARS-CoV-2 in aerosols in hospital facilities and public spaces of a metropolitan center in Brazil.* Environmental Research, 195, 110808. doi: https://doi.org/10.1016/j.envres.2021.110808<br>26/1/2021 | PubMed Search |
| “Although much has been discovered regarding the characteristics of SARS-CoV-2, its presence in aerosols and their implications in the context of the pandemic is still controversial. More research on this topic is needed to contribute to these discussions. Presented herein are the results of ongoing research to detect SARS-CoV-2 RNA in aerosol in different hospital facilities (indoor environments) and public spaces (outdoor environments) of a metropolitan center in Brazil. From May to August 2020, 62 samples were collected using active sampling method (air samplers with filters) and passive method (petri dishes) in two hospitals, with different occupancies and infrastructure for contamination control. Outdoor public spaces such as sidewalks and a bus station were also investigated. Five air samples from four facilities in a hospital tested positive for SARS-CoV-2 in suspended and sedimentable particles. SARS-CoV-2 was found in aerosols inside the Intensive Care Unit (ICU), in the protective apparel removal room, in the room containing patient mobile toilets and used clothes (room with natural ventilation) and in an external corridor adjacent to the ICU, probably coming from infected patients and/or from aerosolization of virus-laden particles on material/equipment. Our findings reinforce the hypothesis of airborne transmission of the new coronavirus, contributing to the planning of effective practices for pandemic control.” | |
| <u>Study type</u> – Primary research with air samples taken indoors and outdoors.<br><u>Setting</u> – Two hospitals and outdoor public spaces.<br><u>Mode of transmission</u> – The findings of the study support airborne transmission with the possibility of aerosolisation and spread over longer distances. | |

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| Controls – The importance of controlling occupancy rates of spaces is enforced by the findings.<br>Open Space – All samples were negative for SARS-CoV-2 RNA suggesting that dilution and dispersal can occur through wind and other environmental factors.<br>Further research – The authors suggest that specific studies are needed on air circulation in closed environments. |

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| Tang JW, Bahnfleth WP, Bluyssen PM, Buonanno G, Jimenez JL, Kurnitski J, Li Y, Miller S, Sekhar C, Morawska L, Marr LC, Melikov AK, Nazaroff WW, Nielsen PV, Tellier R, Wargocki P, Dancer SJ. *Dismantling myths on the airborne transmission of severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2).* J Hosp Infect. 2021 Jan 13;110:89-96. doi: 10.1016/j.jhin.2020.12.022.<br>13/1/2021 | PubMed Search |
| "The Covid-19 pandemic has caused untold disruption and enhanced mortality rates around the world. Understanding the mechanisms for transmission of SARS-CoV-2 is key to preventing further spread but there is confusion over the meaning of "airborne" whenever transmission is discussed. Scientific ambivalence originates from evidence published many years ago, which has generated mythological beliefs that obscure current thinking. This article gathers together and explores some of the most commonly held dogmas on airborne transmission in order to stimulate revision of the science in the light of current evidence. Six 'myths' are presented, explained, and ultimately refuted on the basis of recently published papers and expert opinion from previous work related to similar viruses. There is little doubt that SARS-CoV-2 is transmitted via a range of airborne particle sizes subject to all the usual ventilation parameters and human behaviour. Experts from specialties encompassing aerosol studies, ventilation, engineering, physics, virology and clinical medicine have joined together to present this review, in order to consolidate the evidence for airborne transmission mechanisms and offer justification for modern strategies for prevention and control of Covid-19 in healthcare and community." | |
| Study type – A multidisciplinary narrative review.<br>Setting – Multiple.<br>Mode of transmission – Authors note there is little direct evidence to support any specific pathway of transmission.<br>HVAC controls – Authors note there is sufficiently strong evidence to warrant targeting transmission controls to air handling systems such as avoiding HVAC systems that recirculate or mix air, enhancing particle filtration and effective ventilation. Opening windows is suggested to provide some reduction to the risk of infection from airborne viral particles.<br>Controls – Other effect controls include: measures to control crowding in indoor environments such as public transport are important as are cost effective and easy to implement controls to dilute airborne particle indoors.<br>The six myths that were addressed – (1) Aerosols are droplets with a diameter of 5µm or less (2) All particles larger than 5µm fall within 1-2m of the source (3) If it is short range, it cannot be airborne (4) If the basic reproductive number, $R_0$, is not as large as for measles, then it cannot be airborne (5a) If it is airborne, surgical masks (or cloth face coverings) will not work (5b) The virus is only 100nm (0.1µm) in size so filters and masks will not work (6) Unless it grows in tissue culture, it is not infectious. | |

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| Delikhoon, M., Guzman, M. I., Nabizadeh, R., & Norouzian Baghani, A. (2021). *Modes of Transmission of Severe Acute Respiratory Syndrome-Coronavirus-2 (SARS-CoV-2) and Factors Influencing on the Airborne Transmission: A Review.* International Journal of Environmental Research and Public Health, 18(2), 395. https://doi.org/10.3390/ijerph18020395<br>6/1/2021. | PubMed Search |

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| "The multiple modes of SARS-CoV-2 transmission including airborne, droplet, contact, and fecal–oral transmissions that cause coronavirus disease 2019 (COVID-19) contribute to a public threat to the lives of people worldwide. Herein, different databases are reviewed to evaluate modes of transmission of SARS-CoV-2 and study the effects of negative pressure ventilation, air conditioning system, and related protection approaches of this virus. Droplet transmission was commonly reported to occur in particles with diameter >5 μm that can quickly settle gravitationally on surfaces (1–2 m). Instead, fine and ultrafine particles (airborne transmission) can stay suspended for an extended period of time (≥2 h) and be transported further, e.g., up to 8 m through simple diffusion and convection mechanisms. Droplet and airborne transmission of SARS-CoV-2 can be limited indoors with adequate ventilation of rooms, by routine disinfection of toilets, using negative pressure rooms, using face masks, and maintaining social distancing. Other preventive measures recommended include increasing the number of screening tests of suspected carriers of SARS-CoV-2, reducing the number of persons in a room to minimize sharing indoor air, and monitoring people's temperature before accessing a building. The work reviews a body of literature supporting the transmission of SARS-CoV-2 through air, causing COVID-19 disease, which requires coordinated worldwide strategies." |
| <u>Study type</u> – Structured literature review.<br><u>Setting</u> – Multiple.<br><u>Mode of transmission</u> – Authors state airborne transmission is an important for the spread of SARS-CoV-2. Caution is also urged of the potential of aerosolisation of the virus that has settled on healthcare workers PPE and surfaces and sanitation of surfaces and protective equipment is crucial for reducing aerosol transmission from this source.<br><u>HVAC controls</u> – Air cleaning methods are suggested in association with HVAC systems such as: mechanical air filters, ultra-violet germicidal irradiation (UVGI), high-efficiency particulate air (HEPA) filters and ion generators. Other controls are recommended such as: adequate ventilation or good air-conditioning systems for rooms, utilization of negative pressure rooms, avoiding the direct airflow of others, reducing the number of individuals in a common place to minimise sharing indoor air. |

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| Moreno, T., Pintó, R. M., Bosch, A., Moreno, N., Alastuey, A., Minguillón, M. C., . . . Querol, X. (2021). *Tracing surface and airborne SARS-CoV-2 RNA inside public buses and subway trains.* Environment International, 147, 106326. doi: https://doi.org/10.1016/j.envint.2020.106326<br>9/12/2020 | PubMed Search |
| "Given the widespread concern but general lack of information over the possibility of SARS-CoV-2 infection in public transport, key issues such as passenger personal hygiene, efficient air circulation systems, and the effective disinfection of frequently touched surfaces need to be evaluated to educate the public and diminish the risk of viral transmission as we learn to live with the ongoing pandemic. In this context we report on a study involving the collection of 99 samples taken from inside Barcelona buses and subway trains in May to July 2020. From this sample group 82 (58 surface swabs, 9 air conditioning (a/c) filters, 3 a/c dust, 12 ambient air) were selected to be analysed by RT-PCR for traces of the SARS-CoV-2 virus. Thirty of these selected samples showed evidence for one or more of 3 target RNA gene regions specific for this virus (IP2, IP4, E). Most (24) of these 30 samples showed positivity for only 1 of the 3 RNA targets, 4 samples yielded 2 targets, and 2 samples provided evidence for all 3 targets. RNA remnants were more common in surface swabs from support bars (23 out of 58) than in ambient air inside the vehicles (3 out of 12), with relatively higher concentrations of viral RNA fragments in buses rather than in trains. Whereas subway train a/c filters examined were all virus-free, 4 of the 9 bus a/c filter/dust samples yielded evidence for viral RNA. After nocturnal maintenance and cleaning most buses initially yielding positive results subsequently showed elimination of the RT-PCR signal, although signs of viral RNA remained in 4 of 13 initially positive samples. The presence of such remnant viral traces however does not demonstrate infectivity, which in the | |

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| present study is considered unlikely given the fragmentary nature of the gene targets detected. Nevertheless, best practice demands that close attention to ventilation systems and regular vehicle disinfection in public transport worldwide need to be rigorously applied to be effective at eliminating traces of the virus throughout the vehicle, especially at times when COVID-19 cases are peaking. Additionally, infectivity tests should be implemented to evaluate the efficiency of disinfection procedures to complement the information resulting from RT-PCR analysis. Modelling the probability of infection whilst travelling in buses under different scenarios indicates that forced ventilation greatly reduces the risk.” |
| Study type – Primary research with air and surface samples taken indoors in high foot traffic areas and outside the high traffic areas.<br>Setting – Public transport.<br>Presence of SARS-CoV-2 – Our findings demonstrate that traces of the SARS-CoV-2 viral genome can be detected within public transport vehicles, both on surfaces inside the vehicle and in the ambient air. Although in the case of this study evidence for concentrations of the viral genome was fragmentary, generally weak, and the chances of infectivity considered to be extremely low, our data identified a need for tightening up cleaning procedures.<br>Controls – Obvious ways of reducing the risk of infection in the closed spaces typical of public transport vehicles involve increasing the ventilation (uptake of external air), developing best practice disinfection protocols, and insisting on personal mask protection. |

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| Jarvis, M. C. (2020). *Aerosol Transmission of SARS-CoV-2: Physical Principles and Implications*. Frontiers in Public Health, 8(813). doi:10.3389/fpubh.2020.590041<br>23/11/2020 | PubMed Search |
| “Evidence has emerged that SARS-CoV-2, the coronavirus that causes COVID-19, can be transmitted airborne in aerosol particles as well as in larger droplets or by surface deposits. This minireview outlines the underlying aerosol science, making links to aerosol research in other disciplines. SARS-CoV-2 is emitted in aerosol form during normal breathing by both asymptomatic and symptomatic people, remaining viable with a half-life of up to about an hour during which air movement can carry it considerable distances, although it simultaneously disperses. The proportion of the droplet size distribution within the aerosol range depends on the sites of origin within the respiratory tract and on whether the distribution is presented on a number or volume basis. Evaporation and fragmentation reduce the size of the droplets, whereas coalescence increases the mean droplet size. Aerosol particles containing SARS-CoV-2 can also coalesce with pollution particulates, and infection rates correlate with pollution. The operation of ventilation systems in public buildings and transportation can create infection hazards via aerosols, but provides opportunities for reducing the risk of transmission in ways as simple as switching from recirculated to outside air. There are also opportunities to inactivate SARS-CoV-2 in aerosol form with sunlight or UV lamps. The efficiency of masks for blocking aerosol transmission depends strongly on how well they fit. Research areas that urgently need further experimentation include the basis for variation in droplet size distribution and viral load, including droplets emitted by “superspreader” individuals; the evolution of droplet sizes after emission, their interaction with pollutant aerosols and their dispersal by turbulence, which gives a different basis for social distancing.” | |
| Study type: Narrative review<br>Mode of transmission: Because aerosol transmission does not require coughing but is possible through normal breathing, asymptomatic individuals can infect others by this route. The quantitative importance of aerosol transmission relative to transmission by other routes is still under debate and may vary between environments, but the precautionary principle demands that measures to block this transmission route should be vigorously adopted. | |

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| HVAC Controls: If possible, air should not flow from any person toward other people, especially at face height. Measures for clean air include recirculating air through HEPA filters, ventilating with outside rather than recirculated air, opening windows, using portable air filtration units and using screens to disturb the airflow. Buildings may need individual assessment. |

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| Noorimotlagh, Z., Jaafarzadeh, N., Martínez, S. S., & Mirzaee, S. A. (2021). *A systematic review of possible airborne transmission of the COVID-19 virus (SARS-CoV-2) in the indoor air environment.* Environmental Research, 193, 110612. doi: https://doi.org/10.1016/j.envres.2020.110612<br>10/12/2020 | PubMed Search |
| "At the end of December 2019, the rapid spread of the COVID-19 (SARS-CoV-2) disease and, subsequently, deaths around the world, lead to the declaration of the pandemic situation in the world. At the beginning of the epidemic, much attention is paid to person-to-person transmission, disinfection of virus-contaminated surfaces, and social distancing. However, there is much debate about the routes of disease transmission, including airborne transmission, so it is important to elucidate the exact route of transmission of the COVID-19 disease. To this end, the first systematic review study was conducted to comprehensively search all databases to collect studies on airborne transmission of SARS-CoV-2 in indoor air environments. In total, 14 relevant and eligible studies were included. Based on the findings, there is a great possibility of airborne transmission of SARS-CoV-2 in indoor air environments. Therefore, some procedures are presented such as improving ventilation, especially in hospitals and crowded places, and observing the interpersonal distance of more than 2 m so that experts in indoor air quality consider them to improve the indoor air environments. Finally, in addition to the recommendations of the centers and official authorities such as hand washing and observing social distancing, the route of air transmission should also be considered to further protect health personnel, patients in hospitals, and the public in other Public Buildings." | |
| Study type: Systematic review.<br>Setting: Indoor environments.<br>Mode of transmission: 14 relevant and eligible studies were reviewed. According to the findings of the reviewed studies, there is an important and strong possibility of airborne transmission of SARS-CoV-2 in indoor air environments.<br>HVAC controls: Suggested controls include providing displacement ventilation (outside air supplied at low speed from diffusers near floor level and extracted above the occupied zone, near or on the ceiling), redesigning and increasing the existing ventilation rate and efficiency, use of portable air cleaners, establish a minimum relative humidity standard for indoor environments. Maintenance of ventilation systems, as well as filters or disinfectants in air purifiers, is of the utmost importance.<br>Controls: Isolate the COVID-19 patient with high viral loads in the exhaled air in the first weeks of infection, maintain physical distancing, use face masks, avoid overcrowding of indoor environments, case tracking, isolation and quarantine, hand washing and the use of materials to disinfect surfaces in crowded places. | |

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| Buchan, A.G., Yang, L. & Atkinson, K.D. *Predicting airborne coronavirus inactivation by far-UVC in populated rooms using a high-fidelity coupled radiation-CFD model*. Sci Rep 10, 19659 (2020). https://doi.org/10.1038/s41598-020-76597-y<br>12/11/2020 | PubMed Search |
| "There are increased risks of contracting COVID-19 in hospitals and long-term care facilities, particularly for vulnerable groups. In these environments aerosolised coronavirus released through breathing increases the chance of spreading the disease. To reduce aerosol transmissions, the use of low dose far-UVC lighting to disinfect in- | |

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| room air has been proposed. Unlike typical UVC, which has been used to kill microorganisms for decades but is carcinogenic and cataractogenic, recent evidence has shown that far-UVC is safe to use around humans. A high-fidelity, fully-coupled radiation transport and fluid dynamics model has been developed to quantify disinfection rates within a typical ventilated room. The model shows that disinfection rates are increased by a further 50-85% when using far-UVC within currently recommended exposure levels compared to the room's ventilation alone. With these magnitudes of reduction, far-UVC lighting could be employed to mitigate SARS-CoV-2 transmission before the onset of future waves, or the start of winter when risks of infection are higher. This is particularly significant in poorly-ventilated spaces where other means of reduction are not practical, in addition social distancing can be reduced without increasing the risk." |
| Study type: Model of a single occupancy private room.<br>Setting: Hospitals and long-term care facilities.<br>Controls: "Even in highly-ventilated rooms where satisfactory levels of removal may already exist, far-UVC illumination will further reduce viral concentrations by around 57%." Advantages of in-room far-UVC are that it is not tied to human behaviour and therefore risk of complacency, it would reduce aerosolised SARS-CoV-2 concentrations within a metre of the patient and thus reduce physical distancing limits, and the scenarios showed it would reduce in-room SARS-CoV-2 concentrations to levels comparable to that provided practically by breathing through an N95 mask and therefore could possibly reduce the need and demand for PPE supplies. |

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| Nissen, K., Krambrich, J., Akaberi, D. et al. *Long-distance airborne dispersal of SARS-CoV-2 in COVID-19 wards.* Sci Rep 10, 19589 (2020). https://doi.org/10.1038/s41598-020-76442-2<br>11/11/2020 | PubMed Search |
| "Evidence suggests that SARS-CoV-2, as well as other coronaviruses, can be dispersed and potentially transmitted by aerosols directly or via ventilation systems. We therefore investigated ventilation openings in one COVID-19 ward and central ducts that expel indoor air from three COVID-19 wards at Uppsala University Hospital, Sweden, during April and May 2020. Swab samples were taken from individual ceiling ventilation openings and surfaces in central ducts. Samples were subsequently subjected to rRT-PCR targeting the N and E genes of SARS-CoV-2. Central ventilation HEPA filters, located several stories above the wards, were removed and portions analyzed in the same manner. In two subsequent samplings, SARS-CoV-2 N and E genes were detected in seven and four out of 19 room vents, respectively. Central ventilation HEPA exhaust filters from the ward were found positive for both genes in three samples. Corresponding filters from two other, adjacent COVID-19 wards were also found positive. Infective ability of the samples was assessed by inoculation of susceptible cell cultures but could not be determined in these experiments. Detection of SARS-CoV-2 in central ventilation systems, distant from patient areas, indicate that virus can be transported long distances and that droplet transmission alone cannot reasonably explain this, especially considering the relatively low air change rates in these wards. Airborne transmission of SARS-CoV-2 must be taken into consideration for preventive measures." | |
| Study type: Primary research with samples taken from ventilation openings and central ducts.<br>Setting: three COVID-19 wards in a hospital in Sweden.<br>Mode of transmission: The presented findings indicate airborne dissemination of SARS-CoV-2, especially considering the distance SARS-CoV-2 RNA was dispersed. "The apparent capability of the virus to be transported in air, as we present here, should raise concerns for the risk of infection in smaller, confined spaces in close proximity to contagious patients".<br>HVAC controls: Recommended that service personnel take adequate protective measures while working with the ventilation systems. | |

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| Kennedy, M., Lee, S. J., & Epstein, M. (2021). *Modeling aerosol transmission of SARS-CoV-2 in multi-room facility.* Journal of Loss Prevention in the Process Industries, 69, 104336. doi: https://doi.org/10.1016/j.jlp.2020.104336<br>5/11/2020 | PubMed Search |
| "The versatile and computationally attractive FATE™ facility software package for analyzing the transient behavior of facilities during normal and off-normal conditions is applied to the problem of SARS-CoV-2 virus transmission in single-and multi-room facilities. Subject to the justifiable assumptions of non-interacting virus droplets, room-wide spatially homogeneous virus droplet aerosols and droplet sedimentation in accordance with Stokes law; the FATE code tracks the virus aerosol from a human source through a facility with a practical ventilation system which reconditions, filters, and recycles the air. The results show that infection risk can be reduced by 50 percent for increased facility airflow, 70 percent for increased airflow and the inclusion of a HEPA filter on recirculated ventilation air, and nearly 90 percent for increased airflow, inclusion of a HEPA filter, and wearing a mask. These results clearly indicate that there are operational changes and engineering measures which can reduce the potential infection risk in multi-room facilities." | |
| Type of study: Mechanistic model.<br>Setting: Single-region and multi-region settings<br>HVAC controls: "the FATE model shows that for a single room continuously purging the room atmosphere with outside air and wearing masks are effective measures for reducing infection risk. For a multi-room facility, ventilation, with HEPA filters for recirculated air, together with wearing masks reduces the infection risk. Without HEPA filters, the recirculated air can spread virus aerosols to other rooms sharing the same ventilation system." | |

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| Lelieveld, J., Helleis, F., Borrmann, S., Cheng, Y., Drewnick, F., Haug, G., Pöschl, U. (2020). *Model Calculations of Aerosol Transmission and Infection Risk of COVID-19 in Indoor Environments*. International Journal of Environmental Research and Public Health, 17(21), 8114.<br>https://doi.org/10.3390/ijerph17218114<br>3/11/2020 | PubMed Search |
| "The role of aerosolized SARS-CoV-2 viruses in airborne transmission of COVID-19 has been debated. The aerosols are transmitted through breathing and vocalization by infectious subjects. Some authors state that this represents the dominant route of spreading, while others dismiss the option. Here we present an adjustable algorithm to estimate the infection risk for different indoor environments, constrained by published data of human aerosol emissions, SARS-CoV-2 viral loads, infective dose and other parameters. We evaluate typical indoor settings such as an office, a classroom, choir practice, and a reception/party. Our results suggest that aerosols from highly infective subjects can effectively transmit COVID-19 in indoor environments. This "highly infective" category represents approximately 20% of the patients who tested positive for SARS-CoV-2. We find that "super infective" subjects, representing the top 5–10% of subjects with a positive test, plus an unknown fraction of less—but still highly infective, high aerosol-emitting subjects—may cause COVID-19 clusters (>10 infections). In general, active room ventilation and the ubiquitous wearing of face masks (i.e., by all subjects) may reduce the individual infection risk by a factor of five to ten, similar to high-volume, high-efficiency particulate air (HEPA) filtering. A particularly effective mitigation measure is the use of high-quality masks, which can drastically reduce the indoor infection risk through aerosols." | |
| Study type: Model of environmental factors<br>Setting: Single-region and multi-region. | |

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| Controls: Active ventilation with outside air, ubiquitous wearing of face masks and air filtering.<br>Model: "the model can be used to quantify the effectiveness of various measures taken to reduce the airborne transmission of the virus as the model can be easily modified to represent different confinement settings and ventilation networks". |

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| Zhang, X. S., & Duchaine, C. (2020). *SARS-CoV-2 and Health Care Worker Protection in Low-Risk Settings: a Review of Modes of Transmission and a Novel Airborne Model Involving Inhalable Particles*. Clinical Microbiology Reviews, 34(1), e00184-00120. doi:10.1128/cmr.00184-20<br>28/10/2020 | PubMed Search |
| "Since the beginning of the COVID-19 pandemic, there has been intense debate over SARS-CoV-2's mode of transmission and appropriate personal protective equipment for health care workers in low-risk settings. The objective of this review is to identify and appraise the available evidence (clinical trials and laboratory studies on masks and respirators, epidemiological studies, and air sampling studies), clarify key concepts and necessary conditions for airborne transmission, and shed light on knowledge gaps in the field. We find that, except for aerosol-generating procedures, the overall data in support of airborne transmission—taken in its traditional definition (long-distance and respirable aerosols)—are weak, based predominantly on indirect and experimental rather than clinical or epidemiological evidence. Consequently, we propose a revised and broader definition of "airborne," going beyond the current droplet and aerosol dichotomy and involving short-range inhalable particles, supported by data targeting the nose as the main viral receptor site. This new model better explains clinical observations, especially in the context of close and prolonged contacts between health care workers and patients, and reconciles seemingly contradictory data in the SARS-CoV-2 literature. The model also carries important implications for personal protective equipment and environmental controls, such as ventilation, in health care settings. However, further studies, especially clinical trials, are needed to complete the picture." | |
| Study type: Narrative review<br>Setting: Low-risk healthcare settings.<br>Mode of transmission: "While airborne transmission exists under certain conditions, there is limited direct evidence of it, especially in low-risk health care settings. We must therefore rely primarily on clinical evidence (trials on masks and epidemiological studies) to study transmission; for now, it suggests that the classic airborne route is not significant. A broader airborne model, involving the short-range inhalation route, could better explain current observations." "Transmission of short-range airborne and inhalable aerosols could explain the seemingly contradictory finding that there are viruses in the air and transmission between individuals without contact, but lack of convincing clinical evidence of classic airborne transmission (i.e., long-distance ranges and superiority of respirators)." "In summary, traditional droplets (larger particles with ballistic behavior that deposit onto surfaces), as well as our newly defined inhalable aerosols (particles that can be suspended, breathed in, and impacted at the nose, at the location of highest infectivity), could be the predominant modes of transmission of SARS-CoV-2."<br>Conditions that seem associated with airborne transmission are crowdedness, air currents, poor ventilation, prolonged exposure and close proximity.<br>Controls: Active ventilation with outside air, the ubiquitous wearing of face masks and air filtering. | |

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| Comber, L., O Murchu, E., Drummond, L., Carty, P.G., Walsh, K.A., De Gascun, C.F., Connolly, M.A., Smith, S.M., O'Neill, M., Ryan, M. and Harrington, P. (2021), *Airborne transmission of SARS-CoV-2 via aerosols.* Rev Med Virol e2184.<br>https://doi.org/10.1002/rmv.2184 | PubMed Search |

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| "A key consideration in the Covid-19 pandemic is the dominant modes of transmission of the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) virus. The objective of this review was to synthesise the evidence for the potential airborne transmission of SARS-CoV-2 via aerosols. Systematic literature searches were conducted in PubMed, Embase, Europe PMC and National Health Service UK evidence up to 27 July 2020. A protocol was published and Cochrane guidance for rapid review methodology was adhered to throughout. Twenty-eight studies were identified. Seven out of eight epidemiological studies suggest aerosol transmission may occur, with enclosed environments and poor ventilation noted as possible contextual factors. Ten of the 16 air sampling studies detected SARS-CoV-2 ribonucleic acid; however, only three of these studies attempted to culture the virus with one being successful in a limited number of samples. Two of four virological studies using artificially generated aerosols indicated that SARS-CoV-2 is viable in aerosols. The results of this review indicate there is inconclusive evidence regarding the viability and infectivity of SARS-CoV-2 in aerosols. Epidemiological studies suggest possible transmission, with contextual factors noted. Viral particles have been detected in air sampling studies with some evidence of clinical infectivity, and virological studies indicate these particles may represent live virus, adding further plausibility. However, there is uncertainty as to the nature and impact of aerosol transmission of SARS-CoV-2, and its relative contribution to the Covid-19 pandemic compared with other modes of transmission." | |
| Study type: Rapid review.<br>Mode of transmission: "The results of this review present a collection of evidence from a range of study designs regarding the potential for airborne transmission of SARS-CoV-2 via aerosols. Limited, low quality evidence from a small number of retrospective epidemiological studies suggests possible aerosol transmission of SARS-CoV-2. Furthermore, results from air sampling and virological studies add some plausibility to the potential for SARS-CoV-2 to transmit via aerosols, with limited evidence of clinical infectivity. Overall, while there is some evidence to suggest a potential for SARS-CoV-2 to transmit via aerosols, it is uncertain what contribution it makes, relative to other transmission modes (droplet and contact), to the COVID-19 pandemic and whether such transmission is context dependent, for example low temperature, poorly ventilated or enclosed environments." | |

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| Beggs CB, Avital EJ. 2020. *Upper-room ultraviolet air disinfection might help to reduce COVID-19 transmission in buildings: a feasibility study*. PeerJ 8:e10196<br>https://doi.org/10.7717/peerj.10196<br>13/10/2020 | PubMed Search |
| "As the world's economies come out of the lockdown imposed by the COVID-19 pandemic, there is an urgent need for technologies to mitigate COVID-19 transmission in confined spaces such as buildings. This feasibility study looks at one such technology, upper-room ultraviolet (UV) air disinfection, that can be safely used while humans are present in the room space, and which has already proven its efficacy as an intervention to inhibit the transmission of airborne diseases such as measles and tuberculosis. Using published data from various sources, it is shown that the SARS-CoV-2 virus, the causative agent of COVID-19, is highly likely to be susceptible to UV-C damage when suspended in air, with a UV susceptibility constant likely to be in the region 0.377–0.590 m2/J, similar to that for other aerosolised coronaviruses. As such, the UV-C flux required to disinfect the virus is expected to be acceptable and safe for upper-room applications. Through analysis of expected and worst-case scenarios, the efficacy of the upper-room UV-C approach for reducing COVID-19 transmission in confined spaces (with moderate but sufficient ceiling height) is demonstrated. Furthermore, it is shown that with SARS-CoV-2, it should be possible to achieve high equivalent air change rates using upper-room UV air disinfection, suggesting that the technology might be particularly applicable to poorly ventilated spaces." | |
| Study type: Review and model. | |

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| <u>Controls</u>: The model results suggest that upper-room UVGI, if applied correctly, should be effective at disinfecting SARS-CoV-2 virions suspended in respiratory droplets in the air. It is important to carefully consider the air movement in the room space, in order to eliminate stagnant regions and maximise air movement through the UV field. "One major advantage of upper-room UVGI is that it can be retrospectively fitted into buildings provided that the floor to ceiling height is large enough to ensure that the UV field does not impinge on room occupants". "upper-room UVGI may have potential as an intervention to inhibit the transmission of COVID-19 in buildings, especially in situations where achieving high ventilation rates might otherwise be impractical." |

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| Shao S, Zhou D, He R, Li J, Zou S, Mallery K, Kumar S, Yang S, Hong J. *Risk assessment of airborne transmission of COVID-19 by asymptomatic individuals under different practical settings*. J Aerosol Sci. 2021 Jan;151:105661. doi: 10.1016/j.jaerosci.2020.105661.<br>16/9/2020 | PubMed Search |
| "The lack of quantitative risk assessment of airborne transmission of COVID-19 under practical settings leads to large uncertainties and inconsistencies in our preventive measures. Combining in situ measurements and computational fluid dynamics simulations, we quantify the exhaled particles from normal respiratory behaviors and their transport under elevator, small classroom, and supermarket settings to evaluate the risk of inhaling potentially virus-containing particles. Our results show that the design of ventilation is critical for reducing the risk of particle encounters. Inappropriate design can significantly limit the efficiency of particle removal, create local hot spots with orders of magnitude higher risks, and enhance particle deposition causing surface contamination. Additionally, our measurements reveal the presence of a substantial fraction of faceted particles from normal breathing and its strong correlation with breathing depth." | |
| <u>Study type</u>: Primary research of particle generation during normal breathing and modelling of enclosed spaces.<br><u>Setting</u>: Elevator, small classroom and supermarket. "Our study can be further extended to a broad range of practical settings (e.g., air cabin, restaurant, gym, etc.) with more detailed physics (e.g., exhalation, inhalation flow physics, etc.) and individual characteristics (e.g., exhalation behavior, movement, etc.) as well as more precise HVAC models incorporated to yield more accurate risk assessment under these settings."<br><u>HVAC controls</u>: Optimising ventilation settings (e.g. adding more sites of ventilation) can significantly improve the efficiency of particle removal.<br><u>Controls</u>: Adjusting the placement of occupants in the room to avoid hot spots, frequent cleaning of surfaces prone to contamination, mask wearing. | |

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| Buonanno G, Morawska L, Stabile L. *Quantitative assessment of the risk of airborne transmission of SARS-CoV-2 infection: Prospective and retrospective applications*. Environ Int. 2020 Dec;145:106112. doi: 10.1016/j.envint.2020.106112.<br>6/9/2020 | PubMed Search |
| "Airborne transmission is a recognized pathway of contagion; however, it is rarely quantitatively evaluated. The numerous outbreaks that have occurred during the SARS-CoV-2 pandemic are putting a demand on researchers to develop approaches capable of both predicting contagion in closed environments (predictive assessment) and analyzing previous infections (retrospective assessment).<br>This study presents a novel approach for quantitative assessment of the individual infection risk of susceptible subjects exposed in indoor microenvironments in the presence of an asymptomatic infected SARS-CoV-2 subject. The application of a Monte Carlo method allowed the risk for an exposed healthy subject to be evaluated or, starting from an acceptable risk, the maximum exposure time. We applied the proposed | |

approach to four distinct scenarios for a prospective assessment, highlighting that, in order to guarantee an acceptable risk of 10−3 for exposed subjects in naturally ventilated indoor environments, the exposure time could be well below one hour. Such maximum exposure time clearly depends on the viral load emission of the infected subject and on the exposure conditions; thus, longer exposure times were estimated for mechanically ventilated indoor environments and lower viral load emissions. The proposed approach was used for retrospective assessment of documented outbreaks in a restaurant in Guangzhou (China) and at a choir rehearsal in Mount Vernon (USA), showing that, in both cases, the high attack rate values can be justified only assuming the airborne transmission as the main route of contagion. Moreover, we show that such outbreaks are not caused by the rare presence of a superspreader, but can be likely explained by the co-existence of conditions, including emission and exposure parameters, leading to a highly probable event, which can be defined as a "superspreading event"."

Study type: Modelling assessment of risk of airborne transmission of SARS-CoV-2
Setting: Indoor microenvironments.
Controls: "For all the scenarios investigated, the ventilation conditions strongly influence the risk (or the exposure time) of the exposed subject". "In the case of prospective assessments great attention must be paid to (i) the situations where specific expiratory activity and/or physical activities are conducted (e.g. subjects singing or speaking aloud, or are engaged in heavy exercising activity) as they can lead to high quanta concentrations and, then, risk, also in large closed environments; (ii) crowded indoor environments and air exchange rates which could lead to basic reproduction number R0 > 1 also with reduced exposure times. Indeed, the findings of the study revealed that, the exposure times that guarantee an acceptable risk are very limited in typical environments with natural ventilation. In the case of high forced ventilation, the exposure times are longer, but are well below one hour"
Model: "The proposed approach is of great relevance as it represents an essential tool to be applied in enclosed space, and it can support public health experts, engineers and epidemiologists in planning exposure times for populations in indoor environments during an epidemic."

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| Dai, H., Zhao, B. *Association of the infection probability of COVID-19 with ventilation rates in confined spaces*. Build. Simul. 13, 1321–1327 (2020). https://doi.org/10.1007/s12273-020-0703-5<br>4/8/2020 | PubMed Search |

"A growing number of cases have proved the possibility of airborne transmission of the coronavirus disease 2019 (COVID-19). Ensuring an adequate ventilation rate is essential to reduce the risk of infection in confined spaces. In this study, we estimated the association between the infection probability and ventilation rates with the Wells-Riley equation, where the quantum generation rate (q) by a COVID-19 infector was obtained using a reproductive number-based fitting approach. The estimated q value of COVID-19 is 14–48 h−1. To ensure an infection probability of less than 1%, a ventilation rate larger than common values (100–350 m3/h per infector and 1200–4000 m3/h per infector for 0.25 h and 3 h of exposure, respectively) is required. If the infector and susceptible person wear masks, then the ventilation rate ensuring a less than 1% infection probability can be reduced to a quarter respectively, which is easier to achieve by the normal ventilation mode applied in typical scenarios, including offices, classrooms, buses, and aircraft cabins. Strict preventive measures (e.g., wearing masks and preventing asymptomatic infectors from entering public spaces using tests) that have been widely adopted should be effective in reducing the risk of infection in confined spaces."

Study type: Mathematical modelling of ventilation rate and infection risk.
Setting: Enclosed spaces.
HVAC Controls: "The Infection probability less than 1% requires ventilation rate larger than 100–350 $m^3$/h per infector and 1200– 4000 $m^3$/h per infector for 0.25 h and 3 h of exposure."

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| Mode of transmission: "Although the transmission of COVID-19 occurs mainly via droplets during close contact or via contaminated surfaces, a recent study showed that SARS-CoV-2 remains viable in aerosols for multiple hours." |

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| Chirico, F., Sacco, A., Bragazzi, N. L., & Magnavita, N. (2020). *Can Air-Conditioning Systems Contribute to the Spread of SARS/MERS/COVID-19 Infection? Insights from a Rapid Review of the Literature*. International Journal of Environmental Research and Public Health, 17(17), 6052. https://doi.org/10.3390/ijerph17176052<br>20/8/2020 | PubMed Search |
| "The airborne transmission of SARS-CoV-2 is still debated. The aim of this rapid review is to evaluate the COVID-19 risk associated with the presence of air-conditioning systems. Original studies (both observational and experimental researches) written in English and with no limit on time, on the airborne transmission of SARS-CoV, MERS-CoV, and SARS-CoV-2 coronaviruses that were associated with outbreaks, were included. Searches were made on PubMed/MEDLINE, PubMed Central (PMC), Google Scholar databases, and medRxiv. A snowball strategy was adopted to extend the search. Fourteen studies reporting outbreaks of coronavirus infection associated with the air-conditioning systems were included. All studies were carried out in the Far East. In six out the seven studies on SARS, the role of Heating, Ventilation, and Air Conditioning (HVAC) in the outbreak was indirectly proven by the spatial and temporal pattern of cases, or by airflow-dynamics models. In one report on MERS, the contamination of HVAC by viral particles was demonstrated. In four out of the six studies on SARS-CoV-2, the diffusion of viral particles through HVAC was suspected or supported by computer simulation. In conclusion, there is sufficient evidence of the airborne transmission of coronaviruses in previous Asian outbreaks, and this has been taken into account in the guidelines released by organizations and international agencies for controlling the spread of SARS-CoV-2 in indoor environments. However, the technological differences in HVAC systems prevent the generalization of the results on a worldwide basis. The few COVID-19 investigations available do not provide sufficient evidence that the SARS-CoV-2 virus can be transmitted by HVAC systems." | |
| Study type: Rapid review of the literature concerning outbreaks of coronaviruses (SARS-CoV-1, MERS-CoV, and SARS-CoV-2).<br>Setting: Indoor environments.<br>Mode of transmission: "In summary, in four out of the six studies on SARS-CoV-2, the diffusion of viral particles through HVAC was suspected or supported by computer simulation, while in the other two studies, it was excluded based on epidemiological considerations." | |

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| Melikov AK, Ai ZT, Markov DG. *Intermittent occupancy combined with ventilation: An efficient strategy for the reduction of airborne transmission indoors.* Sci Total Environ. 2020 Nov 20;744:140908. doi: 10.1016/j.scitotenv.2020.140908.<br>15/7/2020 | PubMed Search |
| "It is important that efficient measures to reduce the airborne transmission of respiratory infectious diseases (including COVID-19) should be formulated as soon as possible to ensure a safe easing of lockdown. Ventilation has been widely recognized as an efficient engineering control measure for airborne transmission. Room ventilation with an increased supply of clean outdoor air could dilute the expiratory airborne aerosols to a lower concentration level. However, sufficient increase is beyond the capacity of most of the existing mechanical ventilation systems that were designed to be energy efficient under non-pandemic conditions. We propose an improved control strategy based on source control, which would be achieved by implementing intermittent breaks in room occupancy, specifically that all occupants should leave the room periodically and the room occupancy time should be reduced as much as possible. Under the assumption of | |

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| good mixing of clean outdoor supply air with room air, the evolution of the concentration in the room of aerosols exhaled by infected person(s) is predicted. The risk of airborne cross-infection is then evaluated by calculating the time-averaged intake fraction. The effectiveness of the strategy is demonstrated for a case study of a typical classroom. This strategy, together with other control measures such as continuous supply of maximum clean air, distancing, face-to-back layout of workstations and reducing activities that increase aerosol generation (e.g., loudly talking and singing), is applicable in classrooms, offices, meeting rooms, conference rooms, etc." |
| Study type: Modelling of ventilation and exposure.<br>Setting: Classrooms.<br>HVAC controls: "Ventilation systems supplying clean outdoor air should be operated continuously with the maximum supply airflow rate. It is recommended that steady-state conditions in the room in terms of the supply airflow rate should exist at the time when occupation begins, i.e. the ventilation should be in operation before any occupants enter the room"<br>"Supply of additional air to the room with stand-alone air-handling units, window fans, etc. is recommended, at least during breaks. Possible draught and noise problems due to the high supply air velocity will limit the increased supply airflow rate. In this case the additional equivalent ventilation rate can be complemented with a stand-alone room air cleaner, efficient filtration of air recirculation, and air disinfection. The need to heat any additionally supplied air is another limitation during winter."<br>Controls: Physical distancing, mask wearing, reducing aerosol generating activities such as singing. |

Articles identified at the roundtable

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| US National Academies of Sciences Engineering and Medicine Conference Proceedings. *Airborne Transmission of SARS-CoV-2: Proceedings of a Workshop—in Brief (October, 2020).* https://www.nap.edu/catalog/25958/airborne-transmission-of-sars-cov-2-proceedings-of-a-workshop | Expert |
| "With the rapidly evolving coronavirus disease 2019 (COVID-19) pandemic, researchers are racing to find answers to critical questions about the virus that causes the disease severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). Understanding how the virus is transmitted is among the most important questions, as it will inform efforts to stop its spread. For example, can the virus be transmitted via speech and exhaled breath? How long can aerosols containing the virus linger in the air? How far can these aerosols travel? Is the amount of virus in these aerosols enough to cause infection? These questions and more were the subject of an August 26–27, 2020, National Academies of Sciences, Engineering, and Medicine virtual workshop that convened experts in aerosol science and atmospheric chemistry, building engineering, epidemiology, environmental health, infectious disease, pulmonary medicine, public health, and virology to explore the evidence on airborne transmission of SARS-CoV-2. This publication summarizes the presentations and discussions from the workshop." | |
| Study type: Workshop report.<br>Mode of transmission: "…outbreaks of COVID-19 resulting from a point source (one infected person transmitting to others) have most often occurred in settings where there is crowding or people who are exposed indoors for extended periods of time (e.g., long-term care facilities, correctional facilities, homeless shelters, and bars)."<br>"Butler clarified that droplet and airborne transmission are not mutually exclusive."<br>"Definitively proving the aerosol transmission pathway is challenging and will require more research, according to Milton and William Lindsley, National Institute for Occupational Safety and Health."<br>"Viral half-life in aerosol is approximately 1.1 hours, said Emmie de Wit, Rocky Mountain Laboratories."<br>"…aerosols can also be formed from resuspension of settled dust or aerosols." | |

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| HVAC controls: "Ventilation, she said, should be based on occupancy of the indoor space and there is no "one-size-fits-all" rate to eliminate exposure risk."<br>"Filtration is an effective supplement to ventilation for reducing aerosol concentrations indoors, said Miller. Measures of the effectiveness of filtration systems have been developed"<br>"Germicidal ultraviolet (UV-C) light can be useful in environments where it is otherwise challenging to ventilate or filter, said Miller." |

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| *Air Cleaners, HVAC Filters, and Coronavirus (COVID-19)*. EPA USA https://www.epa.gov/coronavirus/air-cleaners-hvac-filters-and-coronavirus-covid-19 | Expert |
| No abstract – Government advice website. | |
| Study type: USA Government advice on air cleaners - includes advice on selecting an air cleaner.<br>HVAC controls: "Air cleaning and filtration can help reduce airborne contaminants, including particles containing viruses."<br>"The variety and complexity of HVAC systems in large buildings requires professional interpretation of technical guidelines, such as those provided by ASHRAE and CDC. EPA, ASHRAE and CDC recommend upgrading air filters to the highest efficiency possible that is compatible with the system and checking the filter fit to minimize filter air bypass."<br>"Directing the airflow so that it does not blow directly from one person to another reduces the potential spread of droplets that may contain infectious viruses."<br>"Air cleaning may be useful when used along with source control and ventilation, but it is not a substitute for either method." | |

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| Senatore V, Zarra T, Buonerba A, … Naddeo V. *Indoor versus outdoor transmission of SARS-COV-2: environmental factors in virus spread and underestimated sources of risk*. EuroMediterr J Environ Integr. 2021;6(1):30. doi: 10.1007/s41207-021-00243-w. Epub 2021 Feb 10. PMID: 33585671; PMCID: PMC7873670. | Expert |
| "The first case of Coronavirus Disease 2019 (COVID-19), which is caused by Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2), in Europe was officially confirmed in February 2020. On 11 March 2020, after thousands of deaths from this disease had been reported worldwide, the WHO changed their classification of COVID-19 from a public health emergency of international concern to a pandemic. The SARS-CoV-2 virus has been shown to be much more resistant to environmental degradation than other coated viruses. Several studies have shown that environmental conditions can influence its viability and infectivity. This review summarizes current knowledge on the transmission pathways of the novel coronavirus, and directs attention towards potentially underestimated factors that affect its propagation, notably indoor spread and outdoor risk sources. The contributions of significant indoor factors such as ventilation systems to the spread of this virus need to be carefully ascertained. Outdoor risk sources such as aerosolized particles emitted during wastewater treatment and particulate matter (PM), both of which may act as virus carriers, should be examined as well. This study shows the influence of certain underestimated factors on the environmental behavior and survival of the SARS-CoV-2 virus. These aspects of coronavirus propagation need to be accounted for when devising actions to limit not only the current pandemic but also future outbreaks." | |
| Study type: Narrative review.<br>HVAC: "Lu et al. (2020) examined the transmission of the novel coronavirus in a restaurant without natural air circulation, where the clients were seated > 1 m apart. This study found that the main reason for the transmission of the virus in the artificial air flow was the air conditioner, which enabled the infectious droplets to travel for distances of > 1 m." | |

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| Mode of transmission: "HVAC systems, aerosolized particles from wastewater, and particulate matter (PM) have been identified as underestimated infection pathways for the SARS-CoV-2 virus."<br>"Many studies have demonstrated that the spread and transmissibility of SARS-CoV-2 are much greater in indoor environments, especially in hospitals, laboratories, and schools, due to the presence of or proximity to viral sources as well as the increased possibility of direct contact with infected people or items (Huang et al. 2020). It was initially believed that coronaviruses cannot survive outdoors until Van Doremalen et al. (2020) found viable viral particles 3 h after they had been aerosolized." |

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| Farthing TS, Lanzas C. *Assessing the efficacy of interventions to control indoor SARS-Cov-2 transmission: an agent-based modeling approach.* medRxiv. 2021 Jan 22:2021.01.21.21250240. doi: 10.1101/2021.01.21.21250240. Preprint. | Expert |
| "Intervention strategies for minimizing indoor SARS-CoV-2 transmission are often based on anecdotal evidence because there is little evidence-based research to support them. We developed a spatially-explicit agent-based model for simulating indoor respiratory pathogen transmission, and used it to compare effects of four interventions on reducing individual-level SARS-CoV-2 transmission risk by simulating a well-known case study. We found that imposing movement restrictions and efficacious mask usage appear to have the greatest effects on reducing infection risk, but multiple concurrent interventions are required to minimize the proportion of susceptible individuals infected. Social distancing had little effect on reducing transmission if individuals move during the gathering. Furthermore, our results suggest that there is potential for ventilation airflow to expose susceptible people to aerosolized pathogens even if they are relatively far from infectious individuals. Maximizing rates of aerosol removal is the key to successful transmission-risk reduction when using ventilation systems as intervention tools." | |
| Study type: Model based on the Skagit County (Washington state, USA) choir practice outbreak<br>HVAC controls: "Our results are therefore consistent with the findings of (18), who advise that "displacement" ventilation systems, those designed to vertically stratify indoor air by temperature and remove warmer air, are likely able to reduce local SARS-CoV-2 transmission risk"<br>Controls: "Duration limits and efficacious mask usage appear to have the greatest effects on reducing the proportion of susceptible individuals infected, but multiple concurrent interventions are required to minimize the proportion of susceptible individuals infected"<br>Mode of transmission: "...increases in gathering duration, infectious aerosol production, and horizontal air movement all escalate the probability that transmission will occur during gatherings, though the effect is much lesser than that of increasing population density"<br>"...there is potential for forced airflow to expose susceptible people to aerosolized pathogens even if they are relatively far from infectious individuals, and therefore increase transmission risk." | |

# Roundtable on role of airflow and/or ventilation in relation to SARS-CoV-2 transmission in quarantine arrangements

18 February 2021, 4:00pm–5:30pm (AEDT), Videoconference (via Zoom)

## Chair

Professor Michael Kidd AM

## Purpose

Expert discussion on the role of airflow and ventilation in the transmission of SARS-CoV-2 in quarantine arrangements, drawing on evidence where available. The discussion will inform the advice provided to the Australian Health Protection Principal Committee (AHPPC); advice under development by the National COVID-19 Health and Research Advisory Committee (NCHRAC). The roundtable was hosted by the National Health and Medical Research Council (NHMRC) that provides secretariat support to NCHRAC.

## Attendees

- Experts from a range of disciplines were convened including experts with knowledge of airflow and ventilation, virology, aerosol science, occupational hygiene and engineering.
- Members and or representatives of committees also attended, including the Australian Health Protection Principal Committee (AHPPC), Infection Control Expert Group (ICEG), the Public Health Laboratory Network (PHLN), the Communicable Diseases Network Australia (CDNA), the National COVID-19 Clinical Evidence Taskforce Infection Prevention and Control (IPC) Expert Panel and National Covid-19 Health and Research Advisory Committee (NCHRAC).

## Key questions for discussion

Attending experts were asked to discuss available evidence around the following questions.

- What is the role of mechanical vs natural ventilation in SARS-CoV-2 transmission?
- What impact do air flow and/or ventilation interventions have on SARS-CoV-2 transmission? Can personal behaviours (by persons quarantining or staff/contractors in quarantine hotels) affect air flow and impact SARS-CoV-2 transmission?
- What supporting evidence is available?
- In which settings does the evidence apply? And how might this evidence be relevant to the context of quarantine arrangements?
- What other factors relate to airflow and ventilation, particularly in light of the transmissibility of new variants?

## Format

Short presentations from several experts relevant to the key questions were delivered followed by a moderated discussion.

Presenters:

- Professor Kirsty Buising, Deputy Director of the National Centre for Antimicrobial Stewardship; Director, Guidance Group; Infectious Disease Physician, Royal Melbourne Hospital
- Associate Professor Robyn Schofield, Director, Environmental Science Hub, School of Earth Sciences, The University of Melbourne
- Professor Jason Monty, Professor of Fluid Mechanics and Head of Department of Mechanical Engineering, The University of Melbourne
- Ms Kate Cole, Engineer and Certified Occupational Hygienist; Member, National COVID-19 Clinical Evidence Taskforce expert panel for infection prevention and control; Director, Cole Health
- Adjunct Professor Geoff Hanmer, Adjunct Professor of Architecture, University of Adelaide, Architect and Managing Director ARINA.

## Summary of expert discussion

**Learnings from study of air quality, airflow and mitigation strategies in <u>clinical</u> environment (Royal Melbourne Hospital, Western Hospital –Victoria)**

*Note: The outcomes of this study are being prepared for publication.*

- Study stemmed from concern about numerous staff infections of SARS-CoV-2 during Victoria's surge in infections in 2020, including staff who were highly trained in the use of personal protective equipment (PPE). The number of staff infections exceeded what could be conceivably explained by PPE breaches (at peak, >20 staff/day) and included staff that did not have direct patient contact (e.g. ward clerks).
- Air exchange (through ventilation systems) alone as a measure is not adequate. An understanding of airflow (including source [inlet] and exit [outlet]), mixing of air and effective air exchanges in the space/setting/indoor environment is required.
- Heating ventilation and air conditioning (HVAC) systems in hospitals have more air changes per hour (ACH) (usually 12 ACH) than standard building ventilation (typically 2 ACH).
- Based on simulated tests using bubbles and smoke to represent the presence and flow of respiratory particles in laboratory and clinical settings, air cleaners (aka air scrubbers or purifiers) located in the room cleaned the air in the room of particulate matter more quickly and limited how much infected air escapes the room. Simulated tests showed that:
    - without air cleaners in the room, air clearance using standard HVAC alone (with 2 ACH) took 60 minutes; with hospital HVAC (12 ACH) it took 20 minutes.
    - with two scrubbers added to the room, the clearance time dropped dramatically to 5 minutes (6 times faster)
- The addition of air cleaners in all rooms presented a better hallway scenario than if there were no air cleaners in the rooms.
    - Air cleaners in rooms kept nurse stations (located outside rooms) safer. Closed doors to patient rooms helped limit airflow to, and

contamination of, nurse stations. Physical barriers around nurse stations (ZIP wall and air scrubber barrier) also helped to protect nurse stations outside patient rooms.
    - Experiments to determine the optimum number of air cleaners in the corridor of the ward were undertaken; eight air cleaners in the corridor was deemed optimal.
- Based on smoke simulation (smoke being representative of respiratory particles at ~1 micron), patient ventilation hoods[1] were very effective at trapping aerosols and limiting the amount of particulate matter in a patient room. They also offered protection to staff providing patient care or performing aerosol generating procedures.
- Patient/people placement is important relative to the flow of air in the space (applicable to the quarantine setting). Ideally, the airflow path from an infected person to air exhaust should be short. For example, if a person is to be located outside, but within the proximity of rooms where infected people are located, they should be placed away from where the infected air is travelling — away from exhaust. People management is important and well documented.
- A multidisciplinary team met regularly to understand the impact of airflow and ventilation in the clinical setting with a particular focus on mitigation strategies, involving expertise in airflow assessment, aerosol science, fluid dynamics, virology and engineering. This approach was very useful and could inform investigation of SARS-CoV-2 in different indoor environments including, quarantine and aged care facilities. It was noted that case studies are being undertaken to understand the passage of air in other representative settings e.g. the office, elevator, train carriage, lecture theatre, hospital ward.

## Definitions

- The variation in terminology used between disciplines (e.g. aerosol science vs medicine) based on the size of droplets, aerosols and particles was acknowledged.
- It was suggested that it is more important to understand the size of the particles and how they flow in the air than be concerned with the terminology. The use of the term ‘particles’ was suggested to avoid confusion.
- Definitions referred to in expert presentations: Milton[2] and ISO/CEN convention used in assessing the possible health effects of airborne particles / aerosols and defining transmission by exposure path (droplets and aerosols).[3,4,5,6]

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[1] Level 1 device, Therapeutic Goods Administration (TGA) Australian Register of Therapeutic Goods (ARTG) https://search.tga.gov.au/s/search.html?collection=tga-artg&profile=record&meta_i=342671
[2] Milton, D. K. (2020). A Rosetta Stone for Understanding Infectious Drops and Aerosols. *J.Ped. Inf. Dis. Soc.*, *9*(4), 413–415.
[3] Wells WF, Air-borne infection: Study II. Droplets and droplet nuclei., *Am J Epidemiol*, Volume 20, Issue 3, November 1934, Pages 611–618, https://doi.org/10.1093/oxfordjournals.aje.a118097
[4] Xie et al (2007). How far droplets can move in indoor environments – revisiting the Wells evaporation-falling curve*. Indoor Air*. https://onlinelibrary.wiley.com/doi/full/10.1111/j.1600-0668.2007.00469.x
[5] Tellier, R., Li, Y., Cowling, B.J. et al. Recognition of aerosol transmission of infectious agents: a commentary. *BMC Infect Dis* 19, 101 (2019). https://doi.org/10.1186/s12879-019-3707-y
[6] Lindsley WG, Noti JD, et al. Viable influenza A virus in airborne particles from human coughs. J *Occup Environ Hyg*. 2015;12(2):107-13. doi: 10.1080/15459624.2014.973113. PMID: 25523206; PMCID: PMC4734406.

## Infectivity/viral load

- Observations from around the world from super spreader events indicate that 20% of cases account for 80% of spread. It is not yet known how to identify a super spreader.
- New knowledge about SARS-CoV-2 and other respiratory viruses can be applied to SARS-CoV-2 variants. Viral load in aerosols may depend on which part of the respiratory tract the virus is being produced from (e.g. lungs or upper respiratory tract) which may determine the size of the droplets and aerosols.
- Rates of inactivation may differ for different viruses, but is unlikely to differ as much between variants.
- The route for virus infection (e.g. nose, eye) and the dose of virus needed to initiate infection may differ between SARS-CoV-2 variants. e.g. with ACE-2 receptor changes, less dose of the virus may be required.
- It was acknowledged that it is hard to sample the viral viability of aerosols.
- Portable virus samplers for rooms to recover infectious virus from air samples have been noted and are currently being validated (e.g. VIVAS unit).
- A systematic review of SARS-CoV-2 in hospitals reported that high viral loads have been found in hallways, toilets, staff rooms and other public areas and should be considered carefully.[7]
- Occupational hygienists model the workplace risk of infection of SARS-CoV-2 through quantitative models to determine a room's risk of airborne infection and the risk that poses to workers who occupy that space.

## Behaviour of SARS-CoV-2 (or representative particles) relevant for airflow/ventilation considerations

- Particles <100 micron (µm) in size can be inhaled and can remain suspended in the air for a long period of time because typical room air velocities exceed the terminal settling velocities of the particles. Particles evaporate to their nuclei ~0.3 µm and can remain viable/stable for long time.
- Ventilation moves and disperses particles of various sizes.

## Airflow patterns

- Airflow is very difficult and hard to measure but critical to understand. There is currently no industry that could be called on to map out airflow and propose solutions. Almost all solutions for indoor air are proposed by consultants who advise on large-scale HVAC changes.
- Based on testing in a hospital room (Royal Melbourne Hospital lessons discussed above), if the door is opened, the ventilation system mixes the air, and the air travels out the door and into the exhaust. When the door is shut, the air takes the same pathway to the exhaust (outlet) and will find other routes to get there (e.g. through light fittings, cracks in doors or ceilings).

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[7] Birgand G, Peiffer-Smadja N, et al. Assessment of Air Contamination by SARS-CoV-2 in Hospital Settings. JAMA Netw Open. 2020 Dec 1;3(12):e2033232. doi: 10.1001/jamanetworkopen.2020.33232. PMID: 33355679; PMCID: PMC7758808.

- Differences in room temperature versus hallway temperature, even with pressure control, can skew airflow pattern and can lead to very rapid air exchange.

## Mechanical versus natural ventilation

- Facilities that have separate dwellings with separate air conditioning systems, no foyers, corridors or shared spaces work well, for example the Howard Springs in Northern Territory.
- Ventilation systems will affect the movement and therefore control of particles that are more than just those defined as “airborne” from a traditional infection control perspective.
- Mechanical ventilation via HVAC (building ventilation) in a setting such as hotels is very unlikely to optimally reduce risk of transmission, because the ventilation systems are designed to control the climate in the entire building and are not designed to manage local airborne transmission.
- A paper was noted that documented an outbreak of coronavirus in a Dutch nursing home where transmission was associated with inadequate ventilation. Indoor air was only refreshed with outside air based on $CO_2$ concentration measurements. If the $CO_2$ concentration did not reach 1000ppm, indoor air was re-circulated by the system without filtration. The low $CO_2$ was attributed to inactive nursing home patients. Despite wearing of surgical masks, multiple staff and patients were infected. Other wards in the building that were not affected and had outside airflow.[8]
- Pros and cons of mechanical and natural ventilation:

| Ventilation | Advantages | Disadvantages |
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| Natural (open windows / doors) | • Ventilation increased<br>• Passive cooling / controlled ventilation | • Outdoor air threats (smoke, pollen)<br>• Extreme heat and cold issues<br>• Lose airflow control |
| Mechanical (HVAC system) | • Filtration – F9 (removes pollution)<br>• Temperature control<br>• Control Airflow / Create zones | • Stagnant zones<br>• Suffer low relative humidity in winter<br>• Power cuts/black outs |

| Technology | Type | Effective | Safe |
|---|---|---|---|
| Filtration | • High Efficiency Particulate Air (HEPA) only<br>• HEPA + activated Carbon | Yes | Yes |

[8] de Man P, Paltansing S, Ong DSY et al. Outbreak of Coronavirus Disease 2019 (COVID-19) in a Nursing Home Associated With Aerosol Transmission as a Result of Inadequate Ventilation, Clinical Infectious Diseases, 2020; ciaa1270, https://doi.org/10.1093/cid/ciaa1270

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| Ionization / Corona / Electrostatic precipitator | Ionization of the air, creating charged particulates, microbes and gases, removed quickly | Yes | No<br>Creates dangerous reactive oxidized gases |
| Ultraviolet Germicidal Irradiation | • Upper room<br>• In-duct<br>• Less effective in ACH>6 | Yes | Requires specialist installation<br>Not widely used in Australia |

*Hotel specific*

- HVAC systems in hotels are not designed for infection control and are influenced by many factors such as movement of elevators, wind on the building, thermal factors.
- The current Australian standard for building ventilation (AS 1668.2) guarantees some fresh air in a space. [9] In older hotels in particular, it is common to see low amounts of fresh air being produced into spaces. Simple measurements can be undertaken to understand the HVAC environment, to check that fresh air delivery rates and exhausts at least meet AS 1668.2 standards. Most supply and exhaust fans will use adjustable speed motors which means that air flow can be adjusted to a certain extent.
- Supply air is delivered from outside a building (e.g. hotel), enters through a duct and is pushed by fans through into the building. That air is delivered into individual rooms and is most commonly exhausted into the plenum, just above the door/bathroom. Some buildings mix this fresh air with "return" air to a certain proportion.
    - If supply of air to a room is greater than the exhaust the room will be under positive pressure and air will escape typically through gaps in doors/ceiling panels.
    - If supply air is less than the exhaust the room will be under negative pressure. Negative pressure is desirable in terms of infection-control, provided that all rooms in the building are under the same negative pressure. Negative pressure in a room on one side of a hallway will not achieve the desired outcome in terms of infection control if the room positioned opposite in the hallway is at positive pressure. Hence, particles can pass from the room at positive pressure to the room at negative pressure, even if the room doors are closed.
    - Even when a hotel is designed to be under positive, negative or balanced air pressure, this is not always achieved in reality.
- Some fresh/return air is dependent on outdoor temperature and may not return as much air (e.g. in hotter weather) as expected and the capacity of

[9] https://www.standards.org.au/standards-catalogue/sa-snz/manufacturing/me-062/as--1668-dot-2-2012-archive

systems ranges between approximately 50-100%, depending on the system.

- Many mechanically ventilated hotels have insufficient (non-compliant) fresh air flow. This may be why people feel that they need additional fresh air. Measured $CO_2$ levels in hotel rooms can be well over 1,000 parts per million (ppm); the target should be around 600 ppm.

*Doors/windows open or close?*

- There is no clear answer on whether doors/windows in hotel quarantine rooms can be opened or closed. Opening doors/windows ordinarily seems like a good idea but can be problematic due to variability e.g. people might close them, changes in weather.
- There was agreement that this is a complex question to answer and depends on a multitude of dynamic factors, including:
  - Outside air temperature
  - Differences in temperature within a building e.g. room temperature versus hallway temperature
  - Changes and variability in air pressure within a building; challenging to control
  - Design, adequacy and maintenance of the ventilation system.
- Discussion regarding open doors/windows included the following:
  - If you have multiple infected patients in separate rooms and the doors open, this would become problematic, in that the air containing virus would travel to the exhaust, via the same path, through the hallway.
  - Openable windows/doors are good; however, in the context of a large building they can and do facilitate air movement throughout the building, not just in the room with an open window.
  - If a door is opened, the ventilation system mixes the air, and the air travels out the door and into the exhaust (outlet). When the door is shut, the air will find other routes to the exhaust (e.g. via light fittings, cracks in doors or ceilings).

    Several interventions were discussed:
    - Undercutting doors or using grilles on bathroom doors to increase the airflow (from corridors into the room when door opens) toward exhaust, to minimise uncontrolled air escape. However, pressure and temperature dynamics would need to be considered.
    - Using additional seals to minimise air flow in gaps around doors
    - Coordinate when room doors can be opened. For example, plan the timing of room doors opening that are adjacent or opposite each other and minimise presence of people in corridors.

   - Wind direction can impact natural ventilation and could pressurise the room.
   - A well designed HVAC system will rely less on human factors (like opening and closing doors/windows) to be effective. However, if negative pressure in a room is required, a pressure differential cannot be maintained with windows or doors opening.

### Airflow and ventilation risk and mitigation

There was general alignment among expert presenters and participants on identifying/assessing risk and layered mitigation strategies relevant to hotel quarantine arrangements, based on hierarchy of controls[10] and Morawska et al[11]. The same principles apply to other settings such as aged care, hospitals, meat processing plants, cruise ships.

- It was agreed that there are many factors that relate to airflow and ventilation that will increase or decrease the level of risk posed by occupants in spaces where COVID-19 persons are located.
- Key factors to consider in terms of risk include:
  - the provision of outdoor air supply, and rate
  - the level of mixing of supply and exhaust air
  - the location and rate of exhaust
  - the differential pressure leading to understanding whether a space is under positive or negative pressure
  - the air changes per hour
  - use of localised/portable air cleaners
  - the occupancy within a space and the activities that persons within that space are conducting.

*Suggested interventions/strategies to reduce risk of SARS-CoV-2 transmission in quarantine hotels*

It was acknowledged that there have been remarkably few transmission events in Australia quarantine hotels despite the large number of people who have been in hotel quarantine. Most of the cases of transmission that have occurred in hotel quarantine were considered likely to be due to human behaviour (e.g. breaching protocols) or inadequate recommendations for PPE use in hotels rather than ventilation-related transmissions when other protocols were in place and being adhered to. However, it was recognised that aerosol transmission can occur and therefore that there is a risk of transmission occurring in hotel quarantine. This is inclusive of staff who then are at risk of carrying the virus externally. This risk could potentially become greater where more infectious SARS-CoV-2 variants of the virus emerge.

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[10] https://www.cdc.gov/niosh/topics/hierarchy/default.html

[11] Morawska L, Tang, J et al (2020). How can airborne transmission of COVID-19 indoors be minimised? Environment International, 142(January), 105832.

There was agreement that there are reasonable measures that can be undertaken to minimise the risk of airborne transmission in hotel quarantine:

- Each hotel/building considered or used for quarantine purposes should be individually assessed by persons with appropriate expertise where purpose-built facilities or separate buildings (like Howard Springs, NT) are not feasible or available. The assessment of each hotel should include an assessment of the impact of opening/closing window/doors to identify key risks and ability to control or mitigate.
- It is critical to understand airflow between source and exit and exhaust rate.
- Monitor carbon dioxide to identify stagnant air, temperature and relative humidity.
- Engineering controls:
    - avoid air re-circulation and replace contaminated air with clean air
    - use portable air cleaners in rooms and hallways, filtration devices (such as high-efficiency particulate arrestance, HEPA filters)
    - maximise outdoor air intake
        - increasing the number of effective air changes per hour to increase the amount of “clean” or outdoor air delivered to the room to lower the occupant’s level of exposure to airborne viruses and therefore the relative risk of contracting the disease. Diluting indoor airborne virus concentrations can lower the risk of contracting the disease for the same reason that outdoor environments pose less risk of disease transmission.
        - keeping the HVAC system running longer (i.e. 24/7) or running the HVAC system at maximum outside airflow for some time (e.g. 2 hours) before occupancy.
    - disabling demand-controlled ventilation that reduces air supply based on occupancy or temperature during occupied hours.
    - consider placing UV lamps in air ducts to inactivate pathogens; UV lamps/filters are being used in Europe and US. An engineer commented that these may not work in hotels, or might be better used post-occupancy.
- Security guards in hotels could be protected by moving them away from the direction of airflow; using remote monitoring from some distance (e.g. CCTV); using air cleaners in the hallways, and providing appropriate worker protection relative to risk, such as surgical N95 masks and eye protection.
- Eliminate hallways and shared air spaces where possible. Howard Springs facility works well as it does not have a shared ventilation system and does not have hallways or shared common spaces.
- It was noted that the National COVID-19 Clinical Evidence Taskforce Infection Prevention and Control Expert Panel (jointly chaired by Infection Control Expert Group) is currently reviewing evidence for ventilation interventions.

### Other factors to investigate/consider

- Analyse the chain of transmission risk and appropriate risk reduction and control point measures (likened to the Hazard Analysis and Critical Control Point used in food safety) and ensure there is a process for continuous quality improvement.
- Analyse information about escape/transmission events that have occurred in Australian hotel quarantine to understand whether they relate to ventilation or any other control factors and look at hotels where escape/transmission events have not occurred. It was noted that information about when people were and weren't infected has been collected.
- Consider rostered system for staff working in hotel quarantine (e.g. weeks on/off) rather than returning home after each shift worked, with appropriate testing.
- Vaccination in combination with other mitigation strategies will help toward protecting people.

### Other literature suggested by participants


- Chen W, et al. (2020). Short-range airborne route dominates exposure of respiratory infection during close contact. Bdg and Enviro., 176 (March), 106859.
- US National Academies of Sciences Engineering and Medicine Conference Proceedings. Airborne Transmission of SARS-CoV-2: Proceedings of a Workshop—in Brief (October, 2020). https://www.nap.edu/catalog/25958/airborne-transmission-of-sars-cov-2-proceedings-of-a-workshop
- Anand S, Mayya YS. Size distribution of virus laden droplets from expiratory ejecta of infected subjects. *Sci Rep* **10**, 21174 (2020). https://doi.org/10.1038/s41598-020-78110-x
- Lednicky JA, Lauzardo M, Fan ZH, et al. Viable SARS-CoV-2 in the air of a hospital room with COVID-19 patients. Int J Infect Dis. 2020 Nov;100:476-482. doi: 10.1016/j.ijid.2020.09.025. Epub 2020 Sep 16.