COVID-19 and indoor air: Risk mitigating measures and future-proofing

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EXECUTIVE SUMMARY

The COVID-19 pandemic has increased the demand for research on how respiratory viral pathogens spread in indoor spaces, and evidence for the control measures and interventions that can be used to mitigate transmission. This has also prompted a re-examination of the indoor environment more widely, with a focus on how to improve and maintain healthy indoor air quality while mitigating against the risks of pathogens circulating in the community. Future-proofing is needed to mitigate against the emergence of new variants of the SARS-CoV-2 virus, and the potential for endemic COVID-19, as well as future pathogens.

An agreed scope of work was commissioned by Workplace Health and Safety of BC Public Service Agency to answer a set of key questions addressing the relationship between COVID-19 and indoor air:

- What is the risk of transmission of SARS-CoV-2 in indoor spaces via various transmission pathways?
- How does the emergence of new variants influence the risk of transmission indoors?
- What are the key factors that exacerbate the risk of transmission indoors?
- What strategies are most important for mitigating risk, and how can we estimate the impact of various measures?
- What is known about the influence of ventilation in the mitigation of transmission indoors?

The scope of work included a general literature search of academic and grey literature including an evaluation of quality and synthesis of key findings, consultation with key informants and experts in the field, and external review of this document.

KEY FINDINGS

Area of interest	Summary of key findings
What is the risk of transmission of SARS-CoV-2 in indoor spaces via various transmission pathways?	• Evidence to date suggests that most transmission occurs as a result of close contact interactions (short-range exposure to respiratory emissions). • The virus may transmit opportunistically over a longer distance where there is a high source load of virus in the air and in poorly ventilated environments where there is poor clearance of accumulating particles. • Other routes of transmission such as via contaminated surfaces (fomites) and fecal-aerosol transmission may be occurring, although direct evidence of this is limited to date.
How does the emergence of new variants influence the risk of transmission indoors?	• At the time of writing, four variants of concern (VOC) are known to be spreading in Canada, commonly referred to as Alpha, Beta, and Gamma and Delta. • All four VOC are shown to be more transmissible, and VOC are now more prevalent among new cases of COVID-19 than previously circulating strains.

	• Alpha is associated with a higher risk of mortality, and Beta and Gamma have been shown to evade natural and vaccine-induced immunity. Initial investigation of Delta suggests it may result in more severe illness and may show a reduced response to a single dose of vaccine compared to other strains. • Research is ongoing to identify how emerging variants differentially influence transmission, but current research suggests that mutations that increase affinity for the ACE-2 receptor are making transmission more efficient. • Initial study has also demonstrated that persons infected with Alpha may have a higher load (shed more virus) and may be infectious for longer. • Enhanced transmissibility means that a lower dose or shorter duration of exposure can result in transmission, so risks from all transmission routes are heightened. This means stricter adherence to public health measures to mitigate spread is needed.
What are the key factors that exacerbate the risk of transmission indoors?	• Risks of becoming infected by SARS-CoV-2 vary depending on the prevalence of COVID-19 transmission in the community, host factors, personal behaviour, including mask-wearing, and the micro-environment including the physical characteristics of the space (size, layout, and environmental controls) and how users interact within the space (density of users, duration of interaction and nature of activities). • For indoor spaces, measures for reducing transmission risk focus on reducing the 3 C's (closed spaces, crowding, close contact) and the duration, intensity and frequency of contacts with others, and as such reduce the opportunity for exposure, and intensity of exposure, should it occur.
What strategies are most important for mitigating risk, and how can we estimate the impact of various measures?	• Very few interventions have been investigated with respect to reducing SARS-CoV-2 transmission; however, we assume that these technologies are likely still beneficial based on research on other illnesses or other IAQ contaminants (e.g., removal of particulate matter). • Cumulatively, the evidence available regarding the effectiveness of various risk mitigation measures and technologies shows that layered interventions are essential to preventing the spread of disease. • Once a risk mitigation strategy has been implemented, it is critical to review and revise as pandemic conditions shift.
What is known about the influence of ventilation in the mitigation of transmission indoors?	• Ventilation can reduce transmission risks associated with sharing indoor spaces, by reducing the concentration of bioaerosols that do not settle due to gravity and thus increasing the duration of the time that a person could be exposed without becoming infected. • Ventilation does not reduce the risks of transmission arising from close contact with an infected person, or transmission via fomite transmission.

	• It is possible to either under- or over-ventilate a space in a way that might affect transmission; the optimal ventilation rate for a given space is highly context dependent. • Future-proofing indoor spaces will require improved ventilation, integrating complementary technologies, a renewed focus on human-centred design, and may also require changes to codes and standards.

CONTENTS

TERMS OF REFERENCE

INTRODUCTION

Environmental Health Services of the BC Centre for Disease Control (BCCDC) was commissioned by the BC Public Service Agency to assist in identifying the key considerations for reducing the risks of transmission of infectious pathogens such as SARS-CoV-2. The over-arching goal of this document is to identify strategies to reduce the risk of COVID-19 transmission and ensure good indoor air quality (IAQ) in all spaces where the BC Public Service Agency works. The overall objective is to better understand the factors that influence transmission of SARS-CoV-2 indoors and identify the measures that can be taken to mitigate transmission risks in the current COVID-19 pandemic and future-proof against future pandemics. The BCCDC, in collaboration with the National Collaborating Centre for Environmental Health (NCCEH), undertook a rapid scan of the current literature and recent evidence to address several research questions as laid out in the project deliverables.

PROJECT DELIVERABLES

An agreed scope of works was commissioned by the BC Public Service Agency with the following key deliverables:

- A review of the current academic and grey literature addressing the research questions set out as follows:
    - What is the risk of transmission of SARS-CoV-2 in indoor spaces via various transmission pathways?
    - How does the emergence of new variants influence the risk of transmission indoors?
    - What are the key factors that exacerbate the risk of transmission indoors?
    - What strategies are most important for mitigating risk, and how can we estimate the impact of various measures?
    - What is known about the influence of ventilation in the mitigation of transmission indoors?
- Consultation with key informants and external review of the findings.
- A report presenting the synthesized findings of the literature, including a list of references and key resources.

METHODOLOGY

Rapid literature searches pertaining to each of the key research questions were performed by the BCCDC EHS information specialist using Ebscohost databases (includes Medline, CINAHL, Academic Search Complete, ERIC, etc.), Google Scholar, and a general internet search with no date or jurisdictional limit, with a preference for English language documents. Results were reviewed by knowledge translation scientists for relevance. Further examination of bibliographies of key articles were scanned to retrieve more extensive information and forward chaining of key papers added to the search results. Additional grey literature and government websites including guidance documents were scanned for relevant material. Search terms are presented in **Appendix 1** to this document. Expert advice was sought on key concepts and current evidence, and to source additional resources relevant to Canada. External reviewers were sought to provide critical review and feedback to inform this document.

The findings of the study and recommendations for process or operational improvements and/or areas for continued investigation and study are presented in the sections that follow.

Disclaimer: The information provided here is for the purpose of addressing a specific inquiry related to an environmental health issue. The information offered here does not supersede federal, provincial, or local guidance, regulations, or occupational health and safety requirements and/or the advice of a medical professional (where applicable).

LITERATURE REVIEW

PREAMBLE

Humans spend approximately 80-90% of their time indoors and it is no surprise that the quality of the indoor air environment in home and work environments can significantly impact the health and well-being of building occupants.[1,2] In workplaces, indoor air quality (IAQ) can have substantial impacts on employee productivity, cognitive function, the number of sick days taken, with subsequent economic impacts for an employer.[3] Indoor air pollutants are diverse and can include mould, radon, volatile organic compounds, odours and other gases, and infectious pathogens. Acute and chronic exposure to various pollutants can result in a variety of adverse outcomes, therefore removing or reducing exposure is necessary to avoid these outcomes. There are various strategies that can be used to improve indoor air quality such as providing source control of indoor air pollutants, designing ventilation and air cleaning systems to minimize the accumulation of pollutants indoors, and to consider operational, maintenance and monitoring requirements to identify and address IAQ issues.

In the current COVID-19 pandemic, improvements to indoor air quality are also likely to have a positive impact on reducing spread of the SARS-CoV-2 virus among occupants, when used in conjunction with other mitigation measures. The following sections examine the literature on how SARS-CoV-2 transmits indoors, how evolution of the virus may affect transmission indoors, the features of indoor spaces that can exacerbate transmission risks and strategies for reducing transmission risks, including an examination of how ventilation solutions in particular can curtail the spread of SARS-CoV-2 indoors. This literature review is based on the existing published evidence and guidance available at the time of writing.

RESEARCH QUESTION 1: WHAT IS THE RISK OF TRANSMISSION OF SARS-COV-2 IN INDOOR SPACES VIA VARIOUS TRANSMISSION PATHWAYS?

The transmission of SARS-CoV-2 in indoor spaces is influenced by a combination of biological and physical mechanisms of viral transmission, with several pathways by which the virus can move from an infected person to a new susceptible host. This section examines the evidence for the most dominant pathways for SARS-CoV-2 transmission in indoor spaces.

WHAT IS COVID-19 AND HOW DOES IT SPREAD?

Coronavirus disease 2019 (COVID-19) is an illness caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). The SARS-CoV-2 virus is a single-stranded RNA virus that is enveloped in a lipid layer covered in protein spikes or "corona". In simple terms, infection occurs when the SARS-CoV-2 virus binds to a host cell and inserts its viral RNA, resulting in replication of new virus, which can then be released to cause infection of a new host. SARS-CoV-2 is thought to infect a host cell by binding to ACE-2 receptors that are present in the epithelial cells of the upper and lower airways.[4,5] The main route of entry is via the upper respiratory tract or mucous membranes of the face, and once infected, virus replicates predominantly in the tissues of the upper respiratory tract.[5,6] Various physical and biological mechanisms influence how virus is emitted from an infected person.

Replicated virus can accumulate in the mucous, saliva or other respiratory emissions of an infected person and subsequently be released during coughing, sneezing, singing, laughing, shouting, talking or breathing, or transferred to hands by touching of the face. Forceful respiratory actions (e.g., coughs and sneezes) release bursts of respiratory particles intermittently, which range in size from large droplets (e.g., > 100 µm diameter) to smaller aerosols (e.g., < 5 µm diameter). Breathing or speaking tends to be less forceful but occurs more frequently, producing fewer particles per event, which tend to be smaller.[7-13] Shouting or singing tend can produce more respiratory emissions than breathing or quiet speaking, and the quantity of particles released can vary with loudness, phonation, and articulation, with some people (e.g., "super-emitters") emitting a much larger quantity of particles than others.[7,8,11,13-16]

Various physical forces and environmental conditions can influence the likelihood of particles falling to the ground or settling on surfaces or remaining suspended in ambient air.[17-21] Multiple factors including the force with which the particle is emitted, the size and shape, ambient airflow, movement of people, room layout and ventilation can influence how long a particle will remain suspended. Although very large droplets will deposit quickly due to gravity, the fate of the remaining particles is influenced by how much of their mass is evaporated over the subsequent few seconds. As the diameter of the particles decreases due to evaporation, the amount of time required for particles to settle will increase.[22] If enough of their liquid mass evaporates, some particles will remain aloft until they are removed by ventilation or they impact surfaces or people. Environmental factors such as relative humidity and temperature can affect the evaporation of liquid contained in droplets and aerosols, thus influencing the likelihood of particles remaining suspended or settling.

Exposure to just one or a few viral particles is unlikely to result in infection, but the precise dose needed to cause infection may vary. Evidence from animal studies suggests that the infectious dose is likely a few hundred particles but likelihood of infection can depend on the viral load of the source, the route of infection and the immune response of the exposed person.[23-27] An infectious dose may result from a short but intense exposure to a high concentration of virus or following prolonged or repeated exposure to a smaller dose over time. The more frequent close encounters and the longer a susceptible person spends in contact with an infectious person, the greater the likelihood of transmission. Infected persons are more likely to transmit to others on or slightly before the onset of symptoms and can continue to be infectious for several days after symptom onset.[28,29] One study estimated that just under half of transmission events occur before the infectious person displays symptoms (pre-symptomatic spread).[30] About one-third of people may remain asymptomatic for the duration of their infection, although the estimated proportion of asymptomatic persons varies widely in the literature, as does their relative contribution to transmission.[30-32] Pre- and asymptomatic spreaders present a challenge in controlling transmission in communal settings where infected persons may be unaware they are transmitting the virus, and the transmission routes may be different due to the absence of symptoms such as coughing and sneezing.[33-36]

TRANSMISSION PATHWAYS

There has been extensive debate over the main transmission pathways for SARS-CoV-2 since the beginning of the pandemic and the relative importance of each. Much of this debate has been driven by traditional language around respiratory viruses in clinical settings where transmission is defined as either via droplet and contact exposure, or via airborne exposure. These terms are used to inform the type of precautions adopted to limit exposure in a healthcare setting but have been ineffective in communicating with the public about how transmission occurs. The US CDC now defines transmission according to how the virus enters the body (e.g., inhalation of virus, deposition of virus on exposed mucous membranes, and touching mucous membranes with soiled hands).[37] Alternatively, transmission can be defined more broadly as transmission over short- or long-range or via contact with contaminated surfaces (fomites), as is supported by evidence from various epidemiological, observational and modelling studies.[32,38-46] This terminology will be used in the following sections to describe SARS-CoV-2 transmission pathways, which are defined as follows:

- **Short-range transmission**: Short-range transmission refers to transmission resulting from close contact with an infected individual (within 2 m). Virus expelled from an infectious person in their respiratory emissions (e.g., cough, sneeze, talking, breathing) can be propelled directly onto the mucosa (eyes, nose, mouth) of a susceptible person. Close contact also allows for exposure to higher concentrations of aerosols nearer to the source, which can be inhaled by the exposed person.
- **Long-range transmission**: Long-range transmission refers to transmission beyond 2 m from the source. Modelling has shown that most large droplets do not travel beyond 2 m, and hence transmission over longer distances is more likely to be associated with dispersed respiratory emissions that may not settle (e.g., aerosols), but can be inhaled at lower concentrations by a susceptible person. These smaller particles can accumulate over time if they are not removed by ventilation, and a longer duration of exposure can increase the likelihood of inhaling enough viable virus to cause infection.
- **Contact with contaminated surfaces, or *fomites***: An infectious person can contaminate surfaces when their infectious droplets are deposited via coughing, sneezing, or touching

their nose or mouth and then touching a surface (creating fomites). A susceptible person can be infected if they touch the contaminated surface and subsequently touch their eyes, nose, or mouth, provided enough viable virus is transferred to cause infection.

For some viruses, other transmission pathways may be possible if there is exposure to bodily fluids such as feces, blood, or urine that contain infectious virus. While these pathways are likely to be less important in the transmission of respiratory pathogens, such as SARS-CoV-2, they may play a role in some circumstances.

IMPORTANCE OF VARIOUS TRANSMISSION PATHWAYS FOR SARS-COV-2

It is now accepted that most transmission of SARS-CoV-2 occurs indoors and likely results from close interactions with an infected person and exposure to virus-laden particles in their respiratory emissions, but other transmission pathways are possible in some circumstances.[40,42,47-49] Reporting of transmission events in the media and published epidemiological investigations often focuses on rare or unusual events. This type of reporting can be useful in identifying new risk factors but may give unequal weight to accounts of transmission events that are rare compared to routine events and well established pathways of transmission. Caution should therefore be exercised in making an overall assessment of the relative importance of transmission pathways based on media reports, or rare case examples. For the SARS-CoV-2 virus, the relative importance of various transmission pathways is informed by triangulation of evidence from all sources including observation of transmission events and data on secondary attack rates by settings, populations and scenarios, epidemiological investigations, as well as environmental sampling, animal studies, and modelling studies.

SHORT-RANGE TRANSMISSION

The vast majority of COVID-19 outbreaks have been linked to close contact interactions indoors and are most often associated with interactions in the home environment, including shared accommodation or other indoor spaces where there is a high density of people and a period of prolonged contact.[41,50-53] This includes workplaces with close proximity of work stations where there is prolonged contact between workers throughout the duration of a shift, such as in manufacturing and food processing plants.[54,55] The Public Health Agency of Canada defines close contact as interactions between individuals within 2 m, and prolonged contact as interactions of more than 15 minutes over a 24 hour period.[56]

Evidence from animal studies has shown that short-range transmission due to close contact is likely to be more efficient than transmission over longer distances.[23-25] This may be due to large droplets only travelling a short distance before falling to the ground and the concentration of aerosols released due to coughs, sneezes, or other respiratory action being higher in close proximity to the emitter.[57,58] Studies of ferrets have demonstrated that short-range transmission between ferrets in the same cage is very efficient but transmission can also occur between nearby cages.[59,60] Elsewhere, studies of hamsters have provided evidence that transmission may occur via infectious aerosols over relatively short distances or via fomites in a shared cage.[61,62] Some animal studies are limited in their ability to distinguish the exact pathway of infection (e.g., ballistic droplets, short-range aerosols, or contaminated surfaces near the source), and may not report on the symptoms and behaviours of animals studied or experimental conditions. They provide some evidence of more efficient transmission associated with proximity to the source, but caution should be used in comparing animal studies to transmission in humans.

Evidence from contact tracing studies have shown that most transmission occurs among persons who are high-risk close contacts of someone infected with COVID-19.[63-67] Secondary attack rates (SAR), or the proportion of exposed susceptible persons that develop infection, are higher among people who spend time in close contact with each other such as members of the same household,[68] or persons sharing congregate living settings.[69,70] This effect is more pronounced the more time people spend in contact, with higher SAR observed for people who share a living room or a vehicle or engage in verbal interactions.[64,71,72] Crowded spaces, where it is difficult for people to maintain their distance, or settings where close contact interactions are unavoidable, or where mask-wearing is variable (e.g., during shared meals), also feature in transmission events.[66,73] Systematic reviews have estimated SAR in households to be in the region of 17-21%.[74,75] Thomson et al.[75] identified that the SAR was much higher among household members (pooled average of 21.1%) compared to close contacts in non-household settings, such as social events with family and friends (5.9%) and low-risk casual contacts with strangers (1.2%).

People who spend time in close proximity to each other have a greater likelihood of encountering virus-laden particles, either via deposition on mucous membranes or inhalation of concentrated aerosols.[58] A study of train passengers in China found that the attack rate for passengers sharing a train with a person infected with COVID-19 was higher for persons sitting adjacent to the infected person compared to those sharing a row, or seated a few rows away.[73] The attack rate also increased with the duration of co-travel time. This points to the importance of close contact interactions and duration of exposure in transmission events. Current evidence has also shown that public health measures designed to protect against close contact transmission, namely physical distancing and mask-wearing, have led to a reduction in cases.[76,77]

LONG-RANGE TRANSMISSION

Some respiratory activities, such as heavy breathing, speaking, singing, shouting, or laughing, can produce respiratory emissions that are mostly aerosols < 5 µm in diameter. These aerosols can remain suspended in air and be transported by ambient air currents and may take several minutes to settle.[33,78-81] Some smaller aerosols may remain suspended and accumulate in the air over time and could contain some infectious virus, yet the quantity of virus transported over longer distances in this manner and the importance to transmission is still an area of some debate. Some experts propose that SARS-CoV-2 fits the necessary criteria to indicate that airborne transmission is possible, however understanding the relative importance of long-range airborne transmission in the pandemic requires a more nuanced assessment of the evidence.[18,20,82-84]

Under experimental conditions, SARS-CoV-2 has been found to remain viable when airborne over short distances for several hours and has been isolated from air samples greater than 2 m from a COVID-19 patient.[85-87] Although virus-laden aerosols can be transported beyond 2 m, there is limited data to suggest that infectious virus can be transported and remain viable in significant quantities over longer distances. Environmental sampling has detected viral RNA in healthcare settings in the air of hospital wards, isolation rooms, near the toilets of COVID-19 patients, at nurses stations, hospital entrances, and on air handling grates.[87-93] However, detection of SARS-CoV-2 in the air is variable and usually in low concentration, even in locations such as COVID wards where concentrations would be expected to be highest. A systematic review of air sampling for SARS-CoV-2 RNA by Borges et al.[94] found that while many studies detected SARS-CoV-2 in air in high risk areas, including in isolation rooms of SARS-CoV-2 patients, many others did not. This may be due to variation in sampling techniques, but also hints that virus does not usually remain aloft long enough or in sufficient quantity to be detected.[95-99] Studies by Wei et al.[100] and Kim et al.[100,101] detected viral RNA on a many environmental surfaces (44 of 112 surfaces, and 89 of 320 surfaces respectively) in COVID patient rooms but all room air samples were negative, suggesting that suspended aerosols did not remain aloft for very long. The study by Wei et al. however did detect viral RNA in exhaust air of some rooms, indicating that ventilation may have assisted in clearing the room of suspended aerosols.

In non-healthcare settings, SARS-CoV-2 RNA has been detected in ambient air at the entrance to a department store in China, and in public spaces including banks, shopping areas, government buildings and transportation hubs in Iran and a shopping mall and concert hall in Germany.[89,102,103] However, in a study measuring SARS-CoV-2 in the air and on surfaces of busses in Italy in the last week of lockdown and in the first week of reopening, no air or surface samples tested positive for SARS-CoV-2 RNA.[104] The quantity of virus detected in the air is likely influenced by the source load of viral emissions, the duration over which an infected person is emitting, when the emission occurred relative to the timing of sampling, the nature of space into which aerosols are emitted (enclosed or open), the number of infected individuals in a space, and the presence of mitigating measures such as ventilation.

Evidence for the occurrence of long-range transmission (beyond 2 m) comes from examples of clusters and outbreaks where the infected person (index case) and infectees (secondary case(s)) shared a common space but did not report having close contact (within 2 m). Examples include fitness centres and classes,[105-110] restaurants,[111,112] public transport,[113] choirs and music rehearsals,[114-116] nightclubs,[117-120] offices,[121] and religious venues.[122,123] In many of these examples multiple factors may have contributed to transmission such as a poor clearance of aerosols (e.g., enclosed and poorly ventilated spaces), not wearing a mask, participating in activities that generate a higher proportion of aerosol (e.g., vigorous exercise, loud speech or singing), and spending a long duration in that space (e.g., > 15 min). Previous study of infection risks of influenza and tuberculosis during physical exercise in gyms found that infection risks increased with higher occupancy and poor ventilation.[124] In the example of restaurants in China[125] and Korea,[112] secondary cases did not have any direct contact with the index case, with the likely route of exposure via downwind transmission on air currents in the restaurant. In both of these cases, there were no windows or ventilation systems, but air conditioning was present, causing directional air flow from the infected person towards the secondary cases, who were present in the restaurant at the same time. Masks were also not worn by the index nor the secondary cases during eating, and in conversation with others. In the case of the Korean restaurant, two persons were infected, one at 6.5 m distance from the source and one at 4.8 m distance from the source, and genome sequencing confirmed that all cases were infected with an identical strain, confirming that exposure from a different source in the community was unlikely. For some of the outbreaks referred to earlier, full details of the ventilation conditions and the degree of interaction between affected persons is unknown, due to lack of reporting or recall bias.

There are very few examples of clusters or outbreaks that have occurred over a much longer-range between different spaces in the same building or via an unknown source in the community, emphasizing that aerosol transmission over longer distances or through HVAC systems is unlikely to be occurring. Long-range aerosol transmission may have been the cause or a contributing factor for infection in some cases where the index and the secondary cases were never in contact, but shared a common space at different times.[110,126] There have also been some documented cases of transmission between persons who have not occupied the same space at any time, which have been linked to possible vertical natural ventilation shafts,[127] or plumbing stacks[128] in high rise buildings, and one case where it is difficult to determine how infection passed between occupants in adjacent rooms of a quarantine hotel.[129] Some studies have reported the presence of SARS-CoV-2 RNA on ventilation grates, ducts or filters in health care settings and in a nursing home outbreak, however, there does not appear to be evidence of transmission via HVAC ducts recirculating air to other parts of buildings.[130,131]

TRANSMISSION VIA CONTAMINATED SURFACES (FOMITES)

Fomites can become contaminated by deposition of droplets, aerosols, sputum, or feces, either directly, or by cross-contamination by touching an object with contaminated hands. Surfaces that are frequently touched by many people (high-touch surfaces), such as door handles, or faucets may be more important in fomite transmission compared to objects or surfaces that are only touched incidentally and less frequently. The risk of transmission through contact with fomites is not well understood and could depend on the initial concentration of viable virus deposited, its viability on a specific surface over time, and the quantity of virus transferred through touching of the eyes, mouth, or nose.

Several studies have measured the persistence of SARS-CoV-2 on common surfaces under experimental conditions.[86,132-134] Variation in environmental conditions such as temperature, ultraviolet radiation, and humidity can all affect viability.[132,135-137] The virus has been observed to remain viable for longer periods (one to seven days or more) on smooth hard surfaces such as stainless steel, hard plastic, glass, and ceramics, and for shorter periods (several hours to two days) on porous materials such as paper, cardboard, and textiles, although viability may be dependent on other factors such as temperature.[86,132-134,138-142] Survival time on some metals such as copper, aluminum, and zinc is much lower (a few hours), and copper coated surfaces have been investigated for use in infection control on high touch surfaces.[86,134]

Observational studies have detected viral RNA on a wide range of surfaces in settings where persons with COVID-19 have been present, such as hospitals or quarantine rooms.[143] These studies indicate that high touch surfaces such as door handles, garbage cans, bed rails, taps and toilet seats can be contaminated with SARS-CoV-2 RNA.[88,90,91,93,96,100,144,145] Viral RNA has also been detected on many untouched surfaces such as floors, walls, door frames, shelves, ceiling exhaust and window sills.[91,146-148] These studies imply that virus-laden particles can be transported on air currents, in many cases more than 2 m from the source. There is also some evidence that there is less surface contamination in better ventilated spaces. Most of the studies reporting on detection of viral RNA on surfaces did not attempt to culture virus, so it is not known whether detection of RNA represented an infection risk in these studies.

To date there have been few examples of COVID-19 infections where transmission via fomites has been implicated. These have included studies where the secondary cases did not have direct contact or occupy a common space with the index case but may have shared common spaces at a different time such as washrooms or elevators.[126,149,150] In one study, the index patient blew his nose with his hand before touching an elevator button. After exiting the elevator, a secondary case entered and touched the same button, and subsequently flossed his teeth, suggesting the possibility of snot-oral transmission via the common surface of the elevator button.[126] Another case involved users of a squash court in Slovenia. Despite never having direct contact with the index cases, several players using the same change room and squash court as the index case subsequently became infected, suggesting persistence of infective aerosols, although fomite transmission from shared surfaces cannot be ruled out as another possible route of transmission.[110] Another study identified several cases who became infected in a neighbourhood where sewage from a cracked pipe contaminated the streets following rainfall. Environmental testing detected SARS-CoV-2 in street sewage puddles, which local residents walked in, potentially contaminating their shoes. Touching of contaminated shoes, followed by contact with the nose or mouth was proposed as one possible transmission route.[151]

In each of the examples above, fomite transmission cannot be definitely identified as the route of transmission, but it can also not be ruled out as a primary or contributory factor. Tracing fomite transmission, particularly in public spaces, where people who are unknown to each other and share many common surfaces is extremely difficult, but it does not appear that fomite transmission is a major route of transmission based on current evidence.[152] It should also be noted that the application of mitigation measures can influence the dominant transmission pathways, and measures to address potential fomite transmission have been widespread throughout the pandemic. The emphasis on handwashing, hand sanitizing and surface cleaning and disinfection throughout the pandemic may have reduced the potential for fomite transmission more widely.

OTHER TRANSMISSION PATHWAYS

Viable SARS-CoV-2 virus has been detected in bodily fluids other than respiratory particles, such as blood, feces, and urine of infected persons, but current evidence does not indicate that these contribute to major routes of transmission.[32,43,153] For example, conjunctival transmission through the eyes or tears and vertical transmission (from a mother to a fetus) may occur but are likely to be uncommon.[27,32,154,155] Food-borne transmission and transmission via other bodily fluids including blood and urine are unlikely to be occurring based on current evidence.[32,40,156]

Transmission via feces may be possible in some circumstances, but research is still limited on the relative contribution of fecal-oral (e.g., transmission of virus in fecal particles from one person to the mouth of another, or fecal contamination of food, usually by contaminated hands) or fecal-aerosol transmission (e.g., transmission via inhalation of aerosolized fecal particles containing infectious virus). SARS-CoV-2 is shed via feces and patients with more severe COVID-19 have higher concentrations of SARS-CoV-2 in their stool.[157,158] While several studies have reported on the presence of SARS-CoV-2 RNA in feces and in the toilets of SARS-CoV-2 patients, only a few have identified infectious virus.[90,158-162] Fecal aerosol transmission is implicated in a COVID-19 cluster in a high-rise in Guangzhou, China and exposure to sewage is implicated in an outbreak in an urban community with poor sanitation services, also in Guangzhou, China, but neither investigation could be definitive that fecal-oral transmission had occurred.[128,151] Transmission through bathroom vents was also implied in a cluster of 10 cases in an apartment building in Seoul, South Korea, although it is not possible to conclude whether transmission was associated with fecal aerosols or respiratory aerosols, or some other source unrelated to the vents.[127]

SUMMARY

As of June 2021, with over one hundred and seventy million cases of COVID-19 now recorded around the world, there have been several patterns that have emerged to indicate how SARS-CoV-2 is transmitting. Evidence to date suggests that most transmission likely occurs as a result of close contact interactions (exposure respiratory emissions at short-range). The virus may be transmitted over a longer-range (> 2 m) opportunistically where there is a high source load of virus in the air.[22] This can occur in settings where there is a high density of people or activities that lead to a greater generation of aerosols (e.g., exercise or vocalization), over a long duration, and in poorly ventilated environments where there is poor clearance of accumulated emissions, and absence of other mitigating measures such as mask-wearing.[51,57,119] Transmission via fomites may be occurring, but there is limited evidence of this to date, with hygiene measures potentially contributing to keeping fomite transmission low. Other routes of transmission such as fecal-aerosol transmission may be occurring, although direct evidence of this is limited to date.

Many experts have postulated on the significance of airborne transmission, without a discussion of the relative importance of short-range and long-range transmission pathways, whether via aerosols or droplets. For short-range transmission, exposure to both droplets and a higher concentration of aerosols increase the likelihood of an exposed person receiving an infectious dose of the virus. Long-range transmission (> 2 m) within the same room or space is has been shown to occur but is usually accompanied by other exacerbating factors such as a longer duration of exposure or absence of mitigating measures. Long-range aerosol transmission between spaces is very unlikely with only a few examples of where this may have played a role. Although such instances are highly visible in the media, we cannot use these rare instances to infer the role or predominance of these types of transmission in the pandemic overall.

Ultimately, an individual’s risk of becoming infected by SARS-CoV-2 depends on various factors operating at multiple scales: personal behaviours and individual susceptibility, the favourability of local environments, and the overall prevalence of COVID-19 transmission in the community. Public indoor environments may be conducive to viral transmission due to both the nature of the space and how users interact within it (density of users, duration of interaction and nature of activities). Measures to protect against short-range transmission, namely physical distancing and mask-wearing, have led to a reduction in cases; however, these mitigation measures may also contribute to reduced transmission via other routes as well.[76,77,163] It is difficult to exclude contributions of more than one route for some transmission events. For this reason, the public health approach to reducing COVID-19 transmission relies upon comprehensive, layered mitigation strategies that target multiple transmission routes. In BC, this approach has been broadly successful at limiting transmission to levels within the capability of our healthcare system to manage.

RESEARCH QUESTION 2: HOW DOES THE EMERGENCE OF NEW VARIANTS INFLUENCE THE RISK OF TRANSMISSION INDOORS?

OVERVIEW OF VARIANTS OF CONCERN

Thousands of mutations in the SARS-CoV-2 genome have emerged over the course of the pandemic, with the dominant variants shifting over time. Not all mutations have proliferated, and many lineages will die out, but the increasing frequency of some variants across the population infers there is a selective advantage such as increased transmissibility or virulence.[164-167] Transmissibility refers to the ease with which the virus can infect new host, whereas virulence refers to the severity of the infection. Some variants may emerge as "variants of concern" (VOC) due to rapid spread within a population, an increase in the severity of illness, hospitalizations or deaths, or evidence that the variant is evading detection, treatment or natural or vaccine-induced immunity. At the time of writing, four variants are classified as VOC in Canada, which all emerged in the latter half of 2020, and are being closely monitored by public health officials around the world.[168] A new naming convention for VOC was established by the World Health Organization in May 2021.[169] The VOC currently circulating in Canada are:

- **Alpha** (also known as the B.1.1.7, UK, Kent or English variant or 501Y.V1): First detected in England in September 2020. At the time of writing, Alpha had been detected in 137 countries.[170] As of May 30, 2021, a total of 192,469 cases had been detected in Canada and 8,015 in BC, with Alpha the dominant VOC in BC.[171,172]
- **Beta** (also known as the B.1.351, South African variant or 501Y.V2): First detected in South Africa in September 2020. At the time of writing, Beta had been detected in 92 countries.[173] As of May 30, 2021, 1,670 cases had been detected in Canada and about 130 in BC, where there is currently a very low prevalence of this variant.[171,172]
- **Gamma** (also known as the P.1, Brazilian variant, or 501Y.V3): First detected in Brazil in December 2020. At the time of writing, Gamma had been detected in 51 countries.[174] As of May 30, 2021, 11,799 cases had been detected in Canada and about 5761 cases in BC where it is the second most prevalent variant after Alpha.[171,172]
- **Delta** (also known as the B.1.617.2, or Indian variant): First detected in India in December 2020, and early 2021 among international cases with recent travel to India. This variant was declared a VOC by the WHO on May 12, 2021. At the time of writing, Delta had been detected in 50 countries, and 541 cases have been detected in BC, making it the third most prevalent VOC, but based on transmission patterns observed elsewhere Delta is likely to become more prevalent.[172,175]

VOC now make up a greater proportion of new COVID-19 cases in BC (e.g., >80%) compared to non-VOC strains.[172] Research is ongoing to understand the impact of these VOC on efforts to mitigate the spread of the virus. Much of this emerging research is still awaiting peer review, but initial results are providing insights into possible differences in transmissibility, severity of disease, immune response, and whether new or amended public health measures may be required. More is currently known about the Alpha variant than other VOC due to more cases now detected by genomic sequencing compared to the other variants. Current evidence does not indicate that the routes of transmission have changed, however, increased transmissibility implies that risks from all routes of transmission may be heightened for VOC.

EFFECT OF THE VARIANTS ON TRANSMISSIBILITY

The rapid spread of the Alpha variant in the United Kingdom was first observed in the autumn of 2020 leading to widespread global concern about travel-related introductions and subsequent implementation of increased lockdown measures and travel restrictions including increased testing and quarantine measures.[176] It was soon identified in other European countries and evidence of increased transmissibility began to emerge in the form of increasing case numbers, and an increased prevalence of the VOC among new cases.[177-179] Early data from England estimated Alpha to be about 70-75% more transmissible.[179,180] Analysis by Zhao et al.[181] to the end of December 2020 estimated Alpha was 52% more transmissible. A nationwide survey in France between December 2020 and January 2021 calculated that the Alpha variant as approximately 59% more transmissible based on increased prevalence compared to previously circulating variants.[182] Later studies estimated that this may be higher, with estimates of a replicative advantage of Alpha over the previous dominant variant in England to be 83-118% and in Wales, Scotland, Denmark and the USA to be 65-72%.[183] Fewer published studies have reported on the increased transmissibility of Beta, Gamma and Delta, but all appear to be more transmissible compared to previously circulating lineages. One study estimated Beta to be 50% more transmissible than other variants circulating in South Africa.[184] Faria et al.[185] estimated Gamma to be between 1.7- to 2.4-times more transmissible compared to previously circulating variants in Brazil. Observation of the rapid spread of the Delta variant in countries where it is most prevalent at the time of writing (e.g., India and the UK) suggest that it is at least as transmissible as the Alpha variant, but possibly more transmissible.[186,187]

The reasons for increased transmissibility are currently being studied to determine which, if any control measures can be adapted to reduce the spread. Possible reasons for increased transmissibility of a variant could include mechanisms that allow for more efficient infection of cells (thereby decreasing the dose needed to cause infection), an increase in the viral load of the infected person resulting in larger exposure doses released during the infectious period, or a longer duration of infectiousness meaning increased opportunity to cause infection. For some variants, increased transmissibility is likely related to a mutation (e.g., N501Y) that allows the virus to bind more easily to the ACE-2 receptors of a target cell.[180,188,189] Studies have found that the Alpha variant has between three and ten times greater affinity for the ACE-2 receptor compared to previous lineages.[190,191] Other mutations in the spike protein (e.g., K417T, E484K) that are associated with increased binding to the ACE-2 receptor are also present in the Beta and Gamma variants.[185,188] Vogel et al.[192] found that Gamma displayed about twice as high affinity compared to previously circulating lineages. The Delta variant has been found to have other mutations that are associated with increased transmissibility (e.g., L453R, D614G).[186]

Evidence is beginning to emerge on the effect of the variants on the viral load of infected persons, which could influence the concentration of virus emitted during the symptomatic phase. The cycle threshold value (Ct) recorded during COVID-19 testing can be an indicator of how much virus is present, with a low Ct value associated with a higher viral load. In a comparison of nasopharyngeal swabs taken from COVID-19 patients with and without infection with Alpha, statistically significantly lower Ct values were found with the Alpha lineage compared to non-VOC cases.[193] Virus was also found to persist for longer in Alpha cases compared to non-VOC cases. Other studies have also reported lower Ct counts in Alpha cases compared to non-VOC cases, indicating higher viral loads for those infected with the VOC.[194,195] In another study (pre-print), a small but significant association between infection with the Gamma variant and lower Ct values was reported.[185] There is also some indication that the VOC may lead to a longer duration of disease. Kissler et al.[196] reported a longer mean duration of infection of 13.3 days for Alpha cases compared to 8.2 days for non-Alpha cases.

EFFECT OF THE VARIANTS ON VIRULENCE

There is some evidence that VOC may be more virulent, resulting in more severe disease or an increased risk of dying.[177] A pre-print by Grint et al.[197] reports an approximate 67% increased hazard of death by 28 days following a COVID-19 positive test associated with the Alpha variant, which was consistent across all demographic subgroups. A large matched cohort study from the UK with 109,812 participants identified that the risk of dying from Alpha infection was about 64% higher compared with previous lineages.[198] A pre-print by Davies et al.[195] has also reported an increased risk of death for the Alpha variant compared with previous lineages in the UK between November 1st 2020 and February 14th 2021, but did not identify the mechanisms of increased mortality. There is some suggestion that higher viral loads, as indicated by high Ct values, may contribute to changes in disease severity, including increased mortality, but further research is needed. An animal study (pre-print) found evidence of very efficient infection in the lower respiratory tract for hamsters exposed to Alpha and Beta. These hamsters also displayed increased levels of cytokines, which could promote inflammation, although differences in pathogenicity compared to previous lineages were not observed.[199] A pre-print from Brazil comparing risk of death from COVID-19 infection in Nov-Dec 2020 to Feb 2021 found an increase in the case fatality rate across all age groups, with a higher proportional increase of death among younger people (20-59 years old) and those without pre-existing conditions than in the earlier wave.[200] Apart from those under 20 years old, there was also an increase in the proportion of severe cases. The implications are that infections with Gamma have an increased risk of severe disease and death compared to previous strains. Early indications suggest that Delta may result in more severe disease, with an increased risk of hospitalization reported for cases infected with the Delta variant in the UK.[187,201] More research is needed for all VOC to understand how they impact virulence, particularly for Beta, Gamma and Delta variants.[187,201]

EFFECTS OF THE VARIANTS ON IMMUNITY

One of the main concerns with any new variant is potential for evasion of natural or vaccine induced immunity. More community spread of the virus provides opportunities for further evolutionary adaptations for evading immunity, underscoring the importance of reducing community spread as much as possible. Research is ongoing to identify if, and how, variants may be evading immunity by studying the immune response in cells infected with the new strains, and the response in blood sera from persons with previous COVID-19 infection or persons who have been vaccinated using the currently available COVID-19 vaccines. For the Alpha variant, the immune response does not appear to be significantly impaired as demonstrated in tests with blood sera from patients with previous COVID-19 infection.[202] Laboratory studies by Brown et al.[203] did not find an escape from immunity for Alpha or signs of increased risk of reinfection. Sera from persons vaccinated with the Pfizer-

BioNTech vaccine was observed to effectively block the binding of the virus to the ACE-2 receptor, with only slightly decreased effectiveness for Alpha compared to the previous lineages.[191] In comparison, tests of blood sera from persons with prior COVID-19 infection showed a reduced neutralization of Beta compared to earlier strains, with one study reporting about a 13-fold decrease in neutralization, and inferring a potential risk of reinfection.[188,202] Wibmer et al.[204] also found an increased resistance to neutralizing antibodies for the Beta lineage compared to previous strains, suggesting potential for reinfection. One reason for the difference between Alpha and Beta may be the E484K mutation that affects binding and neutralization. This mutation is present in the Beta and Gamma lineages, but not in the Alpha lineage, and could be responsible for significantly decreased neutralizing activity.[202,205] Evidence of significant levels of reinfection in Manaus, Brazil where a high proportion of the population (76%) showed signs of prior infection, is thought to be associated with the Gamma variant evading the natural immunity that might have been conferred from prior infection. Initial study of the effectiveness of vaccines against symptomatic disease found a reduced effectiveness for dose 1 for the Delta (33.5%) compared to the Alpha variant (51.1%) for both the Oxford AstraZeneca and Pfizer-BioNTech vaccines, but similar levels of protection against both VOC were achieved after the second dose.[187,206]

RECOMMENDATIONS FOR NON-PHARMACEUTICAL INTERVENTIONS (NPI) IN INDOOR SPACES

Research is ongoing to understand how the evolution of the SARS-CoV-2 virus affects the spread of the virus and implications for the current measures to mitigate spread. For those involved in designing or implementing public health measures, changes in how the virus transmits and changes to its virulence could influence the measures adopted or adapted. Evidence to date indicates that the VOC are more transmissible, can lead to more severe outcomes and Beta and Gamma may evade immunity. Transmissibility is likely affected by more efficient binding to ACE-2 receptors and potentially by increased viral loads, and longer persistence of viral shedding. This means that an exposure to a lower initial dose or exposure over a shorter duration compared to previously circulating variants could result in infection. While the variants appear more transmissible, to date there does not appear to be a change in the mechanisms of viral shedding or behaviour of infectious bioaerosols or the way they transmit. This suggests that current measures to reduce transmission should continue to be applied, but with greater consistency, closing gaps in mitigation measures where there is low adherence or slack implementation.

To date, new measures related to reducing the spread of variants have been associated with reducing community spread and travel-related introductions of the virus, focussing on testing, quarantine, isolation, and contact tracing. Additional public health recommendations and revised orders have been focused on limiting direct person-to-person contacts as much as possible. This has resulted in a reintroduction or strengthening of lockdown measures in affected regions or countries by re-closure of schools, entertainment venues, recreational facilities, and limits on attendees or occupancy for certain activities or venues, public curfews to restrict population mobility, and encouraging working from home. Additional travel restrictions and quarantine requirements for returning travellers have sought to limit the new introductions from outside of regions or countries.[207]

There have been few additional changes in recommended non-pharmaceutical interventions (NPIs) to reduce community spread of variants, beyond a re-emphasis of personal protective behaviours such as physical distancing and mask-wearing. There has been no published evidence of how a change in existing mitigation measures (e.g., such as an increase in physical distancing) would reduce spread of VOC compared to the previous lineages. Most agencies emphasize maintaining current approaches and working to strengthen adherence among the public. On an organizational level, encouraging a layered approach to reduce transmission continues to be recommended. Individual "layers" include use of masks, reinforcing distancing, keeping group sizes small, continuing to encourage hand hygiene, enhancing ventilation indoors, reducing unnecessary travel, increasing vaccination, and managing public expectations of reopening.[177,207-209] A review of jurisdictional guidance for masking in 14 regions reported that most had not changed their guidance in response to variants. Austria, Germany and France were the only regions to change recommendations for wearing of public face coverings, upgrading their recommendation from a non-medical face covering to a medical mask or equivalent based on improved filter efficiency and fit.[210] Recent literature is reporting on the benefits of double masking or mask modifications to improve mask fit.[211] Recommendations for physical distancing have remained unchanged to date, as have the use of partitions in retail spaces and recommendations for improved ventilation. For a deeper discussion on implementing a layered approach, whether through the hierarchy of controls or another model, please see Section 4 of this document.

Despite the lack of recommended changes to existing, or implementation of new measures to reduce the spread of variants, organizations may consider a re-evaluation of transmission potential in high-risk and high-capacity settings. Refreshing risk assessments based on the characteristics of the space (e.g., size, level of ventilation), the type of occupants (e.g., number and risk level of occupants) and the types of activities that take place in the space (e.g., level of emissions generated, duration of occupancy throughout the day) is warranted. This process can be used to identify weaknesses in existing mitigation plans, and opportunities for enhancing measures, as well as providing an opportunity to revisit messaging that reemphasizes the importance of various measures in the context of the VOC.

Further VOC are likely to emerge in the future, but reducing community spread and ensuring good adherence to current public health recommendations will reduce the chance of these taking hold.[212] Well designed and fully implemented mitigation plans will help reduce spread of the virus in the community and reduce the opportunities for viral replication and evolution of new mutations that lead to VOC. These measures will be required in combination with vaccine roll-out, improved surveillance and genomic testing.[212]

RESEARCH QUESTION 3: WHAT ARE THE KEY FACTORS THAT EXACERBATE THE RISK OF TRANSMISSION INDOORS?

A review of reports of outbreaks, clusters and epidemiological investigations provides additional evidence of the characteristics of indoor spaces and activities most often associated with viral transmission (**Appendix 2**). In this section, we combine a review of previous outbreaks with additional evidence from public health and exposure science to understand what factors most influence the risk of transmission in shared indoor spaces. Early in the pandemic, factors that were found to be common among many large COVID-19 outbreaks, prior to significant uptake of population wide mitigation measures, were commonly referred to as the 3 Cs - crowded places, close contacts, and confined/enclosed spaces).[50,119] Additional factors were later identified to be important in transmission including continuous exposure, absence of control measures such as masking, activities such as singing or exercise, community-specific factors such as level of community spread and individual factors such as contagiousness (super-spreaders), or susceptibility to infection.[213]

OCCUPANCY AND CROWDING

Crowding reduces the ability for individuals to maintain distance from each other. Crowding increases exposure to concentrated bursts of respiratory emissions due to close proximity contact, as well as exposure to smaller respiratory particles that remain suspended and move around on air currents and can accumulate in an enclosed space over time.[8,82,214,215]

Defining what is “crowded” can be difficult without also understanding how respiratory particles move within a room. Each occupant in a room is the source of a ‘thermal plume’ that affects airflow around their bodies, as well as the movement of their own respiratory particles.[216] This means that although respiratory particles are most dense around the source, air warmed by the occupant’s own body heat can entrain those particles, lift them, and “cast” them upward into the room, even after they have been directed downward (e.g., coughing toward the ground). As the air cools and sinks, respiratory particles likewise sink and may contact other occupants. Similarly, particles from seated occupants can been lifted up into the breathing zone of those standing nearby. Crowding increases the likelihood that one or more people will be within this “hot zone” of an infected individual, increasing the risk that they will inhale enough virus-laden particles to establish an infectious dose. Having more people in the space also increases the probability that one or more infectious people will be present, especially where there is a high level of community spread. All of these factors underscore the importance of minimizing occupancy whenever possible.

Physical distancing is key to establishing occupancy limits. Globally, nations have established physical distancing requirements of roughly 1 or 2 m, based on assumptions regarding the ballistic range of larger droplets. Distancing also reduces the risk of transmission due to smaller particles, which are diluted as one moves farther from the source. Although the underpinnings of the 2 m rule have been sharply criticised,[217] physical distancing should not be viewed as a way to eliminate risk, but rather to limit the greatest part of that risk, being exposure to the hot zone. Physical distancing is also practiced in combination with other interventions like masking and the use of physical barriers. A previous systematic review and meta-analysis found that combined use of physical distancing and masking reduced the risk of transmission by 80%, based on data from SARS, MERS, and SARS-CoV-2, and 2 m was better than 1 m.[76] Very recently, the US CDC reduced its physical distancing requirement from 6 feet to 3 feet for young school children, based partly on data that found no significant difference in transmission rates among school districts using different minimum distances; however, it should be noted that this may not be appropriate for settings involving adults, and in all the school districts studied, mask requirements were in place but observance of these requirements was not confirmed on the ground.[218]

CHARACTERISTICS OF THE SPACE

Small and enclosed spaces where there is no clearance of accumulated air or where there are directional air flows within a space can increase the risk of exposure when an infectious person is present. In addition to occupancy or crowding, certain characteristics of the indoor space could affect the likelihood of high-risk exposures. Some of these include:

- Presence or absence of ventilation and operation at appropriate rates (discussed in the next section).
- The use of stand-alone "comfort" devices that do not bring in additional air but may create strongly directional air flows (e.g., fans and air conditioners).
- Presence or absence of openable windows for supplementary dilution ventilation.
- Presence of large structures, barriers, or furniture that may affect air flow or mixing in unexpected ways, or cause occupants to be concentrated in certain areas.

CHARACTERISTICS OF THE OCCUPANTS

In addition to occupant behaviour and overall compliance with public health recommendations, the intrinsic characteristics of those occupying the room also affects the likelihood of transmission:

- *Intrinsic characteristics of those infected.* The stage of the illness and the severity of infection can influence the nature of the respiratory emissions released and the concentration (or viral load) of infectious virus in these emissions. Cases with a lower Ct (<28) were associated with a significantly higher transmission risk, implying that a low Ct value equates to a higher viral load.[219] A high-risk activity (e.g., singing), which releases a high concentration of droplets and aerosols, carried out by an individual with high viral loads further amplifies the risk to people sharing the space. Some people may also be naturally more likely to shed virus compared to others (so called super-emitters).[7]
- *Intrinsic characteristics of the potential hosts.* High risk groups may be more susceptible to infection, with age being one of the most important determinants of risk. Immunocompromised persons and those with underlying health conditions are also at greater risk of developing severe illness from SARS-CoV-2 infection. Immunocompromised persons may have a prolonged course of infection, which may also favour mutation of the virus.[220]

CHARACTERISTICS OF THE INTERACTION AND ACTIVITIES THAT TAKE PLACE IN THE SPACE

The most important factors in transmission are proximity to and duration spent in contact with an infected person. Research has shown consistently that the duration of contact is a primary factor in whether transmission occurs.[221] Wu et al.[72] found that physical contact, shared living space, or shared vehicle with an index case were significant risk factors for secondary infection. Duration is an important factor in both short- and long-range transmission. The longer people spend in a crowded environment, the greater the accumulation of emitted air where it is not cleared with ventilation, resulting in an increased source load of emissions released over time. For example one minute of loud speaking by an infected individual could produce up to 1000 virion containing particles.[81] Person-to-person interactions such as greetings and social interactions, sharing of food, drinks or equipment, and shared transport can increase opportunities for all main transmission routes due to increased shared air and surfaces.

The outbreaks reviewed in **Appendix 2** highlight a number of higher risk activities, including loud talking/shouting, singing, and high-intensity exercise. These activities result in the emission of large quantities of respiratory emissions, which exacerbates transmission risk by increasing the concentration of virus-laden particles present and decreasing the time required to acquire an infectious dose. Intense vocalization and vigorous activity also increases the volume of air inhaled by a susceptible host sharing the same airspace.[124]

ENVIRONMENTAL CONDITIONS

Research is ongoing to understand how environmental conditions affect the persistence of SARS-CoV-2. Research has focused on the effects of temperature, humidity, ultraviolet light, and combinations of different conditions.

- *Temperature.* There is now ample evidence to indicate that high temperatures are more effective for deactivating the SARS-CoV-2 virus, and the virus is more persistent at colder temperatures. Studies have found that virus can remain viable for several days to weeks at 4°C, but stability decreases with increasing temperature, with survival being as little as 30 minutes at 56°C.[132,139,222-224]
- *Humidity*. The effects on humidity are more complex, as humidity may influence how droplets move and their rate of decay and can influence susceptibility of individuals to infection.[225] Humid conditions can reduce evaporation of liquid contained in respiratory droplets, reducing aerosolization and allowing droplets to fall to the ground or settle on surfaces more readily. In contrast, warm dry environments could enhance evaporation of droplets, resulting in a greater number of aerosols being dispersed.[226] The potential to remain infectious for longer under cool, dry conditions has been demonstrated to other coronaviruses and SARS-CoV-2 in aerosols and on surfaces.[222,225,227,228] Humidity can also affect the susceptibility of respiratory systems to viral infection, with dry conditions reducing the effectiveness of the mucosal lining of the respiratory tract to prevent infection.[225]

- *Light.* Ultraviolet (UV) light has been shown to reduce viral loads for respiratory viruses, including SARS-CoV-1 in clinical and other controlled settings.[229,230] Germicidal effects can occur between 200-320 nm, which covers the range of UV produced by natural sunlight (UV-B, 280-320 nm) and UV produced by lamps for specific applications (UV-C, below 280 nm).[231-235] Various configurations of UV lamps (e.g., wall mounted, ceiling mounted, portable units) are currently used in different commercial and clinical settings for disinfection in indoor spaces. UV disinfection is not instantaneous and can vary by intensity and duration of exposure to UV.

SUMMARY

Spaces characterized by crowding, proximity of interactions (e.g., within 2 m including verbal interactions, sharing meals), enclosed spaces with limited ventilation, long duration of contact (e.g., > 15 minutes), activities that require heavy breathing (e.g., exercise, singing, cheering) and locations with absent or poorly implemented controls have featured in COVID-19 clusters and outbreaks.[56,80,124,236] These exacerbating factors increase the potential for short-range exposure to droplets, concentrated bursts of aerosols, and potential fomite transmission via shared surfaces. Several of these factors may collectively increase the opportunity for infectious aerosols to accumulate in sufficient quantity, over a sufficient duration, and increase the risk of exposure of a susceptible host to an infectious dose of virus. Thus, these exacerbating factors increase the risk of transmission via multiple routes simultaneously, and measures to prevent transmission must likewise be multi-layered and consistently applied. The next section presents some of the approaches to mitigating transmission risks indoors.

RESEARCH QUESTION 4: WHAT STRATEGIES ARE MOST IMPORTANT FOR MITIGATING RISK, AND HOW CAN WE ESTIMATE THE IMPACT OF VARIOUS MEASURES?

The objective of risk mitigation measures recommended by public health is to reduce community level impacts by slowing infection rates, reducing overall case numbers, and reducing pressure on public services such as hospitals, to allow time for vaccines to be distributed. Risk mitigation must also be equitable, ensuring that health outcomes are not the result of an inability to engage in risk mitigation. Risk mitigation measure should also be applied in a layered approach.

HIERARCHY OF CONTROLS

The field of occupational health and hygiene has long relied on the Hierarchy of Controls (**Figure 1**) to guide the selection of control measures. The principle is that measures higher up on the hierarchy are more effective in reducing the risk for a greater number of people, and that measures further down the hierarchy (some at the individual level) should be implemented as needed to mitigate any remaining risk.

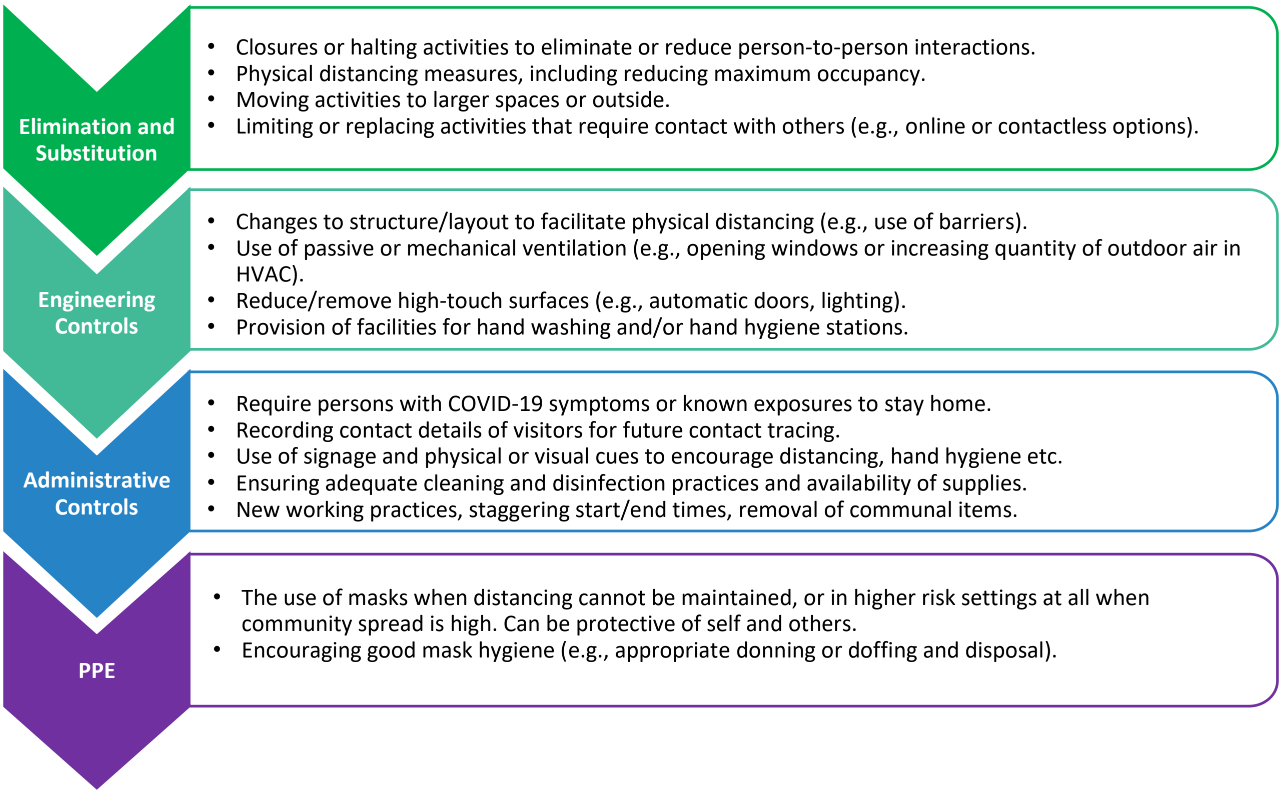

Figure 1 Applying the hierarchy of controls for reducing risks of transmission of COVID-19 in indoor spaces.

Applying the hierarchy during a pandemic has been somewhat challenging because, in an emergency, it may be necessary to activate multiple levels at once (or in reverse order) rather than proceeding in a stepwise fashion. For example, although PPE is at the "bottom" of the hierarchy, implementing a mask mandate is much faster and less costly than some engineering controls, like reconfiguring a workspace or installing new air cleaning technology. The hierarchy of controls may also have health equity implications, as not all facilities or organizations will have the same capabilities or financial resources to implement health-protecting measures. Thus, it may be necessary to target funding or policy action to specific occupants, types of work, buildings, or zones of buildings to ensure that some people are not experiencing increased risk due to the inability to apply the fastest or most effective measures.

However, as we shift from a medium-term emergency to a long-term reality in which respiratory disease plays a greater role in planning indoor spaces, the hierarchy remains a useful conceptual tool to guide new investments and policy development. Acknowledging health equity objectives – ensuring that disease transmission does not disproportionately impact specific occupants or parts of the workforce – will remain a key feature of long-term planning.

ELIMINATION

Elimination refers to actions that will fully remove the potential for SARS-CoV-2 exposure. In the context of the COVID-19 pandemic, this means isolating those infected from others, whether that be within the home itself or by preventing those infected from attending work or school until the illness resolves. Persons known to have been exposed or those recently returning from travel have also been asked to quarantine for a fixed period of time (e.g., 14 days). This approach has been very effective in preventing community spread in some countries. There are many reasons why isolation of the sick and quarantine of those at risk of infection has not been completely effective in reducing spread elsewhere. Compliance with public health advice is not always universal for many reasons, which may be financial (e.g., no access to sick pay), lack of ability to work from home, lack of awareness or requirements, lack of enforcement, or lack of perceived risk from non-compliance.

Another significant challenge in elimination of risks is the potential for persons to be infectious prior to experiencing symptoms, and some people remaining asymptomatic throughout their infection.[30,31,36] Due to the potential for pre-symptomatic and asymptomatic transmission, the only way to completely eliminate the risk of infection, where there is community spread of the virus, is to eliminate meeting in the office (move to 100% remote work). At present, vaccination of all occupants may not completely eliminate the risk but can reduce the likelihood of transmission and severity of disease for currently circulating strains of the virus. Some variants of concern (VOC) have shown ability to evade vaccine-induced immunity to some degree, although receiving both doses as recommended improves vaccine effectiveness (see **Section 2**). Continued surveillance is needed to monitor the emergence of new VOC and the effectiveness of vaccines to prevent infection or symptomatic disease (further discussion of vaccination is beyond the scope of this document).[237]

ENGINEERING CONTROLS

Engineering controls refer to efforts to re-design or modify the physical environment to reduce transmission risk. Re-designing the occupied space may include removing workstations to accommodate distancing requirements or re-configuring workstations such that occupants no longer face each other. Other means may be to designate unidirectional flow of traffic in halls and stairways. All of these activities allow occupants to move about with an expanded personal bubble, allowing them to minimize the proximity and duration of contacts. Physical barriers and ventilation have been the focus of most engineering controls throughout the COVID-19 pandemic.

PHYSICAL BARRIERS

Physical barriers prevent larger respiratory particles from immediately invading another person's breathing zone, which is defined by a radius roughly 30 cm around a person's nose.[238] However, barriers are believed to be less effective against smaller droplets, which can loft over the barrier. Abuhegazy et al.[19] modelled air flows in a typical classroom and found that glass barriers reduced the total amount of small particles (1 µm) deposited on students by about 63%, although the presence of barriers slowed clearance of the remaining airborne particles via ventilation. These results highlight the need to use physical barriers judiciously. They can be used beneficially to isolate a worker who would otherwise be exposed to many different people in a single day (e.g., a triage nurse in enclosed kiosk), but in other contexts the interruption of air flow may cause more harm than good. For example, positioning plexiglass barriers in an open-air patio hinders the otherwise almost immediate dilution of particles.

VENTILATION

There is no evidence to show definitively that ventilation decreases the number of SARS-CoV-2 infections. However, there are a number of documented instances in which aerosol transmission appears to have occurred in under-ventilated spaces or in the presence of strongly directional air flow (e.g., an AC unit blowing from one person to another) (**Appendix 2**). It is reasonable to assume that increasing the exchange of stale indoor air for fresh outdoor air will decrease the concentration of respiratory particles that have not already settled to the floor, and ventilation has generally been shown to reduce respiratory infections for other opportunistic airborne diseases like influenza (next sub-section). For these reasons, the following low-cost ventilation improvements have been widely recommended (for detailed resources see ASHRAE[239] and WHO,[240] as well as the compendium of IAQ resources in **Appendix 3**). Facilities should endeavour to address as many of these as practical:

- Running HVAC systems on *100% **outdoor air*** (or as near to as possible).
- ***Disabling demand-controlled ventilation***, so that a high ventilation rate is maintained despite changes in occupancy.
- ***Running HVAC fans constantly***, including at low levels during periods of low occupancy.
- ***Installing MERV 13 filters*** whenever possible, accounting for the resulting pressure drop and potential underventilation. It should be noted that although the SARS-CoV-2 RNA has been found in ductwork and HVAC filters,[130,241] there has been no transmission associated with these findings. There is currently no evidence that SARS-CoV-2 can transmit through ductwork to affect other areas of the building. Therefore, installing higher MERV filters (and potentially causing underventilation of specific rooms due to the pressure drop) is questionable in terms of public health benefit, and the need to verify ventilation adequacy locally (throughout the building) should be emphasized.
- ***Opening windows*** is a simple solution to immediately improve air quality and has been a key public health recommendations since the beginning of the pandemic.[242] Bluyssen et al.[243] found that establishing cross ventilation by opening doors and windows in an office environment (25 m^2) out-performed the existing mixing ventilation system; however, opening only windows or only the door (natural ventilation) appeared to redistribute the

particles in the room and did not provide better air quality than the existing ventilation system.[19,243]

- Ensure that ***exhaust fans*** (especially in bathrooms) are running constantly, due to the potential for toilet flushing to create aerosols from human waste that may contain the SARS-CoV-2 virus. Although SARS-CoV-2 has often been found in hospital toilets used by patients,[90] and transmission due to aerosolization of feces may have occurred in rare instances,[127,128] public washrooms have not revealed themselves to be major sources of outbreaks during the pandemic.

In addition to the above widely recommended measures, ***CO_2 monitoring*** has been proposed as rapid means for building managers to continually assess and address ventilation adequacy in shared spaces. This technique relies on low-cost sensors to monitor the time-weighted average of CO_2 levels within a space. As the length of occupancy and the number of occupants increases, CO_2 levels within the space will increase relative to outdoor ambient levels (e.g., 400-450 ppm) if fresh air exchange is insufficient for that use. CO_2 monitoring allows occupants to take action, such as opening a window or reducing occupancy, when CO_2 level surpass some agreed upon action limit. However, there are a number of concerns with using CO_2 monitors as a COVID-19 risk mitigation tool, which are discussed more thoroughly in a recent NCCEH document.[244]

AIR CLEANERS AND PURIFIERS

Air cleaners (e.g., HEPA filters) and air purifiers (e.g., UVGI systems) have also been proposed as an alternative to ventilation in spaces that have no existing ventilation, or ventilation upgrades are difficult. These devices may provide some benefits but also have limitations.[245] One common consideration that is often overlooked is the sizing of the device for the space it is intended to treat, based on the clean air delivery rate (CADR) stated on the device. End-users may underestimate the number or size of devices required to provide the level of treatment equivalent to conventional ventilation systems.

- ***HEPA-equipped portable air cleaners*** are widely recommended as a supplement for enclosed spaces due to their ability to remove airborne particles from the air flowing through them. Although it is logical that actively filtering the air is better than occupying a space with no ventilation and no filtering, the use of portable air cleaners is not fool proof either. Bluyssen et al.[243] found that a portable air cleaner operating at a flow rate of 1200 m^3/h performed better than the existing mixing ventilation system for a 25 m^2 office space with 6 workstations. However, its effectiveness varied depending on its position in the room, it caused drafts in some locations (causing discomfort and also potentially increase transmission risk) and most of the occupants expressed dissatisfaction with the noise produced. These results highlight the difficulty of relying on portable air cleaners without substantial verification of the set-up, although such devices are almost certainly better than occupying an unventilated space.
- ***Ultraviolet germicidal irradiation (UVGI)*** devices based on wavelengths in the UV-C range have been used in hospitals and clinical environments for many years. There are various configurations depending on the placement of the devices (e.g., in duct, upper room, portable units etc.).[246] The literature on the effect of UV-C on coronaviruses finds that it can

be effective against enveloped, single-stranded RNA viruses (e.g., SARS, MERS),[231,233,234,247] and more recent study indicates that UV-C can inactivate SARS-CoV-2.[235,248-250] The germicidal effects however depend on the duration and intensity of exposure and factors such as shadowing, obstructions, dust on the lamps, and dirt on surfaces, which can shield microorganisms from UV-C.[231,247,251] UVGI devices can only inactivate pathogens that pass in proximity to the lamps, so configuration and placement of any device is key as to whether or not it can contribute to reducing transmission indoors. There are also significant risks of damage to human skin and eyes from direct and prolonged exposure to UV-C irradiation, so devices must be contained or shielded to prevent harm. Some devices may produce ozone, so users should be aware of these added hazards. Although these devices show promise, at present, we are unaware of any UVGI-based air disinfection device that has been approved for use by Health Canada for reduction of COVID-19 transmission. New technologies that incorporate less harmful wavelengths such as far-UVC, may have fewer limitations for shielding, and may show future potential for use in public spaces if the absence of harms can be proven.

- ***Other air cleaning technologies*** on the market claim to be effective against COVID-19 by physically removing particles from the air (e.g., electrostatic precipitators, ion generators) or inactivating airborne pathogens (e.g., plasma generators, and ozone generators). Like HEPA filters, portable devices are limited by the quantity of air they can treat, and their effectiveness depends on their placement in a room (e.g., free from obstruction, near the source of emissions, etc.). Caution is also required to ensure no additional hazards are introduced into a space. Some devices can generate ozone, a respiratory irritant, and should not be used indoors.[245] Ozone generators in particular are not recommended for occupied spaces due to the respiratory hazards posed. Although some of these devices may be effective in reducing some air pollutants, we are unaware of any published evidence to demonstrate a reduction in COVID-19 transmission. In general, consumers should be wary of new technologies making claims regarding disinfection and/or reducing COVID-19 transmission; some of the products making false or misleading claims have been posted on Health Canada's website.[252]

ADMINISTRATIVE CONTROLS – HOW TO SHARE SPACES SAFELY

Administrative controls include changes to how people interact in a space to minimize opportunities for close contact and to reduce interactions with shared spaces, items, or surfaces. Having a COVID-19 safety plan is part of the package of administrative controls workplaces have had to adopt. Administrative controls include ***reducing occupancy*** by shifting to remote work or staggering workdays or hours and ***reducing contact*** among employees by establishing cohorts, closing unventilated spaces, and having unavoidable group activities outdoors or in larger spaces.[253] This includes an emphasis on observing COVID-19 protocols in break rooms and when socializing or commuting with other co-workers. In instances where occupants have to share an unventilated space or perform aerosol-generating activities (e.g., a dental office), procedures such as airing-out or ***fallow times*** have been used. These have been generally successful in avoiding workplace outbreaks. Other administrative controls can include the use of signage and visual cues to encourage and provide reminders to wear a mask, observe one-way traffic markers, or follow good hand hygiene, ensuring workplaces have adequate supplies and access to hand washing and hand-hygiene stations, and recording worker and visitor details for contact tracing purposes should it be required.

Perhaps one of the least utilized strategies during emergency conditions is engagement with occupants, not only to explain the nature of the risks to ensure compliance, but also to train those occupants to understand the risks such that they are equipped to make good risk-based decisions. One means to educate individuals about risk is ***web and app-based risk calculators***.[254-256] These have become an important means to interface with individuals and provide them with a framework to understand how various factors work together to increase or decrease risk of transmission. These calculators consider factors such as user location, size of the gathering, the nature of the activity, and mask use, but also individual factors such as health status and pre-existing conditions. Although most COVID-19 risk assessment apps are targeted at individuals, there are several risk assessment tools that have been developed for use by site managers seeking to understand transmission risks based on site-specific data (e.g., this tool for aerosol transmission risk[257]), which can then be used to assess transmission risk in various scenarios.

Another uncommon approach is to train occupants on indoor air quality (IAQ) awareness. This involves educating occupants about IAQ concepts and equipping them with tools that allow them to monitor IAQ and take action where necessary. One example of this is the use of CO_2 sensing, as described above, as a tool to train occupants to learn when to take ventilatory action. In Germany, classrooms have been equipped CO_2 sensors, which are being used to train teachers and students to be mindful of shared air and to periodically open windows; the intent of this is to entrench the habit and later remove the CO_2 sensor.[258] There are several caveats to this approach: 1) commercially available CO_2 sensors vary greatly in sensitivity and accuracy; 2) fixation on the digital readout can be counterproductive as the readout is not as important as whether CO_2 levels are trending upward or downward; and 3) IAQ awareness requires allowing occupants to have some control over ventilation, specifically the ability to open windows, which may not be advisable in spaces in which maintaining pressure differentials is required (e.g., a lab environment must be positively pressurized vs. the fume hoods).

PERSONAL AND GROUP PROTECTIVE EQUIPMENT

Personal protective equipment (PPE) has traditionally been considered an additional control measure when other measures have already been implemented and is not intended to be a substitute for other control measures. The use of masks as PPE in common spaces however has been increasingly mandated where there is a high level of community spread in the local population. Mask-wearing has been found to reduce the number of cases and growth rate of COVID-19 infections where there is widespread adherence, and where used in combination with other NPI such as hand hygiene and physical distancing.[211] Masks vary in their ability to block exposure to respiratory particles due to mask construction and fit, but can contribute to source control for the protection of others (group protection) and personal protection of the wearer. The most effective masks are those that provide a good fit around the nose, sides, and chin, and are made of materials that provide a high level of particle filtration, while maintaining breathability. Special consideration should be given to persons with cognitive difficulties or physical disabilities when considering appropriate mask use, including workers with difficulty breathing due to existing medical conditions.

Additional precautions may be needed for workers who are not able to wear a mask during work, and "mask breaks" outside the workplace may be needed for persons who find it difficult to wear a mask continuously. A detailed presentation of the literature on the effectiveness of masks, and considerations for safe use of masks is available from the NCCEH.[211]

DESIGNING AN EFFECTIVE RISK MITIGATION STRATEGY

Given the range of options available, and the limited data regarding the individual effectiveness of these options, how do we choose amongst the range of technological and non-technological options to create a suite of preventive measures? The following key recommendations were drawn from various workplace risk assessment tools, which can be found in the references:[259,260]

1. Gather information regarding the occupancy, activities, and physical characteristics of each occupied space in the building. In some cases, HVAC consultation or audits may be necessary to understand ventilation characteristics.
2. Identify and rank risk of occupied spaces based on information in **Section 3** or from risk matrices.
3. Prioritize actions for the highest risk occupants first. If it is possible to move occupants to a lower risk space, consider the feasibility of this before implementing interventions.
4. Apply a hazard control strategy, like the hierarchy of controls, remaining aware that in an emergency it may be necessary to activate multiple levels at once or in reverse order.
5. Layer measures as necessary; higher risk areas and occupants need higher level protections.
6. Evaluate the effectiveness of risk mitigation measures through periodic review (next section).
7. Plan for long-term IAQ improvements for future proofing (**Section 5**).

EVALUATING THE IMPACT OR EFFECTIVENESS OF RISK MITIGATION STRATEGIES

Although considerable effort has been put into designing risk assessment tools, workplace safety plans, and supporting resources, evaluation or monitoring the effectiveness of this plan is not usually elaborated upon.[261-263] The following are some approaches to assessing the success of a COVID-19 risk mitigation strategy.

- Assess compliance: Are employees able to carry out the plan in the way it's described?
- Stakeholder satisfaction: Do occupants feel safe in the space?
- Learning from transmission events: Are there any activities, processes, or spaces in which exposures are occurring more often? Do the exposures that happen in the workplace exceed that which is to be expected in the community? Typically, this level of information is not accessible until after a public health response has been initiated due to workplace exposure.
- Periodic review: Is there a plan in place to review and update the workplace safety plan to account for changing information or a shift in the level of risk in the community, and to communicate that change with other occupants?
- Exit strategy: Is there a plan in place for returning to normal operations? Which mitigation measures can be relaxed, and which should become common practice? Follow up with

occupants is required to understand how common perceptions of risk may have changed, and what measures (or hybrid measures) would help them to continue feeling safe in the future.

RESEARCH QUESTION 5: WHAT IS KNOWN ABOUT THE INFLUENCE OF VENTILATION IN THE MITIGATION OF TRANSMISSION INDOORS?

As the focus on aerosol transmission of SARS-CoV-2 has sharpened, increasing emphasis has been placed on the importance of ventilation and air cleaning devices as a risk mitigation measure. This is because, as particles decrease in diameter due to evaporation, the time required for them to settle due to gravity increases exponentially. At a given point (which shifts depend on conditions, noted above), the particle will no longer settle due to gravity. Instead, other mechanisms (electrostatic attraction, impaction, etc) are the main modes through which the smallest particles are cleared from the air and this occurs over an extended time frame.[264] If these particles are not physically removed from the space (ventilation) and/or removed from the air itself (air cleaning), there is potential for them to accumulate to the point that another occupant would acquire an infectious dose in the time spent in the room, depending on how long the virus remains viable.

Ventilation and air cleaning aim to reduce aerosol transmission risk. Critically, however, when two people are standing close together and talking (close contact), especially if they are unmasked, they are producing and exchanging thousands of respiratory particles per second,[81] and increasing ventilation would have minimal impact on this rapid exchange. In addition, ventilation or air exchange only acts upon particles that are aloft for long enough to be entrained in an air flow and drawn out of the room. Larger particles that follow a “ballistic” trajectory wind up on surfaces, where they may contribute to fomite transmission, although the risk of fomite transmission is believed to be low.[152]

This is not to say that ventilation is futile. If close contact interactions are eliminated (e.g., through distancing or plexiglass barriers), ventilation will reduce the risk of longer-range transmission, effectively buying more time for occupants of a shared space. This section will focus on the uses of, evidence for and caveats regarding ventilation and air cleaning as a means to mitigate SARS-CoV-2 transmission risk indoors.

IMPORTANT TERMINOLOGY

Part of the challenge with communicating the benefits and limits of ventilation as a risk mitigation measure is the confusion around the meaning of specific terms. For clarity, ***ventilation*** refers to the exchange of stale room air for “fresh” air, whether that be outdoor air, or some portion of recirculated/filtered air drawn from within the building itself. Ventilation can be achieved passively, by taking advantage of natural forces like wind and buoyancy to create air flows (***natural ventilation***), or actively through the use of blowers or fans and ductwork to force air through to the spaces that need it (***mechanical ventilation***). Because this forced air is also usually heated, treated, or cooled, it is often referred to generally as a heating, ventilation, and air conditioning (HVAC) system. Ventilation (air exchange) is distinct from ***air cleaning or purification*** (filtration, UVGI, etc.), which focus on removing gaseous or particulate contaminants from the air, or for other devices like fans and portable air conditioning units, which move air around but do not bring in fresh air. Ventilation rates can be expressed as **air changes per hour** (ACH, the number of room volumes of air that are replaced each) or **volumetric flow** (litres per second) per person/occupant or per area.

EFFECTIVENESS OF VENTILATION ON RESPIRATORY DISEASE TRANSMISSION

Previous studies have found that ventilation has a positive effect on reducing the occurrence of respiratory infections in hospitals and other settings. These studies have been reviewed extensively by several previous authors.[265-267] However, the majority of these studies examined the effect of the presence or absence of intentional ventilation (mechanical or natural) compared to no ventilation at all. More recent studies have provided a more quantitative assessment of the relationship between ventilation rates and respiratory infections. Zhu et al.[268] showed that students living in a dormitory with mechanical ventilation and 100% outdoor air experienced fewer laboratory-confirmed acute respiratory infections than students living in a building reliant on infiltration only (no mechanical or intentional natural ventilation). Yang et al.[269] collected temperature, relative humidity and CO_2 data from dormitories over several seasons and found that night-time ventilation rates were associated with the occurrence of common colds and influenza in both summer and winter. Interestingly, the data showed a closer association with ventilation rate expressed per occupant (L per second per person) than when expressed as air changes per hour. Finally, Du et al.[270] found that modulating ventilation rates to maintain CO_2 levels < 1000 pm was associated with a 97% decrease in tuberculosis (TB) incidence among contacts of 27 TB cases initially housed in a student residence, who were then followed over 5 years. These studies provide some useful insight into the minimal ventilation rates necessary to prevent disease but have limited value in informing optimal ventilation (next section).

CONSIDERATIONS FOR OPTIMIZING VENTILATION IN A SPACE

Creating healthy indoor air is not as simple as increasing the air changes in a space. There are many engineering and environmental factors that must be considered when attempting to minimize exposure to infectious respiratory particles in a space:

- ***Ventilation rate***: Although it is generally accepted in professional practice that 2 ACH is too low to prevent potentially harmful exposure to bioaerosols, including respiratory viruses, over-ventilating a space can also lead to increased exposure if other occupants are in the wrong place at the wrong time. For example, Pantelic and Tham[271] found that with a mixing ventilation system, increasing from 6 to 12 ACH resulted in greater upward or rebounding air flow as the air left the overhead diffuser and then hit the floor. This likewise appeared to loft cough droplets and increase exposure to a thermal breathing mannikin seated in front of the cough simulator. Similarly, devices like air conditioners, fans, or even an open window on a moving bus can facilitate the transfer of respiratory particles, as was observed in transmission events in restaurants in Korea and Guangzhou.[112,113,125]
- ***System and configuration***: The type of ventilation system and its configuration will affect how air is mixed in a room and the path that particles will follow as they are through and drawn out of the room. As reviewed by Lipinski et al.,[22] the different types of ventilation systems commonly in use will affect how a cloud of emitted respiratory particles will move throughout a room, and whether that flow is laminar (displacement ventilation) or turbulent (mixing ventilation, use of fans/air conditioners, open windows). For a mixing ventilation system, the placement of supply and exhaust grills, and the type of diffuser used greatly affect the degree of mixing; when mixing was poor, increasing the ACH actually increased

the exposure of other room occupants (thermal mannikins) to the tracer gas used to simulate respiratory particles from a prone patient.[272] However, there is no clear superiority of displacement ventilation over mixing ventilation either. Shajahan et al.[273] reviewed data on these two systems for hospitals settings and found that although displacement ventilation tended to lessen exposure for occupants when farther away from the source (compared to mixing ventilation), it increased exposure risk for occupants if they were close to the source or close to the exhaust vent.

- ***Fraction of outdoor air.*** Buildings that recirculate air need to distinguish between the volume that is drawn from within the building vs that drawn from outdoors. A room that is receiving the recommended ACH may still have poor air quality if too many of those air volumes are being drawn from within the building. During the pandemic, facilities managers have been asked to ensure that the largest possible fraction of outdoor air is used.
- ***Maintaining pressure differentials*** is a critical consideration for high-risk environments like laboratories, where opening windows or exhaust ventilation might serve to reduce positive pressure in the room and induce leakage from the fume hood.
- ***Controlling humidity and temperature within recommended limits*****:** Environmental conditions like relative humidity and temperature affect both the rate of evaporation of a droplet and subsequently the survival of airborne viruses. For SARS-CoV-2, there has been considerable interest in temperature and humidity effects and their effects on transmission.[274] However, the optimum relative humidity for controlling most bioaerosols (fungi, viruses, and bacteria) is 40-60% for temperatures within the range of human thermal comfort. Current recommendations are to maintain relative humidity within this range.
- ***HVAC maintenance unlikely to enhance the risk transmission:*** As expected for any particle that does not immediately settle, some particles bearing SARS-CoV-2 will be drawn into and deposited on HVAC components, such as grilles, ductwork, and filters.[130,241] Some organizations have even recommended daily disinfection of HVAC grilles.[275] However, there is no evidence of COVID-19 transmission due to touching of grilles, soiled filters, etc., and the risk of transmission via fomites is believed to be low.[152] Nevertheless, HVAC filters in particular may harbour a number of potentially pathogenic organisms (under non-pandemic conditions) and so standard precautions when changing filters and cleaning ductwork are warranted.[276]
- ***Human movement creates random effects:*** Perhaps the greatest difficulty in optimizing ventilation for a space is the random effects caused by occupant themselves. In addition to the effect of thermal plumes emanating from occupants' bodies,[216] occupants also create a turbulent "wake flow" when moving about, and similarly opening doors creates turbulent vortices.[267] Generation of turbulence helps to further mix air, which could be considered beneficial in a mixing ventilation system; however, wake flows and door opening can also draw contaminated air along with it. This may be of greater concern when an occupant is moving from a "dirty zone" (e.g., a sick room or other contaminated space) into a clean room. This can be minimized if occupants limit their movements in the space. In Germany, one school opted to install individualized exhaust ventilation above each seated student.[277] Similarly, Pantelic et al.[278] explored the use of a personalized desktop ventilation system and found that although it was momentarily overwhelmed by cough droplets directed at the

recipient's face, use of the system resulted in an overall reduction in the intake fraction compared to a standard mixing ventilation system.

FORWARD THINKING: STRATEGIES AND RESOURCES FOR "FUTURE-PROOFING" INDOOR AIR

The COVID-19 pandemic has prompted widespread support for IAQ improvements. Although how this approach is broadly dependent on the setting (e.g., public buildings, private residences, congregate living facilities, etc.), substantial challenges exist. IAQ must satisfy multiple goals of pandemic resilience, climate resilience, energy efficiency, and occupant satisfaction. IAQ improvements must also fit into the overall scheme of indoor environmental quality (IEQ), which also encompasses thermal comfort, acoustic comfort (noise), and visual comfort (lighting). Although a full discussion of strategies for future proofing is beyond the scope of this document, the following strategies may provide the basis for further useful discussion:

- ***Taking stock: conduct detailed audits of existing indoor spaces and their deficiencies***. The pandemic has increased awareness of how many public and private spaces are substantially under-ventilated. The first step is to conduct a thorough assessment of HVAC system performance and ensure that ventilation requirements are met in all occupied spaces. Audits should also take note of both ventilation assets (e.g., openable windows, outdoor spaces) and liabilities (dead zones, etc) in the building (or the organization's building stock) as a whole.
- ***Technological innovation***. There are many technical innovations that can help create better ventilated, healthier buildings. Tools such as building information modelling and computational fluid dynamics help architects and engineers 1) understand air flows; 2) collaborate on design improvements; and 3) model specific challenges, such as the occurrence of an airborne outbreak.[2] Shifting from large-scale, centralized building systems to distributed systems designed for that specific zone of the building may also help to provide better control over air flow.[279] Recently, the growth in low-cost, wireless IAQ sensors has made it possible to continuously monitor indoor environments for a variety of contaminants, including CO_2 as an indicator of ventilation inadequacy. This technology allows IAQ deficits to be quickly identified and remedied, with or without engagement of the occupants.[280,281] Similarly, wearable technology like proximity sensors can increase occupant awareness of time spent in close contact with other occupants, and also assist in contact tracing should an outbreak occur.[282] Although proximity sensors were deployed in a time of crisis, some aspects or functions of these devices may be useful in understanding occupancy and crowding in buildings going forward. New building materials with lower emissions, as well as new plant- or microorganism-based biotechnologies for air cleaning (biofilters, bioscrubbers, membrane bioreactors) may help to eliminate types or levels of contaminants that cannot be addressed through conventional technologies.[1] In short, there are numerous fronts on which technological advancement will create new opportunities for IAQ improvements, although these technologies range widely in terms of cost and ease of implementation.
- ***Human-centred design***. Human-centred design seeks to understand the needs of the end user and how he or she might experience the design of a space or a building, while at the

same time integrating technology in manner that is intuitive and enhances the experience.[283] One of the major complaints with IAQ is having little or no control over interior conditions. However, many of the IAQ monitoring systems available in the marketplace can be made visible and shared with occupants. This creates accountability for building managers, but also enables managers to engage occupants in moderating IAQ and may help IAQ issues to be more rapidly identified and resolved. Furthermore, as mentioned previously, making building function visible and manipulable to users can help educate users about IAQ and engage their participation in creating healthy air. However, one criticism of this approach is that it can make occupants hyper-aware of air quality, particularly if occupants have not been adequately capacitated to interpret shifts in monitor readings.[244]

- ***Creation of new health-based standards.*** Current IAQ standards such as those promulgated by ASHRAE have the benefit of decades of practice and refinement, and these standards have been broadly adopted into Canada's national and provincial building codes. However, it is important to note that ASHRAE standards are fundamentally comfort-based, and although health impacts and health evidence have been an increasingly important aspect of ASHRAE's practice, occupant health is not at the centre of these standards. Competing initiatives, such as the WELL Building Standard focus specifically on promoting the physical and mental health of occupants through building design. As we move into a period of significant investment and re-design of indoor spaces, it may be useful to consider how building standards may need to be adapted (whether voluntarily or through building code changes) to achieve IEQ goals.

SUMMARY

The literature provides some insight into ventilation and respiratory disease transmission, including that of SARS-CoV-2. However, there are several **important caveats:**

- Ventilation addresses only a portion of the risk posed by virus-laden respiratory particles. It prevents the accumulation of very small particles that would not otherwise settle due to gravity, preventing longer-range transmission risk. However, ventilation has little to no impact on the exchange of respiratory particles at short-range, which is happening over the course of seconds to minutes.
- The number of cases that occur ***solely*** due to long-range transmission (that are affected by ventilation) is unclear, but likely small. This is not to say that aerosols do not play a role in the type of close encounters that result in transmission, but ventilation likely would not have been effective in preventing short-range transmission regardless.
- Regardless of the role of aerosol transmission in the pandemic, public health measures are layered so as to provide protection against multiple routes of transmission. Measures to mitigate aerosols transmission (opening windows, ventilation, air filtration) are almost universally included in public health recommendations.

CONCLUSIONS AND RECOMMENDATIONS

Indoor air quality is a key determinant of individual and population health. Although the COVID-19 pandemic has sharpened the urgency around improving indoor air quality, IAQ improvements are also necessary to address public health issues related to contaminated urban environments, sick building syndrome, climate resilience (wildfire smoke responses), and improving productivity and occupant satisfaction generally.

The relative magnitude of IAQ benefits on COVID-19 transmission are partly dependent on the role of aerosol transmission in the pandemic, which despite amplification in the media remains unclear. Nevertheless, public health measures aim to address all potential modes of transmission. For that reason, IAQ improvements like ventilation, air filtration, air cleaning, etc., have been key components of the multi-layered public health response since the beginning of the pandemic. Maintaining this holistic view of transmission, which is not solely dependent on environmental factors, but also contact patterns/interactions, socioeconomic factors, and host or individual factors, is critical to eliminating the conditions in which transmission may occur.[221]

This review has provided a holistic introduction to SARS-CoV-2, with a focus on environmental factors and the role of ventilation in particular. Although we have discussed the importance of ventilation in mitigating the risk of transmission due to very small virus-laden particles, ventilation and air cleaning must be used in conjunction with other measures. In addition, the marginal benefits of any ventilation of air-cleaning strategy will depend on a wide range of variables in specific spaces with specific population. Substantial improvements in IAQ can be made through relatively simple strategies, which have been widely promulgated throughout the pandemic (**Appendix 3**); however, optimizing ventilation for infection control requires a much greater level of expertise and technical assessment. In addition, making such technological investments will also require planning and investment to evaluate the impact of those improvements.

As we move forward from the pandemic, organizations will need to transition from the emergency measures necessary for business continuity toward a new steady state that addresses vulnerabilities contributing to the COVID-19 pandemic. This transition will require organizations to establish new objectives for indoor environmental quality, to invest in IAQ assessment and HVAC audits to understand the root problems, and to explore new technological innovations that will promote occupant health without de-centring the human experience.

APPENDIX 1. LITERATURE SEARCH TERMS

Rapid literature searches pertaining to each of the key research questions were performed by the BCCDC EHS information specialist using EBSCOhost databases (includes Medline, CINAHL, Academic Search Complete, ERIC, etc.), Google Scholar, and a general internet search with no date or jurisdictional limit, with a preference for English language documents. Further examination of bibliographies of key articles were scanned to retrieve more extensive information and forward chaining was used to add papers to the search results. Additional grey literature and government websites including guidance documents were scanned for relevant material. The search terms used in the literature search are presented below.

Theme: COVID-19 and indoor air quality or ventilation; Consideration of the public health benefit or burden of poor indoor air quality (COVID-19, radon, particulate matter, VOCs, etc.)

Search Terms: Variants and Boolean operator combinations, e.g.:
PECO
POPULATION OR PROBLEM
("indoor air" OR indoor OR "air quality" OR IAQ)
air AROUND(10) (inside OR indoor)

Exposure
(coronavirus OR "corona virus" OR ncov OR "novel cov" OR COVID-19 OR SARSCOV-2 OR Sars-Cov-19 OR SarsCov-19 OR SARSCOV2019 OR "severe acute respiratory syndrome cov 2" OR "2019 ncov" OR "2019ncov")
(radon OR VOC OR PM OR "particulate matter" OR dust)

Comparison
(ventilate OR ventilation OR ventilate OR hvac OR circulation OR purification OR flow)
(quality OR concentration OR PPM OR PM2.5 OR "particulate matter" OR VOC OR radon)

Outcome
(reduction OR reduce OR improve OR improvement OR mitigation OR mitigate)
(savings OR cost OR benefit OR "cost benefit" OR cost-benefit OR effective OR effectiveness OR efficient OR efficiency OR economic OR burden)
(impact OR assessment OR evaluation OR evaluate OR outcome OR compare OR comparison OR analysis OR analyses)

Theme: Variants of concern and transmission/mitigation – public health response
Search terms: Variants and Boolean operator combinations, e.g.:

PECO
Population/Problem
(variant OR lineage OR mutation OR strain)
AND
(B.1.1.7 OR "VOC 202012/01" OR 501Y.V1 OR 20I/501Y.V1 OR B.1.351 OR 501Y.V2 OR 501Y.V3)
(emerging OR concern OR UK OR KENT OR ENGLISH OR "south africa" OR Brazil)
Exposure
(transmit OR transmissibility OR transmission OR infect OR dose OR spread OR "severity of disease" OR airway OR droplet OR aerosol OR sputum OR mucus OR mucous OR fomite OR airborne OR

epidemiology OR epidemiological OR investigation OR outbreak OR cluster OR duration OR exposure OR case OR report)
AND
(control OR mitigation OR mitigate OR mask OR ventilate OR ventilation OR clean OR disinfect OR distancing OR distance OR guideline OR guidance OR action OR respond OR response)
(coronavirus OR "corona virus" OR ncov OR "novel cov” OR COVID-19 OR SARSCOV-2 OR Sars-Cov-19 OR SarsCov-19 OR SARSCOV2019 OR "severe acute respiratory syndrome cov 2" OR "2019 ncov” OR "2019ncov”)

APPENDIX 2. SELECTED EXAMPLES OF COVID-19 OUTBREAKS THAT HIGHLIGHT INDOOR RISK FACTORS.

Sources	Setting	Description	Attack Rates	Potential Contributing Factors
Shen et al. 2020	Bus trip	68 individuals rode together on a bus to an event, and then back again on the same bus and in the same seats. The index case was seated roughly in the middle of the bus, and an open window at the front of the bus may have helped to mix respiratory particles (large and small) throughout the bus.	35.3% of people riding the bus with the infected individual on a return journey.	Close contact/crowding; drafts or turbulent air.
Park et al. 2020	Call centre, in which transmission occurred among workers on one side of the office floor plan.	Workers in a call centre on the 11^{th} floor of a building; the company occupied 4 floors but there was little interaction between floors. Ventilation evaluated but not identified as an issue by the authors, although relatively even spread throughout the space may suggest an aerosol component.	43.5% among those on the 11^{th} floor where the majority of cases occurred; most of these cases restricted to one side of the workspace.	Loud speech, close interaction between workers throughout the day.
Lu et al. 2020; Li et al. 2020	Restaurant	An almost total lack of fresh air flow, sealed exhaust grates and zonal air conditioning created a pocket of air at one end of the room, in which the index case was seated with 20 other people	48% among those within the pocket of air were infected. However, no server or patron outside of the pocket was infected, emphasizing the need for both proximity and duration of contact.	Crowding and prolonged interaction. Very little or no air exchange to clear aerosols. Drafts from the air conditioner may have assisted the spread of droplets and aerosols within the pocket.

Jang et al. 2020; Bae et al. 2020	Fitness Center	Virus spread amongst instructors at a workshop was carried back and transmitted to students at 12 fitness centres.	26% overall among students exposed to instructors in fitness class. No cases observed in small classes or in low-intensity classes.	High-intensity exercise generating large numbers of virus-laden respiratory particles in a small space; movement of participants back and forth through each other's plumes.
Miller et al. 2020; Hamner et al. 2020	Auditorium	62 people attended a 2.5-h choir practice. Participants were seated next to each other in chairs and also shared food.	87% among those attending the choir practice were infected.	Loud singing; poor ventilation; close and prolonged personal interaction; shared objects and high-touch surfaces (fomites).
Brlek et al. 2020	Squash court	The sole incident in which same time-same place exposure did NOT occur between the index case and subsequent cases. Index case played squash with a partner who contracted the virus, as did two subsequent pairs using the same court over the next 2 hours.	Insufficient information	Ventilation was not evaluated, but lack of ventilation may have allowed virus-laden particles to accumulate in the court. The door handle was a common touch surface.
Kang et al. Lin et al.	Outbreak in multi-unit residential building	Three households connected on the same vertical plumbing stack tested positive for the same strain of SARS-SoV-2, the first on the 15th floor followed by two others on the 25th and 27th floor; no other cases in the building were found. Potential transmission route investigated through tracer gas studies and CFD modelling.	Insufficient information	Negative pressure in the upper floor bathrooms due to wind effects could have caused fecal aerosols to be drawn upward from the 15th floor suite and into the two upper-floor suites. The top of the plumbing stack was had been illegally modified in a way that would have facilitated this flow.

APPENDIX 3. COMPENDIUM OF RESOURCES ON INDOOR AIR QUALITY

Organization	Resource	Link
American Society of Heating, Refrigerating and Air-Conditioning Engineers. (ASHRAE)	Residential healthcare guidance on COVID-19 (Residential Care Task Group)	https://www.ashrae.org/file%20library/technical%20resources/covid-19/ashrae-residential-healthcare-c19-guidance.pdf
	Commercial C19 guidance	https://www.ashrae.org/File%20Library/Technical%20Resources/COVID-19/ASHRAE-Commercial-C19-Guidance.pdf
	Guidance for building operations during the COVID-19 pandemic	https://www.ashrae.org/file%20library/technical%20resources/ashrae%20journal/2020journaldocuments/72-74_ieq_schoen.pdf
	Building Readiness Guide (Aug 2020)	https://www.ashrae.org/about/news/2020/ashrae-epidemic-task-force-releases-updated-building-readiness-guide
Canadian Agency for Drugs &Technologies (CADTH)	Heating, ventilation and air conditioning systems in public spaces	https://cadth.ca/sites/default/files/covid-19/hd0002-covid-19-hvac-report-final.pdf
Canadian Committee on Indoor Air Quality	Addressing COVID-19 in buildings – module 15	https://iaqresource.ca/wp-content/uploads/2020/09/CCIAQB-Module15-Eng.pdf
European Centres for Disease Prevention and Control	Heating, ventilation and air-conditioning systems in the context of COVID-19: first update	https://www.ecdc.europa.eu/en/publications-data/heating-ventilation-air-conditioning-systems-covid-19
Federal Environment Office, Germany	Infectious aerosols in indoor spaces (In German)	https://www.umweltbundesamt.de/themen/gesundheit/umwelteinfluesse-auf-den-menschen/innenraumluft/infektioese-aerosole-in-innenraeumen#was-sind-aerosole-
	Proper airing reduces risk of SARS-CoV-2 infection.	https://www.umweltbundesamt.de/en/press/pressinformation/proper-airing-reduces-risk-of-sars-cov-2-infection
Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA)	How to operate HVAC and other building service systems to prevent the spread of the coronavirus (SARS-CoV-2) disease (COVID-19) in workplaces	https://www.rehva.eu/fileadmin/user_upload/REHVA_COVID-19_guidance_document_V4_09122020.pdf
	COVID-19 guidance directory	https://www.rehva.eu/activities/covid-19-guidance
Health and Safety Executive England (HSE)	Role of ventilation in controlling SARS-CoV-2 transmission, 30 September 2020	https://www.gov.uk/government/publications/emg-role-of-ventilation-in-controlling-sars-cov-2-transmission-30-september-2020
Health Canada	Ventilation and the indoor environment	https://www.canada.ca/en/health-canada/services/publications/healthy-living/ventilation-indoor-environment.html
	Addressing moisture and mould in your home	https://www.canada.ca/en/health-canada/services/publications/healthy-living/addressing-moisture-mould-your-home.html
Health Information and Quality Authority (HIQA)	Database of public health guidance on COVID-19	https://www.hiqa.ie/reports-and-publications/health-technology-

Organization	Resource	Link
		assessment/covid-19-public-health-guidance-database
Health Protection Surveillance Centre	Guidance on non-healthcare building ventilation during COVID-19	https://www.hpsc.ie/a-z/respiratory/coronavirus/novelcoronavirus/guidance/infectionpreventionandcontrolguidance/buildingsandfacilitiesguidance/Guidance%20on%20non%20HCbuilding%20ventilation%20during%20COVID-19.pdf
Independent Scientific Advisory Group for Emergencies (SAGE)	An urgent plan for safer schools	https://www.independentsage.org/wp-content/uploads/2020/11/Safe-schools-v4b1.pdf
National Collaborating Centre for Environmental Health (NCCEH)	The basics of SARS-CoV-2 transmission	https://ncceh.ca/documents/evidence-review/basics-sars-cov-2-transmission
	COVID-19 in indoor environments – air and surface disinfection measures	https://ncceh.ca/documents/guide/covid-19-indoor-environments-air-and-surface-disinfection-measures
	COVID-19 precautions for multi-unit residential buildings	https://www.ncceh.ca/documents/guide/covid-19-precautions-multi-unit-residential-buildings
	Role of heating, ventilation, and air conditioning systems in the public health response to COVID-19 (OEH Webinar)	https://www.youtube.com/watch?app=desktop&v=CDAfnVpBr0A&feature=youtu.be
	Role of ventilation in influencing COVID-19 transmission risk	https://ncceh.ca/content/blog/role-ventilation-influencing-covid-19-transmission-risk
	Air cleaning technologies for indoor spaces during the COVID-19 pandemic	https://ncceh.ca/content/blog/air-cleaning-technologies-indoor-spaces-during-covid-19-pandemic
	Can CO_2 sensors be used to assess COVID-19 transmission risk?	https://ncceh.ca/content/blog/can-co2-sensors-be-used-assess-covid-19-transmission-risk
	Fomites and the COVID-19 pandemic: An evidence review on its role in viral transmission	https://ncceh.ca/documents/evidence-review/fomites-and-covid-19-pandemic-evidence-review-its-role-viral-transmission
	Indoor CO_2 sensors for COVID-19 risk mitigation: Current guidance and limitations	https://ncceh.ca/documents/field-inquiry/indoor-co2-sensors-covid-19-risk-mitigation-current-guidance-and
	Masking during the COVID-19 pandemic – An update of the evidence	https://ncceh.ca/documents/guide/masking-during-covid-19-pandemic-update-evidence
National Energy Management Institute	Ventilation Verification	https://www.nemionline.org/ventilation-verification/
National Research Council of Canada (NRC)	NRC's indoor air strategies and solutions	https://nrc.canada.ca/en/corporate/planning-reporting/nrcs-indoor-air-strategies-solutions
Occupational Health Clinics for Ontario Workers Inc.	Ventilation checklist, risk management matrix	https://www.ohcow.on.ca/airborne-transmission-risk-and-control.html
Public Health Agency of Canada (PHAC)	COVID-19: Guidance on indoor ventilation during the pandemic	https://www.canada.ca/en/public-health/services/diseases/2019-novel-coronavirus-infection/guidance-

Organization	Resource	Link
		documents/guide-indoor-ventilation-covid-19-pandemic.html
Public Health England	COVID-19: ventilation of indoor spaces to stop the spread of coronavirus	https://www.gov.uk/government/publications/covid-19-ventilation-of-indoor-spaces-to-stop-the-spread-of-coronavirus
Public Health Ontario	COVID-19 transmission through large respiratory droplets and aerosols…what we know so far	https://www.publichealthontario.ca/-/media/documents/ncov/covid-wwksf/2021/05/wwksf-transmission-respiratory-aerosols.pdf?la=en
Schools for Health	Risk reduction strategies for reopening schools	https://schools.forhealth.org/risk-reduction-strategies-for-reopening-schools/
Scientific Advisory Group for Emergencies (UK)	Role of ventilation in controlling SARS-CoV-2 transmission (30September 2020)	https://www.gov.uk/government/publications/emg-role-of-ventilation-in-controlling-sars-cov-2-transmission-30-september-2020
Scientific Advisory Group for Emergencies (UK)	Potential application of air cleaning devices and personal decontamination to manage transmission of COVID-19, 4 November2020	https://www.gov.uk/government/publications/emg-potential-application-of-air-cleaning-devices-and-personal-decontamination-to-manage-transmission-of-covid-19-4-november-2020
Scottish Government	Coronavirus (COVID-19): ventilation guidance - November 2020	https://www.gov.scot/publications/coronavirus-covid-19-ventilation-guidance---november-2020/pages/ventilation/
Statistics Canada	Indoor air quality in Canada	https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3810001801
US Centers for Disease Control and Prevention (CDC)	Ventilation in buildings	https://www.cdc.gov/coronavirus/2019-ncov/community/ventilation.html
	Operating schools during COVID-19 (last updated Feb 11, 2021)	https://www.cdc.gov/coronavirus/2019-ncov/community/schools-childcare/schools.html
US Environmental Protection Agency (USEPA)	Indoor air in homes and coronavirus (COVID-19)	https://www.epa.gov/coronavirus/indoor-air-homes-and-coronavirus-covid-19
	IAQ tools for schools – preventive maintenance guidance documents	https://www.epa.gov/iaq-schools/indoor-air-quality-tools-schools-preventive-maintenance-guidance-documents
	Indoor air quality tools for schools action kit	https://www.epa.gov/iaq-schools/indoor-air-quality-tools-schools-action-kit
	Framework for healthy indoor environments in schools	https://www.epa.gov/iaq-schools/framework-healthy-indoor-environments-schools
World Health Organization (WHO)	Coronavirus disease (COVID-19): Ventilation and air conditioning	https://www.who.int/news-room/q-a-detail/coronavirus-disease-covid-19-ventilation-and-air-conditioning
	Roadmap to improve and ensure good indoor ventilation in the context of COVID-19	https://www.who.int/publications/i/item/9789240021280
Yale School of Public Health	COVID-19 safety guidelines for specific school spaces	https://publichealth.yale.edu/research_practice/interdepartmental/covid/schools/spaces/
	Ventilation key to reducing risk	https://publichealth.yale.edu/research_practice/interdepartmental/covid/schools/ventilation/

REFERENCES

1. González-Martín J, Kraakman NJR, Pérez C, Lebrero R, Muñoz R. A state–of–the-art review on indoor air pollution and strategies for indoor air pollution control. Chemosphere. 2021;262:128376. Available from: https://doi.org/10.1016/j.chemosphere.2020.128376.

2. Megahed NA, Ghoneim EM. Indoor air quality: rethinking rules of building design strategies in post-pandemic architecture. Environ Res. 2021;193:110471. Available from: https://doi.org/10.1016/j.envres.2020.110471.

3. Al Horr Y, Arif M, Kaushik A, Mazroei A, Katafygiotou M, Elsarrag E. Occupant productivity and office indoor environment quality: A review of the literature. Build Environ. 2016;105:369-89. Available from: https://doi.org/10.1016/j.buildenv.2016.06.001.

4. Cevik M, Kuppalli K, Kindrachuk J, Peiris M. Virology, transmission, and pathogenesis of SARS-CoV-2. BMJ. 2020;371:m3862. Available from: https://doi.org/10.1136/bmj.m3862.

5. Triggle CR, Bansal D, Ding H, Islam MM, Farag EABA, Hadi HA, et al. A comprehensive review of viral characteristics, transmission, pathophysiology, immune response, and management of SARS-CoV-2 and COVID-19 as a basis for controlling the pandemic. Front Immunol. 2021;12(338). Available from: https://doi.org/10.3389/fimmu.2021.631139.

6. Wölfel R, Corman VM, Guggemos W, Seilmaier M, Zange S, Müller MA, et al. Virological assessment of hospitalized patients with COVID-2019. Nature. 2020 May;581(7809):465-9. Available from: https://doi.org/10.1038/s41586-020-2196-x.

7. Asadi S, Wexler AS, Cappa CD, Barreda S, Bouvier NM, Ristenpart WD. Aerosol emission and superemission during human speech increase with voice loudness. Sci Rep. 2019 Feb;9(1):2348. Available from: https://doi.org/10.1038/s41598-019-38808-z.

8. Mürbe D, Fleischer M, Lange J, Rotheudt H, Kriegel M. Aerosol emission is increased in professional singing OSF Preprints. 2020 Sep 9:1-10. Available from: https://doi.org/10.31219/osf.io/znjeh.

9. Johnson GR, Morawska L, Ristovski ZD, Hargreaves M, Mengersen K, Chao CYH, et al. Modality of human expired aerosol size distributions. J Aerosol Sci. 2011 Dec 1;42(12):839-51. Available from: https://doi.org/10.1016/j.jaerosci.2011.07.009.

10. Morawska L, Johnson GR, Ristovski ZD, Hargreaves M, Mengersen K, Corbett S, et al. Size distribution and sites of origin of droplets expelled from the human respiratory tract during expiratory activities. J Aerosol Sci. 2009 Mar;40(3):256-69. Available from: https://doi.org/10.1016/j.jaerosci.2008.11.002.

11. Gregson FKA, Watson NA, Orton CM, Haddrell AE, McCarthy LP, Finnie TJR, et al. Comparing aerosol concentrations and particle size distributions generated by singing, speaking and breathing. Aerosol Sci Technol. 2021;55(6):681-91. Available from: https://doi.org/10.1080/02786826.2021.1883544.

12. Anfinrud P, Stadnytskyi V, Bax CE, Bax A. Visualizing speech-generated oral fluid droplets with laser light scattering. N Engl J Med. 2020;382:2061-3. Available from: https://doi.org/10.1056/NEJMc2007800.

13. Alsved M, Matamis A, Bohlin R, Richter M, Bengtsson PE, Fraenkel CJ, et al. Exhaled respiratory particles during singing and talking. Aerosol Sci Technol. 2020;54(11):1245-8. Available from: https://doi.org/10.1080/02786826.2020.1812502.

14. Gupta JK, Lin C-H, Chen Q. Characterizing exhaled airflow from breathing and talking. Indoor Air. 2010;20(1):31-9. Available from: https://doi.org/10.1111/j.1600-0668.2009.00623.x.

15. Asadi S, Wexler AS, Cappa CD, Barreda S, Bouvier NM, Ristenpart WD. Effect of voicing and articulation manner on aerosol particle emission during human speech. PLOS ONE. 2020 Jan 27, 2020;15(1):e0227699. Available from: https://doi.org/10.1371/journal.pone.0227699.

16. Asadi S, Bouvier N, Wexler AS, Ristenpart WD. The coronavirus pandemic and aerosols: does COVID-19 transmit via expiratory particles? Aerosol Sci Technol. 2020 Jun;54(6):635-8. Available from: https://doi.org/10.1080/02786826.2020.1749229.

17. Choi H, Chatterjee P, Coppin JD, Martel JA, Hwang M, Jinadatha C, et al. Current understanding of the surface contamination and contact transmission of SARS-CoV-2 in healthcare settings. Env Chem Lett. 2021 Feb 11. Available from: https://doi.org/10.1007/s10311-021-01186-y.

18. Carducci A, Federigi I, Verani M. Covid-19 airborne transmission and its prevention: waiting for evidence or applying the precautionary principle? Atmosphere. 2020;11(710):1-21. Available from: https://doi.org/10.3390/atmos11070710.

19. Abuhegazy M, Talaat K, Anderoglu O, Poroseva SV. Numerical investigation of aerosol transport in a classroom with relevance to COVID-19. Phys Fluids. 2020;32(10):103311. Available from: https://doi.org/10.1063/5.0029118.

20. Tang JW, Bahnfleth WP, Bluyssen PM, Buonanno G, Jimenez JL, Kurnitski J, et al. Dismantling myths on the airborne transmission of severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2). J Hosp Infect. 2021;110:89-96. Available from: https://doi.org/10.1016/j.jhin.2020.12.022.

21. Kohanski MA, Lo LJ, Waring MS. Review of indoor aerosol generation, transport, and control in the context of COVID-19. Int Forum Allergy Rhinol. 2020;10(10):1173-9. Available from: https://doi.org/10.1002/alr.22661.

22. Lipinski T, Ahmad D, Serey N, Jouhara H. Review of ventilation strategies to reduce the risk of disease transmission in high occupancy buildings. Int J Thermofluids. 2020;7-8:100045. Available from: https://doi.org/10.1016/j.ijft.2020.100045.

23. Bao L, Gao H, Deng W, Lv Q, Yu H, Liu M, et al. Transmission of severe acute respiratory syndrome coronavirus 2 via close contact and respiratory droplets among human angiotensin-converting enzyme 2 mice. J Infect Dis. 2020;222(4):551-5. Available from: https://doi.org/10.1093/infdis/jiaa281.

24. Kim Y-I, Kim S-G, Kim S-M, Kim E-H, Park S-J, Yu K-M, et al. Infection and rapid transmission of SARS-CoV-2 in ferrets. Cell Host Microbe. 2020;27(5):704-9.e2. Available from: https://doi.org/10.1016/j.chom.2020.03.023.

25. Sia SF, Yan L-M, Chin AWH, Fung K, Choy K-T, Wong AYL, et al. Pathogenesis and transmission of SARS-CoV-2 in golden hamsters. Nature. 2020;583(7818):834-8. Available from: https://doi.org/10.1038/s41586-020-2342-5.

26. Chan JF-W, Yuan S, Zhang AJ, Poon VK-M, Chan CC-S, Lee AC-Y, et al. Surgical mask partition reduces the risk of noncontact transmission in a golden Syrian hamster model for coronavirus disease 2019 (COVID-19). Clin Infect Dis. 2020;71(16):2139-49. Available from: https://doi.org/10.1093/cid/ciaa644.

27. Deng W, Bao L, Gao H, Xiang Z, Qu Y, Song Z, et al. Ocular conjunctival inoculation of SARS-CoV-2 can cause mild COVID-19 in rhesus macaques. Nat Commun. 2020;11(1):4400. Available from: https://doi.org/10.1038/s41467-020-18149-6.

28. Pan Y, Zhang D, Yang P, Poon LLM, Wang Q. Viral load of SARS-CoV-2 in clinical samples. Lancet Infect Dis. 2020;20(4):411-2. Available from: https://doi.org/10.1016/s1473-3099(20)30113-4.

29. To KK-W, Tsang OT-Y, Leung W-S, Tam AR, Wu T-C, Lung DC, et al. Temporal profiles of viral load in posterior oropharyngeal saliva samples and serum antibody responses during infection by SARS-CoV-2: an observational cohort study. Lancet Infect Dis. 2020;20(5):565-74. Available from: https://doi.org/10.1016/S1473-3099(20)30196-1.

30. Moghadas SM, Fitzpatrick MC, Sah P, Pandey A, Shoukat A, Singer BH, et al. The implications of silent transmission for the control of COVID-19 outbreaks. Proc Nat Acad Sci USA. 2020;117(30):17513-5. Available from: https://doi.org/10.1073/pnas.2008373117.

31. Oran D, Topol E. The proportion of SARS-CoV-2 infections that are asymptomatic: a systematic review. Ann Intern Med. 2021 Jan 22. Available from: https://doi.org/10.7326/M20-6976.

32. Kampf G, Brüggemann Y, Kaba HEJ, Steinmann J, Pfaender S, Scheithauer S, et al. Potential sources, modes of transmission and effectiveness of prevention measures against SARS-CoV-2. J Hosp Infect. 2020;106(4):678-97. Available from: https://doi.org/10.1016/j.jhin.2020.09.022.

33. Anderson EL, Turnham P, Griffin JR, Clarke CC. Consideration of the aerosol transmission for COVID-19 and public health. Risk Anal. 2020;40(5):902-7. Available from: https://doi.org/10.1111/risa.13500.

34. Koizumi N, Siddique AB, Andalibi A. Assessment of SARS-CoV-2 transmission among attendees of live concert events in Japan using contact-tracing data. J Travel Med. 2020;27(5). Available from: https://doi.org/10.1093/jtm/taaa096.

35. Hu Z, Song C, Xu C, Jin G, Chen Y, Xu X, et al. Clinical characteristics of 24 asymptomatic infections with COVID-19 screened among close contacts in Nanjing, China. Sci China Life Sci. 2020 May 1;63(5):706-11. Available from: https://doi.org/10.1007/s11427-020-1661-4.

36. Qiu X, Nergiz AI, Maraolo AE, Bogoch II, Low N, Cevik M. Defining the role of asymptomatic and pre-symptomatic SARS-CoV-2 transmission; a living systematic review. Clin Microbiol Infect. 2021 Jan 20. Available from: https://doi.org/10.1016/j.cmi.2021.01.011.

37. US Centers for Disease Control and Prevention. Scientific brief: SARS-CoV-2 transmission. Atlanta, GA: US Department of Health & Human Services; 2021 May 7. Available from: https://www.cdc.gov/coronavirus/2019-ncov/science/science-briefs/sars-cov-2-transmission.html?CDC_AA_refVal=https%3A%2F%2Fwww.cdc.gov%2Fcoronavirus%2F2019-ncov%2Fscience%2Fscience-briefs%2Fscientific-brief-sars-cov-2.html.

38. World Health Organization. Modes of transmission of virus causing COVID-19: implications for IPC precaution recommendations. Scientific brief. Geneva, Switzerland: WHO; 2020 Mar 29. Available from: https://www.who.int/news-room/commentaries/detail/modes-of-transmission-of-virus-causing-covid-19-implications-for-ipc-precaution-recommendations.

39. Public Health Ontario. COVID-19 transmission through large respiratory droplets and aerosols…what we know so far. Toronto, ON: Queen's Printer for Ontario; 2021 May 20. Available from: https://www.publichealthontario.ca/-/media/documents/ncov/covid-wwksf/2021/05/wwksf-transmission-respiratory-aerosols.pdf?la=en.

40. Public Health Ontario. COVID-19 routes of transmission – what we know so far Toronto, ON: Queen's Printer for Ontario; 2020 Dec 1. Available from: https://www.publichealthontario.ca/-/media/documents/ncov/covid-wwksf/2020/12/routes-transmission-covid-19.pdf?la=en.

41. Office of the Chief Science Advisor of Canada. The role of bioaerosols and indoor ventilation in COVID-19 transmission. Report from the COVID-19

Expert Panel of the Chief Science Advisor of Canada. Ottawa, ON: Government of Canada; 2020 Sep. Available from: http://science.gc.ca/eic/site/063.nsf/vwapj/Report-bioaerosols-and-ventilation.pdf/$file/Report-bioaerosols-and-ventilation.pdf.

42. Public Health Agency of Canada. COVID-19: main modes of transmission. Ottawa, ON: PHAC; 2020 Nov 5. Available from: https://www.canada.ca/en/public-health/services/diseases/2019-novel-coronavirus-infection/health-professionals/main-modes-transmission.html.

43. Tang S, Mao Y, Jones RM, Tan Q, Ji JS, Li N, et al. Aerosol transmission of SARS-CoV-2? Evidence, prevention and control. Environ Int. 2020;144:106039-. Available from: https://doi.org/10.1016/j.envint.2020.106039.

44. Drossinos Y, Stilianakis NI. What aerosol physics tells us about airborne pathogen transmission. Aerosol Sci Technol. 2020;54(6):639-43. Available from: https://doi.org/10.1080/02786826.2020.1751055.

45. Cherrie J, Cherrie M, Davis A, Holmes D, Semple S, Steinle S, et al. Contamination of air and surfaces in workplaces with SARS-CoV-2 virus: a systematic review. medRxiv. 2021 Jan 26. Available from: https://doi.org/10.1101/2021.01.25.21250233.

46. Meyerowitz E, Richterman A, Gandhi R, Sax P. Transmission of SARS-CoV-2: a review of viral, host, and environmental factors. Ann Intern Med. 2021;174(1):69-79. Available from: https://doi.org/10.7326/M20-5008.

47. World Health Organization. Transmission of SARS-CoV-2: implications for infection prevention precautions. Geneva, Switzerland: WHO; 2020 Jul 9. Available from: https://www.who.int/news-room/commentaries/detail/transmission-of-sars-cov-2-implications-for-infection-prevention-precautions.

48. US Centers for Disease Control and Prevention. How COVID-19 spreads. Altanta, GA: US Department of Health & Human Services; 2020 Oct 28. Available from: https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/how-covid-spreads.html.

49. European Centre for Disease Prevention and Control. Transmission of COVID-19. Solna, Sweden: ECDC; 2020 Aug 10. Available from: https://www.ecdc.europa.eu/en/covid-19/latest-evidence/transmission.

50. Leclerc QJ, Fuller NM, Knight LE, Group CC-W, Funk S, Knight GM. What settings have been linked to SARS-CoV-2 transmission clusters?[version 2; peer review: 2 approved]. Wellcome Open Res. 2020 Jun 5;5:83. Available from: https://doi.org/10.12688/wellcomeopenres.15889.2.

51. Qian H, Miao T, Liu L, Zheng X, Luo D, Li Y. Indoor transmission of SARS-CoV-2. Indoor Air. 2020 Oct 31. Available from: https://doi.org/10.1111/ina.12766.

52. Adam DC, Wu P, Wong JY, Lau EHY, Tsang TK, Cauchemez S, et al. Clustering and superspreading potential of SARS-CoV-2 infections in Hong Kong. Nat Med. 2020 Sep 17. Available from: https://doi.org/10.1038/s41591-020-1092-0.

53. Wang Y, Tian H, Zhang L, Zhang M, Guo D, Wu W, et al. Reduction of secondary transmission of SARS-CoV-2 in households by face mask use, disinfection and social distancing: a cohort study in Beijing, China. BMJ Glob Health. 2020;5(5):e002794. Available from: https://doi.org/10.1136/bmjgh-2020-002794.

54. Murti M, Achonu C, Smith BT, Brown KA, Kim JH, Johnson J, et al. COVID-19 workplace outbreaks by industry sector and their associated household transmission, Ontario, Canada, January – June, 2020. medRxiv. 2020 Nov 30. Available from: https://doi.org/10.1101/2020.11.25.20239038.

55. Bui D, McCaffrey K, Friedrichs M, LaCross N, Lewis N, Sage K, et al. Racial and ethnic disparities among COVID-19 cases in workplace outbreaks by industry sector — Utah, March 6–June 5, 2020. Morb Mortal Wkly Rep. 2020;69:1133–8. Available from: http://dx.doi.org/10.15585/mmwr.mm6933e3.

56. Public Health Agency of Canada. Community-based measures to mitigate the spread of coronavirus disease (COVID-19) in Canada. Ottawa, ON: PHAC; 2020 Oct 15. Available from: https://www.canada.ca/en/public-health/services/diseases/2019-novel-coronavirus-infection/health-professionals/public-health-measures-mitigate-covid-19.html.

57. Liu L, Li Y, Nielsen PV, Wei J, Jensen RL. Short-range airborne transmission of expiratory droplets between two people. Indoor Air. 2017;27(2):452-62. Available from: https://doi.org/10.1111/ina.12314.

58. Banik RK, Ulrich AK. Evidence of short-range aerosol transmission of SARS-CoV-2 and call for universal airborne precautions for anesthesiologists during the COVID-19 pandemic. Anesth Analg. 2020 Aug;131(2):e102-e4. Available from: https://dx.doi.org/10.1213%2FANE.0000000000004933.

59. Kutter JS, de Meulder D, Bestebroer TM, Lexmond P, Mulders A, Richard M, et al. SARS-CoV and SARS-CoV-2 are transmitted through the air between ferrets over more than one meter distance. Nat Commun. 2021;12(1):1653. Available from: https://doi.org/10.1038/s41467-021-21918-6.

60. Richard M, Kok A, de Meulder D, Bestebroer TM, Lamers MM, Okba NMA, et al. SARS-CoV-2 is transmitted via contact and via the air between ferrets. Nat Commun. 2020;11(1):3496. Available from: https://doi.org/10.1038/s41467-020-17367-2.

61. Port JR, Yinda CK, Owusu IO, Holbrook M, Fischer R, Bushmaker T, et al. SARS-CoV-2 disease severity and transmission efficiency is increased for airborne but not fomite exposure in Syrian hamsters. bioRxiv. 2020 Dec 28. Available from: https://doi.org/10.1101/2020.12.28.424565.

62. Zhang C, Guo Z, Li N, Cui H, Meng K, Liu L, et al. Impact of prior infection on protection and transmission of SARS-CoV-2 in golden hamsters. bioRxiv. 2021 Jan 30. Available from: https://doi.org/10.1101/2021.01.30.428920.

63. Bi Q, Wu Y, Mei S, Ye C, Zou X, Zhang Z, et al. Epidemiology and transmission of COVID-19 in 391 cases and 1286 of their close contacts in Shenzhen, China: a retrospective cohort study. Lancet Infect Dis. 2020;20(8):911-9. Available from: https://doi.org/10.1016/S1473-3099(20)30287-5.

64. Ng OT, Marimuthu K, Koh V, Pang J, Linn KZ, Sun J, et al. SARS-CoV-2 seroprevalence and transmission risk factors among high-risk close contacts: a retrospective cohort study. Lancet Infect Dis. 2021;21(3):333-43. Available from: https://doi.org/10.1016/S1473-3099(20)30833-1.

65. Cheng H-Y, Jian S-W, Liu D-P, Ng T-C, Huang W-T, Lin H-H, et al. Contact tracing assessment of COVID-19 transmission dynamics in Taiwan and risk at different exposure periods before and after symptom onset. JAMA Intern Med. 2020;180(9):1156-63. Available from: https://doi.org/10.1001/jamainternmed.2020.2020.

66. Fisher K, Tenforde M, Feldstein L, Lindsell C, Shapiro N, Files D, et al. Community and close contact exposures associated with COVID-19 among symptomatic adults ≥18 Years in 11 outpatient health care facilities — United States, July 2020. Morb Mortal Wkly Rep. 2020;69(36):1258-64. Available from: http://dx.doi.org/10.15585/mmwr.mm6936a5.

67. Burke RM, Balter S, Barnes E, Barry V, Bartlett K, Beer KD, et al. Enhanced contact investigations for nine early travel-related cases of SARS-CoV-2 in the United States. PLOS ONE. 2020;15(9):e0238342. Available from: https://doi.org/10.1371/journal.pone.0238342.

68. Jing QL, Liu MJ, Zhang ZB, Fang LQ, Yuan J, Zhang AR, et al. Household secondary attack rate of COVID-19 and associated determinants in Guangzhou, China: a retrospective cohort study. Lancet Infect Dis. 2020;20(10):1141-50. Available from: https://doi.org/10.1016/S1473-3099(20)30471-0.

69. Yi H, Ng ST, Farwin A, Pei Ting Low A, Chang CM, Lim J. Health equity considerations in COVID-19: geospatial network analysis of the COVID-19 outbreak in the migrant population in Singapore. J Travel Med. 2020;28(2). Available from: https://doi.org/10.1093/jtm/taaa159.

70. Gorny AW, Bagdasarian N, Koh AHK, Lim YC, Ong JSM, Ng BSW, et al. SARS-CoV-2 in migrant worker dormitories: geospatial epidemiology supporting outbreak management. Int J Infect Dis. 2021;103:389-94. Available from: https://doi.org/10.1016/j.ijid.2020.11.148.

71. Li W, Zhang B, Lu J, Liu S, Chang Z, Peng C, et al. Characteristics of household transmission of COVID-19. Clin Infect Dis. 2020 Nov 5;71(8):1943-6. Available from: https://doi.org/10.1093/cid/ciaa450.

72. Wu J, Huang Y, Tu C, Bi C, Chen Z, Luo L, et al. Household transmission of SARS-CoV-2, Zhuhai, China, 2020. Clin Infect Dis. 2020;71(16):2099-108. Available from: https://doi.org/10.1093/cid/ciaa557.

73. Hu M, Lin H, Wang J, Xu C, Tatem AJ, Meng B, et al. Risk of coronavirus disease 2019 transmission in train passengers: an epidemiological and modeling study. Clin Infect Dis. 2020;72(4):604-10. Available from: https://doi.org/10.1093/cid/ciaa1057.

74. Madewell ZJ, Yang Y, Longini IM, Jr, Halloran ME, Dean NE. Household transmission of SARS-CoV-2: a systematic review and meta-analysis. JAMA Netw Open. 2020;3(12):e2031756-e. Available from: https://doi.org/10.1001/jamanetworkopen.2020.31756.

75. Thompson HA, Mousa A, Dighe A, Fu H, Arnedo-Pena A, Barrett P, et al. Report 38: SARS-CoV-2 setting-specific transmission rates: a systematic review and meta-analysis. London, UK: Imperial College COVID-19 response team; 2020 Nov 27. Available from: https://www.imperial.ac.uk/media/imperial-college/medicine/mrc-gida/2020-11-27-COVID19-Report-38.pdf.

76. Chu DK, Akl EA, Duda S, Solo K, Yaacoub S, Schünemann HJ, et al. Physical distancing, face masks, and eye protection to prevent person-to-person transmission of SARS-CoV-2 and COVID-19: a systematic review and meta-analysis. The Lancet. 2020;395(10242):1973-87. Available from: https://doi.org/10.1016/S0140-6736(20)31142-9.

77. Arav Y, Klausner Z, Fattal E. Theoretical investigation of pre-symptomatic SARS-CoV-2 person-to-person transmission in households. medRxiv. 2020 Sep 24. Available from: https://doi.org/10.1101/2020.05.12.20099085.

78. Bourouiba L. Turbulent gas clouds and respiratory pathogen emissions: potential implications for reducing transmission of COVID-19. JAMA. 2020;323(18):1837-8. Available from: https://doi.org/10.1001/jama.2020.4756.

79. Borak J. Airborne transmission of COVID-19. Occup Med. 2020 Jul 17;70(5):297-9. Available from: https://doi.org/10.1093/occmed/kqaa080.

80. Somsen GA, van Rijn C, Kooij S, Bem RA, Bonn D. Small droplet aerosols in poorly ventilated spaces and SARS-CoV-2 transmission. Lancet Respir Med. 2020 2020;8(7):658-9. Available from: https://dx.doi.org/10.1016%2FS2213-2600(20)30245-9.

81. Stadnytskyi V, Bax CE, Bax A, Anfinrud P. The airborne lifetime of small speech droplets and their potential importance in SARS-CoV-2 transmission. Proc Nat Acad Sci USA. 2020 Jun;117(22):11875-7. Available from: https://doi.org/10.1073/pnas.2006874117.

82. Fennelly KP. Particle sizes of infectious aerosols: implications for infection control. Lancet Respir Med. 2020;8(9):914-24. Available from: https://doi.org/10.1016/S2213-2600(20)30323-4.

83. Buonanno G, Stabile L, Morawska L. Estimation of airborne viral emission: quanta emission rate of SARS-CoV-2 for infection risk assessment. Environ Int. 2020;141:105794. Available from: https://doi.org/10.1016/j.envint.2020.105794.

84. Morawska L, Cao J. Airborne transmission of SARS-CoV-2: the world should face the reality. Environ Int. 2020 Apr 10;139:105730. Available from: https://doi.org/10.1016/j.envint.2020.105730.

85. Fears AC, Klimstra WB, Duprex P, Hartman A, Weaver SC, Plante KS, et al. Persistence of severe acute respiratory syndrome coronavirus 2 in aerosol suspensions. Emerg Infect Dis. 2020 Sep;29(9). Available from: https://doi.org/10.3201/eid2609.201806.

86. van Doremalen N, Bushmaker T, Morris DH, Holbrook MG, Gamble A, Williamson BN, et al. Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. N Engl J Med. 2020;382:1564-7. Available from: https://doi.org/10.1056/NEJMc2004973.

87. Lednicky JA, Lauzardo M, Fan H, Jutla AS, Tilly TB, Gangwar M, et al. Viable SARS-CoV-2 in the air of a hospital room with COVID-19 patients. Int J Infect Dis. 2020 Aug 4;100:476-82. Available from: https://doi.org/10.1016/j.ijid.2020.09.025.

88. Santarpia JL, Rivera DN, Herrera V, Morwitzer MJ, Creager H, Santarpia GW, et al. Aerosol and surface contamination of SARS-CoV-2 observed in quarantine and isolation care. Sci Rep. 2020;10(12732). Available from: https://doi.org/10.1038/s41598-020-69286-3.

89. Liu Y, Ning Z, Chen Y, Guo M, Liu Y, Gali NK, et al. Aerodynamic analysis of SARS-CoV-2 in two Wuhan hospitals. Nature. 2020;582(7813):557-60. Available from: https://doi.org/10.1038/s41586-020-2271-3.

90. Ding Z, Qian H, Xu B, Huang Y, Miao T, Yen H-L, et al. Toilets dominate environmental detection of severe acute respiratory syndrome coronavirus 2 in a hospital. Sci Total Environ. 2021;753:141710. Available from: https://doi.org/10.1016/j.scitotenv.2020.141710.

91. Chia PY, Coleman KK, Tan YK, Ong SWX, Gum M, Lau SK, et al. Detection of air and surface contamination by SARS-CoV-2 in hospital rooms of infected patients. Nat Commun. 2020;11(1):2800. Available from: https://doi.org/10.1038/s41467-020-16670-2.

92. Rahmani AR, Leili M, Azarian G, Poormohammadi A. Sampling and detection of corona viruses in air: a mini review. Sci Total Environ. 2020;740:140207. Available from: https://doi.org/10.1016/j.scitotenv.2020.140207.

93. Razzini K, Castrica M, Menchetti L, Maggi L, Negroni L, Orfeo NV, et al. SARS-CoV-2 RNA detection in the air and on surfaces in the COVID-19 ward of a hospital in Milan, Italy. Sci Total Environ. 2020;742:140540. Available from: https://doi.org/10.1016/j.scitotenv.2020.140540.

94. Borges JT, Nakada LYK, Maniero MG, Guimarães JR. SARS-CoV-2: a systematic review of indoor air sampling for virus detection. Environ Sci Poll Res. 2021 Feb 25. Available from: https://doi.org/10.1007/s11356-021-13001-w.

95. Cheng VC-C, Wong S-C, Chan VW-M, So SY-C, Chen JH-K, Yip CC-Y, et al. Air and environmental sampling for SARS-CoV-2 around hospitalized patients with coronavirus disease 2019 (COVID-19). Infect Control Hosp Epidemiol. 2020:1-8. Available from: https://doi.org/10.1017/ice.2020.282.

96. Ong SWX, Tan YK, Chia PY, Lee TH, Ng OT, Wong MSY, et al. Air, surface environmental, and personal protective equipment contamination by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) from a symptomatic patient. JAMA. 2020 Mar 4;323(16):1610-2. Available from: https://doi.org/10.1001/jama.2020.3227.

97. Faridi S, Niazi S, Sadeghi K, Naddafi K, Yavarian J, Shamsipour M, et al. A field indoor air measurement of SARS-CoV-2 in the patient rooms of the largest hospital in Iran. Sci Total Environ. 2020;725:138401. Available from: https://doi.org/10.1016/j.scitotenv.2020.138401.

98. Ahn JY, An S, Sohn Y, Cho Y, Hyun JH, Baek YJ, et al. Environmental contamination in the isolation rooms of COVID-19 patients with severe pneumonia requiring mechanical ventilation or high-flow oxygen therapy. J Hosp Infect. 2020;106(3):570-6. Available from: https://doi.org/10.1016/j.jhin.2020.08.014.

99. Masoumbeigi H, Ghanizadeh G, Yousefi Arfaei R, Heydari S, Goodarzi H, Dorostkar Sari R, et al. Investigation of hospital indoor air quality for the presence of SARS-CoV-2. J Environ Health Sci Eng. 2020;18(2):1259-63. Available from: https://doi.org/10.1007/s40201-020-00543-3.

100. Wei L, Lin J, Duan X, Huang W, Lu X, Zhou J, et al. Asymptomatic COVID-19 patients can contaminate their surroundings: an environment sampling study. mSphere. 2020;5(3):e00442-20. Available from: https://doi.org/10.1128/mSphere.00442-20.

101. Kim UJ, Lee SY, Lee JY, Lee A, Kim SE, Choi OJ, et al. Air and environmental contamination caused by COVID-19 patients: a multi-center study. J Korean Med Sci. 2020;35(37):e332-e. Available from: https://doi.org/10.3346/jkms.2020.35.e332.

102. Hadei M, Mohebbi SR, Hopke PK, Shahsavani A, Bazzazpour S, Alipour M, et al. Presence of SARS-CoV-2 in the air of public places and transportation. Atmos Pollut Res. 2021;12(3):302-6. Available from: https://doi.org/10.1016/j.apr.2020.12.016.

103. Gehrke SG, Förderer C, Stremmel W. SARS-CoV-2 airborne surveillance using non-powered cold traps. medRxiv. 2021 Jan 21. Available from: https://doi.org/10.1101/2021.01.19.21250064.

104. Di Carlo P, Chiacchiaretta P, Sinjari B, Aruffo E, Stuppia L, De Laurenzi V, et al. Air and surface measurements of SARS-CoV-2 inside a bus during normal operation. PLOS ONE. 2020;15(11):e0235943. Available from: https://doi.org/10.1371/journal.pone.0235943.

105. Franklin M. Outbreak connected to Calgary fitness club balloons to more than 40 cases. CTV News. 2020 Jul 23. Available from: https://calgary.ctvnews.ca/outbreak-connected-to-calgary-fitness-club-balloons-to-more-than-40-cases-1.5037041.

106. Jang S, Han SH, Rhee J-Y. Cluster of coronavirus disease associated with fitness dance classes, South Korea. Emerg Infect Dis. 2020;26(8):1917-20. Available from: https://doi.org/10.3201/eid2608.200633.

107. Bae S, Kim H, Jung T-Y, Lim J-A, Jo D-H, Kang G-S, et al. Epidemiological characteristics of COVID-19 outbreak at fitness centers in Cheonan, Korea. J Korean Med Sci. 2020;35(31):e288. Available from: https://doi.org/10.3346/jkms.2020.35.e288.

108. Lendacki F, Teran R, Gretsch S, Fricchione M, Kerins J. COVID-19 outbreak among attendees of an exercise facility — Chicago, Illinois, August–September 2020. Morb Mortal Wkly Rep. 2021;70(9):321-5. Available from: http://dx.doi.org/10.15585/mmwr.mm7009e2.

109. Groves L, Usagawa L, Elm J, Low E, Manuzak A, Quint J, et al. Community transmission of SARS-CoV-2 at three fitness facilities — Hawaii, June–July 2020. Morb Mortal Wkly Rep. 2021;70(9):316-20. Available from: http://dx.doi.org/10.15585/mmwr.mm7009e1.

110. Brlek A, Vidovič Š, Vuzem S, Turk K, Simonović Z. Possible indirect transmission of COVID-19 at a squash court, Slovenia, March 2020: case report. Epidemiol Infect. 2020;148(e120):1-3. Available from: https://doi.org/10.1017/S0950268820001326.

111. Lu J, Gu J, Li K, Xu C, Su W, Lai Z, et al. COVID-19 outbreak associated with air conditioning in restaurant, Guangzhou, China, 2020. Emerg Infect Dis. 2020;26(7):1628-31. Available from: https://dx.doi.org/10.3201/eid2607.200764.

112. Kwon KS, Park JI, Park YJ, Jung DM, Ryu KW, Lee JH. Evidence of long-distance droplet transmission of SARS-CoV-2 by direct air flow in a restaurant in Korea. J Korean Med Sci. 2020 Nov 30;35(46):e415. Available from: https://doi.org/10.3346/jkms.2020.35.e415.

113. Shen Y, Li C, Dong H, Wang Z, Martinez L, Sun Z, et al. Community outbreak investigation of SARS-CoV-2 transmission among bus riders in Eastern China. JAMA Intern Med. 2020;180(12):1665-71. Available from: https://doi.org/10.1001/jamainternmed.2020.5225.

114. Hamner L, Dubbel P, Capron I, Ross A, Jordan A, Lee J, et al. High SARS-CoV-2 attack rate following exposure at a choir practice — Skagit County, Washington, March 2020. Morb Mortal Wkly Rep. 2020;69:606–10. Available from: https://www.cdc.gov/mmwr/volumes/69/wr/mm6919e6.htm.

115. Miller SL, Nazaroff WW, Jimenez JL, Boerstra A, Buonanno G, Dancer SJ, et al. Transmission of SARS-CoV-2 by inhalation of respiratory aerosol in the Skagit Valley Chorale superspreading event. Indoor Air. 2020;00:1-10. Available from: https://doi.org/10.1111/ina.12751.

116. Charlotte N. High rate of SARS-CoV-2 transmission due to choir practice in France at the beginning of the COVID-19 pandemic. J Voice. 2020 Dec 23. Available from: https://doi.org/10.1016/j.jvoice.2020.11.029.

117. Muller N, Kunze M, Steitz F, Saad N, Mühlemann B, Beheim-Schwarzbach J, et al. Severe acute respiratory syndrome coronavirus 2 outbreak related to a nightclub, Germany, 2020. Emerg Infect Dis. 2021;27(2):645-8. Available from: https://dx.doi.org/10.3201/eid2702.204443.

118. Sugano N, Ando W, Fukushima W. Cluster of SARS-CoV-2 infections linked to music clubs in Osaka, Japan: asymptomatically infected persons can transmit the virus as soon as 2 days after infection. J Infect Dis. 2020. Available from: https://doi.org/10.1093/infdis/jiaa542.

119. Furuse Y, Sando E, Tsuchiya N, Miyahara R, Yasuda I, Ko YK, et al. Clusters of coronavirus disease in communities, Japan, January-April 2020. Emerg Infect Dis. 2020 Jun 10;26(9). Available from: https://doi.org/10.3201/eid2609.202272.

120. Furuse Y, Ko YK, Saito M, Shobugawa Y, Jindai K, Saito T, et al. Epidemiology of COVID-19 outbreak in Japan, January–March 2020. Jpn J Infect Dis. 2020; advance publication. Available from: https://doi.org/10.7883/yoken.jjid.2020.271.

121. Park SY, Kim YM, Yi S, Lee S, Na BJ, Kim CB, et al. Coronavirus disease outbreak in call center, South Korea. Emerg Infect Dis. 2020;26(8):1666-70. Available from: https://doi.org/10.3201/eid2608.201274.

122. James A, Eagle L, Phillips C, Hedges DS, Bodenhamer C, Brown R, et al. High COVID-19 attack rate among attendees at events at a church - Arkansas, March 2020. Morb Mortal Wkly Rep. 2020;69(20):632-5. Available from: https://doi.org/10.15585/mmwr.mm6920e2.

123. Katelaris A, Wells J, Clark P, Norton S, Rockett R, Arnott A, et al. Epidemiologic evidence for airborne transmission of SARS-CoV-2 during church singing, Australia, 2020. Emerg Infect Dis. 2021 Jun. Available from: https://doi.org/10.3201/eid2706.210465.

124. Andrade A, Dominski FH, Pereira ML, de Liz CM, Buonanno G. Infection risk in gyms during physical exercise. Environ Sci Poll Res. 2018 Jul;25(20):19675-86. Available from: https://doi.org/10.1007/s11356-018-1822-8.

125. Li Y, Qian H, Hang J, Chen X, Cheng P, Ling H, et al. Probable airborne transmission of SARS-CoV-2 in a poorly ventilated restaurant. Build Environ. 2021;196:107788. Available from: https://doi.org/10.1016/j.buildenv.2021.107788.

126. Xie C, Zhao H, Li K, Zhang Z, Lu X, Peng H, et al. The evidence of indirect transmission of SARS-CoV-2 reported in Guangzhou, China. BMC Public Health. 2020;20(1):1202. Available from: https://doi.org/10.1186/s12889-020-09296-y.

127. Hwang SE, Chang JH, Bumjo O, Heo J. Possible aerosol transmission of COVID-19 associated with an outbreak in an apartment in Seoul, South Korea, 2020. Int J Infect Dis. 2020 Dec 16. Available from: https://doi.org/10.1016/j.ijid.2020.12.035.

128. Kang M, Wei J, Yuan J, Guo J, Zhang Y, Hang J. Probable evidence of fecal aerosol transmission of SARS-CoV-2 in a high-rise building. Ann Intern Med. 2020. Available from: https://doi.org/10.7326/M20-0928.

129. Eichler N, Thornley C, Swadi T, Devine T, McElnay C, Sherwood J, et al. Transmission of severe acute respiratory syndrome coronavirus 2 during border quarantine and air travel, New Zealand (Aotearoa). Emerg Infect Dis. 2021;May. Available from: https://doi.org/10.3201/eid2705.210514.

130. Horve PF, Dietz L, Fretz M, Constant DA, Wilkes A, Townes JM, et al. Identification of SARS-CoV-2 RNA in healthcare heating, ventilation, and air conditioning units. medRxiv. 2020 Jun 28. Available from: https://doi.org/10.1101/2020.06.26.20141085.

131. de Man P, Paltansing S, Ong DSY, Vaessen N, van Nielen G, Koeleman JGM. Outbreak of Coronavirus Disease 2019 (COVID-19) in a nursing home associated with aerosol transmission as a result of inadequate ventilation. Clin Infect Dis. 2020. Available from: https://doi.org/10.1093/cid/ciaa1270.

132. Chin AWH, Chu JTS, Perera MRA, Hui KPY, Yen H-L, Chan MCW, et al. Stability of SARS-CoV-2 in different environmental conditions. Lancet Microbe. 2020;1(1):e10. Available from: https://doi.org/10.1016/S2666-5247(20)30003-3.

133. Kampf G, Todt D, Pfaender S, Steinmann E. Persistence of coronaviruses on inanimate surfaces and their inactivation with biocidal agents. J Hosp Infect. 2020;104(3):246-51. Available from: https://doi.org/10.1016/j.jhin.2020.01.022.

134. Pastorino B, Touret F, Gilles M, Lamballerie Xd, Charrel R. Prolonged infectivity of SARS-CoV-2 in fomites. Emerg Infect Dis. 2020 Sep;26(9). Available from: https://doi.org/10.3201/eid2609.201788.

135. Ratnesar-Shumate S, Williams G, Green B, Krause M, Holland B, Wood S, et al. Simulated sunlight rapidly inactivates SARS-CoV-2 on surfaces. J Infect Dis. 2020;222(2):214-22. Available from: https://doi.org/10.1093/infdis/jiaa274.

136. Riddell S, Goldie S, Hill A, Eagles D, Drew TW. The effect of temperature on persistence of SARS-CoV-2 on common surfaces. Virol J. 2020;17(1):145. Available from: https://doi.org/10.1186/s12985-020-01418-7.

137. Simmons SE, Carrion R, Alfson KJ, Staples HM, Jinadatha C, Jarvis WR, et al. Deactivation of SARS-CoV-2 with pulsed-xenon ultraviolet light: implications for environmental COVID-19 control. Infect Control Hosp Epidemiol. 2020:1-4. Available from: https://doi.org/10.1017/ice.2020.399.

138. Corpet D. Why does SARS-CoV-2 survive longer on plastic than on paper? Med Hypotheses. 2021 Nov 28;146:110429. Available from: https://doi.org/10.1016/j.mehy.2020.110429.

139. Harbourt D, Haddow A, Piper A, Bloomfield H, Kearney B, Fetterer D, et al. Modeling the stability of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) on skin, currency, and clothing. PLoS Negl Trop Dis. 2020 Jul 3. Available from: https://doi.org/10.1371/journal.pntd.0008831.

140. Jones C. Environmental surface contamination with SARS-CoV-2 - a short review J Hum Virol Retrovirolog. 2020;8(1):15-9. Available from: https://doi.org/10.15406/jhvrv.2020.08.00215.

141. Kasloff SB, Strong JE, Funk D, Cutts TA. Stability of SARS-CoV-2 on critical personal protective equipment. Sci Rep. 2021 Jan 13;11(984). Available from: https://doi.org/10.1038/s41598-020-80098-3.

142. Liu Y, Li T, Deng Y, Liu S, Zhang D, Li H, et al. Stability of SARS-CoV-2 on environmental surfaces and in human excreta. J Hosp Infect. 2020;107:105-7. Available from: https://doi.org/10.1016/j.jhin.2020.10.021.

143. Zhou J, Otter JA, Price JR, Cimpeanu C, Garcia DM, Kinross J, et al. Investigating SARS-CoV-2 surface and air contamination in an acute healthcare setting during the peak of the COVID-19 pandemic in London. Clin Infect Dis. 2020 Jun 2. Available from: https://doi.org/10.1093/cid/ciaa905.

144. Guo Z, Wang Z, Zhang S, Li X, Li L, Li C, et al. Aerosol and surface distribution of severe acute respiratory syndrome coronavirus 2 in hospital wards, Wuhan, China, 2020. Emerg Infect Dis. 2020;26(7):1583-91. Available from: https://dx.doi.org/10.3201/eid2607.200885.

145. Colaneri M, Seminari E, Novati S, Asperges E, Biscarini S, Piralla A, et al. Severe acute respiratory syndrome coronavirus 2 RNA contamination of inanimate surfaces and virus viability in a health care emergency unit. Clin Microbiol Infect. 2020;26(8):1094.e1-.e5. Available from: https://doi.org/10.1016/j.cmi.2020.05.009.

146. Dargahi A, Jeddi F, Vosoughi M, Karami C, Hadisi A, Ahamad Mokhtari S, et al. Investigation of SARS-CoV-2 virus in environmental surface. Environ Res. 2021;195:110765. Available from: https://doi.org/10.1016/j.envres.2021.110765.

147. Dumont-Leblond N, Veillette M, Bhérer L, Boissoneault K, Mubareka S, Yip L, et al. Positive no-touch surfaces and undetectable SARS-CoV-2 aerosols in long-term care facilities: An attempt to understand the contributing factors and the importance of timing in air sampling campaigns. Am J Infect Control. 2021 Feb 11. Available from: https://doi.org/10.1016/j.ajic.2021.02.004.

148. Orenes-Piñero E, Baño F, Navas-Carrillo D, Moreno-Docón A, Marín JM, Misiego R, et al. Evidences of SARS-CoV-2 virus air transmission indoors using several untouched surfaces: A pilot study. Sci Total Environ. 2021 Jan 10;751:142317. Available from: https://doi.org/10.1016/j.scitotenv.2020.142317.

149. Cai J, Sun W, Huang J, Gamber M, Wu J, He G. Indirect virus transmission in cluster of COVID-19 cases, Wenzhou, China, 2020. Emerg Infect Dis. 2020;26(6):1343-5. Available from: https://dx.doi.org/10.3201/eid2606.200412.

150. Liu J, Huang J, Xiang D. Large SARS-CoV-2 outbreak caused by asymptomatic traveler, China. Emerg Infect Dis. 2020;26(9):2260-3. Available from: https://dx.doi.org/10.3201/eid2609.201798.

151. Yuan J, Chen Z, Gong C, Liu H, Li B, Li K, et al. Coronavirus disease 2019 outbreak likely caused by sewage exposure in a low-income community: Guangzhou, China, April 2020. SSRN. 2020 May. Available from: http://dx.doi.org/10.2139/ssrn.3618204.

152. Chen T. Fomites and the COVID-19 pandemic: an evidence review on its role in viral transmission. Vancouver, BC: National Collaborating Centre for Environmental Health; 2021 Mar 23. Available from: https://ncceh.ca/documents/evidence-review/fomites-and-covid-19-pandemic-evidence-review-its-role-viral-transmission.

153. Jeong HW, Kim S-M, Kim H-S, Kim Y-I, Kim JH, Cho JY, et al. Viable SARS-CoV-2 in various specimens from COVID-19 patients. Clin Microbiol Infect. 2020;26(11):1520-4. Available from: https://doi.org/10.1016/j.cmi.2020.07.020.

154. Qing H, Yang Z, Shi M, Zhang Z. New evidence of SARS-CoV-2 transmission through the ocular surface. Graefes Arch Clin Exp Ophthalmol. 2020. Available from: https://doi.org/10.1007/s00417-020-04726-4.

155. Schwartz DA, Morotti D, Beigi B, Moshfegh F, Zafaranloo N, Patanè L. Confirming vertical fetal infection with coronavirus disease 2019: neonatal and pathology criteria for early onset and transplacental transmission of Severe Acute Respiratory Syndrome Coronavirus 2 from infected pregnant mothers. Arch Pathol Lab Med. 2020;144(12):1451-6. Available from: https://doi.org/10.5858/arpa.2020-0442-SA.

156. Leblanc J-F, Germain M, Delage G, O'Brien S, Drews SJ, Lewin A. Risk of transmission of severe acute respiratory syndrome coronavirus 2 by transfusion: a literature review. Transfusion. 2020;60(12):3046-54. Available from: https://doi.org/10.1111/trf.16056.

157. Gupta S, Parker J, Smits S, Underwood J, Dolwani S. Persistent viral shedding of SARS-CoV-2 in faeces - a rapid review. Colorectal Dis. 2020;22(6):611-20. Available from: https://doi.org/10.1111/codi.15138.

158. Xiao F, Tang M, Zheng X, Liu Y, Li X, Shan H. Evidence for gastrointestinal infection of SARS-CoV-2. Gastroenterology. 2020;158(6):1831-3. Available from: https://doi.org/10.1053/j.gastro.2020.02.055.

159. Chen Y, Chen L, Deng Q, Zhang G, Wu K, Ni L, et al. The presence of SARS-CoV-2 RNA in the feces of COVID-19 patients. J Med Virol. 2020;92(7):833-40. Available from: https://doi.org/10.1002/jmv.25825.

160. Heneghan C, Spencer E, Brassey J, Pluddermann A, Onakpoya I, Evans D, et al. SARS-CoV-2 and the role of orofecal transmission: systematic review [version 1; peer review: 1 approved with reservations]. F1000Research. 2021;10(231). Available from: https://doi.org/10.12688/f1000research.51592.1.

161. Hindson J. COVID-19: faecal–oral transmission? Nat Rev Gastroenterol Hepatol. 2020 Mar 25;17(5):259. Available from: https://doi.org/10.1038/s41575-020-0295-7.

162. Wang W, Xu Y, Gao R, Lu R, Han K, Wu G, et al. Detection of SARS-CoV-2 in different types of clinical specimens. JAMA. 2020;323(18):1843-4. Available from: https://doi.org/10.1001/jama.2020.3786.

163. Volpp K, Kraut B, Ghosh S, Neatherlin J. Minimal SARS-CoV-2 transmission after implementation of a comprehensive mitigation strategy at a school — New Jersey, August 20–November 27, 2020. Morb Mortal Wkly Rep. 2021;70:377-81. Available from: http://dx.doi.org/10.15585/mmwr.mm7011a2.

164. Hou YJ, Chiba S, Halfmann P, Ehre C, Kuroda M, Dinnon KH, et al. SARS-CoV-2 D614G variant exhibits efficient replication ex vivo and transmission in vivo. Science. 2020;370(6523):1464-8. Available from: https://doi.org/10.1126/science.abe8499.

165. Tegally H, Wilkinson E, Giovanetti M, Iranzadeh A, Fonseca V, Giandhari J, et al. Emergence and rapid spread of a new severe acute respiratory syndrome-related coronavirus 2 (SARS-CoV-2) lineage with multiple spike mutations in South Africa. medRxiv. 2020 Dec 22. Available from: https://doi.org/10.1101/2020.12.21.20248640.

166. Volz E, Hill V, McCrone JT, Price A, Jorgensen D, O'Toole Á, et al. Evaluating the effects of SARS-CoV-2 spike mutation D614G on transmissibility and pathogenicity. Cell. 2021;184(1):64-75.e11. Available from: https://doi.org/10.1016/j.cell.2020.11.020.

167. van Dorp L, Richard D, Tan CCS, Shaw LP, Acman M, Balloux F. No evidence for increased transmissibility from recurrent mutations in SARS-CoV-2. Nat Commun. 2020;11(1):5986. Available from: https://doi.org/10.1038/s41467-020-19818-2.

168. US Centers for Disease Control and Prevention. Scientific brief: emerging SARS-CoV-2 variants. Atlanta GA: US Department of Health & Human Services; 2021 Jan 28. Available from: https://www.cdc.gov/coronavirus/2019-ncov/more/science-and-research/scientific-brief-emerging-variants.html.

169. World Health Organization. SARS-CoV-2 variants of concern and variants of interest. Geneva: WHO; 2021 May 31. Available from: https://www.who.int/en/activities/tracking-SARS-CoV-2-variants/.

170. O'Toole A, Hill V. B.1.1.7. Edinburgh, Scotland: Rambaut Group, University of Edinburgh; 2021 [updated May 25]; Available from: https://cov-lineages.org/global_report_B.1.1.7.html.

171. Public Health Agency of Canada. Coronavirus disease 2019 (COVID-19): epidemiology update. Ottawa, ON: PHAC; 2021 May 30. Available from: https://health-infobase.canada.ca/covid-19/epidemiological-summary-covid-19-cases.html.

172. BC Centre for Disease Control. Weekly update on variants of concern (VOC). Vancouver, BC: BCCDC; 2021 May 27. Available from: http://www.bccdc.ca/Health-Info-Site/Documents/VoC/VoC_Weekly_05272021.pdf.

173. O'Toole A, Hill V. B.1.351. Edinburgh, Scotland: Rambaut Group, University of Edinburgh; 2021 [updated May 25]; Available from: https://cov-lineages.org/global_report_B.1.351.html.

174. O'Toole A, Hill V. P.1. Edinburgh, Scotland: Rambaut Group, University of Edinburgh; 2021 [updated May 25]; Available from: https://cov-lineages.org/global_report_P.1.html.

175. O'Toole A, Hill V. B.1.617.2. Edinburgh, UK: Rambaut Group, University of Edinburgh; 2021 May 19. Available from: https://cov-lineages.org/global_report_B.1.617.2.html.

176. Volz E, Mishra S, Chand M, Barrett JC, Johnson R, Geidelberg L, et al. Transmission of SARS-CoV-2 lineage B.1.1.7 in England: insights from linking epidemiological and genetic data. medRxiv. 2021 Jan 4. Available from: https://doi.org/10.1101/2020.12.30.20249034.

177. European Centre for Disease Prevention and Control. Risk assessment: SARS-CoV-2 - increased circulation of variants of concern and vaccine rollout in the EU/EEA, 14th update. Solna, Sweden: ECDC; 2021 Feb 15. Available from: https://www.ecdc.europa.eu/en/publications-data/covid-19-risk-assessment-variants-vaccine-fourteenth-update-february-2021.

178. Davies N, Abbott A, Barnard R, Jarvis C, Kucharski A, Munday J, et al. Estimated transmissibility and impact of SARS-CoV-2 lineage B.1.1.7 in England. Science. 2021 Mar 3;372(6538). Available from: https://doi.org/10.1126/science.abg3055.

179. Davies N, Barnard R, Jarvis C, Kucharski A, Munday J, Pearson C, et al. Estimated transmissibility and severity of novel SARS-CoV-2 variant of concern 202012/01 in England. Preliminary report. London, UK: Centre for Mathematical Modelling of Infectious Diseases, London School of Hygiene and Tropical Medicine; 2020 Dec 31. Available from: https://cmmid.github.io/topics/covid19/reports/uk-novel-variant/2020_12_31_Transmissibility_and_severity_of_VOC_202012_01_in_England_update_1.pdf.

180. Leung K, Shum MH, Leung GM, Lam TT, Wu JT. Early transmissibility assessment of the N501Y mutant strains of SARS-CoV-2 in the United Kingdom, October to November 2020. Euro Surveill. 2021;26(1):2002106. Available from: https://doi.org/10.2807/1560-7917.ES.2020.26.1.2002106.

181. Zhao S, Lou J, Cao L, Zheng H, Chong MKC, Chen Z, et al. Quantifying the transmission advantage associated with N501Y substitution of SARS-CoV-2 in the UK: an early data-driven analysis. J Travel Med. 2021;28(2). Available from: https://doi.org/10.1093/jtm/taab011.

182. Gaymard A, Bosetti P, Feri A, Destras G, Enouf V, Andronico A, et al. Early assessment of diffusion and possible expansion of SARS-CoV-2 Lineage 20I/501Y.V1 (B.1.1.7, variant of concern 202012/01) in France, January to March 2021. Euro Surveill. 2021;26(9):2100133. Available from: https://doi.org/10.2807/1560-7917.ES.2021.26.9.2100133.

183. Grabowski F, Preibisch G, Giziński S, Kochańczyk M, Lipniacki T. SARS-CoV-2 variant of concern 202012/01 has about twofold replicative advantage and acquires concerning mutations. medRxiv. 2021 Feb 21. Available from: https://doi.org/10.1101/2020.12.28.20248906.

184. Pearson C, Russell T, Davies N, Kucharski A, CMMID COVID-19 working group, Edmunds J, et al. Estimates of severity and transmissibility of novel SARS-CoV-2 variant 501Y.V2 in South Africa, 2021. London, UK: Centre for Mathematical Modelling of Infectious Diseases, London School of Hygiene and Tropical Medicine; 2021 Jan 11. Available from: https://cmmid.github.io/topics/covid19/sa-novel-variant.html.

185. Faria NR, Mellan TA, Whittaker C, Claro IM, Candido DdS, Mishra S, et al. Genomics and epidemiology of the P.1 SARS-CoV-2 lineage in Manaus, Brazil. Science. 2021;372(6544):815-21. Available from: https://doi.org/10.1126/science.abh2644.

186. European Centre for Disease Prevention and Control. Threat assessment brief: emergence of SARS-CoV-2 B.1.617 variants in India and situation in the EU/EEA. Solna, Sweden: ECDC; 2021 May 11. Available from: https://www.ecdc.europa.eu/en/publications-data/threat-assessment-emergence-sars-cov-2-b1617-variants.

187. European Centre for Disease Prevention and Control. Assessing SARS-CoV-2 circulation, variants of concern, non-pharmaceutical interventions and vaccine rollout in the EU/EEA, 15th update. Solna, Sweden: ECDC; 2021 Jun 10. Available from: https://www.ecdc.europa.eu/sites/default/files/documents/RRA-15th-update-June%202021.pdf.

188. Li Q, Nie J, Wu J, Zhang L, Ding R, Wang H, et al. No higher infectivity but immune escape of SARS-CoV-2 501Y.V2 variants. Cell. 2021 Feb 23. Available from: https://doi.org/10.1016/j.cell.2021.02.042.

189. Villoutreix BO, Calvez V, Marcelin A-G, Khatib A-M. In silico investigation of the new UK (B.1.1.7) and South African (501Y.V2) SARS-CoV-2 variants with a focus at the ACE2-Spike RBD interface. Int J Mol Sci. 2021;22(4):1695. Available from: https://doi.org/10.3390/ijms22041695.

190. Laffeber C, de Koning K, Kanaar R, Lebbink JH. Experimental evidence for enhanced receptor binding by rapidly spreading SARS-CoV-2 variants. bioRxiv. 2021 Feb 22. Available from: https://doi.org/10.1101/2021.02.22.432357.

191. Liu H, Zhang Q, Wei P, Chen Z, Aviszus K, Yang J, et al. The basis of a more contagious 501Y.V1 variant of SARS-COV-2. bioRxiv. 2021 Feb 2. Available from: https://doi.org/10.1101/2021.02.02.428884.

192. Vogel M, Chang X, Sousa Augusto G, Mohsen MO, Speiser DE, Bachmann MF. SARS-CoV-2 variant with higher affinity to ACE2 shows reduced sera neutralization susceptibility. bioRxiv. 2021 Mar 4. Available from: https://doi.org/10.1101/2021.03.04.433887.

193. Calistri P, Amato L, Puglia I, Cito F, Giuseppe AD, Danzetta ML, et al. Infection sustained by lineage B.1.1.7 of SARS-CoV-2 is characterised by longer persistence and higher viral RNA loads in nasopharyngeal swabs. Int J Infect Dis. 2021 Mar 5. Available from: https://doi.org/10.1016/j.ijid.2021.03.005.

194. Kidd M, Richter A, Best A, Cumley N, Mirza J, Percival B, et al. S-variant SARS-CoV-2 lineage B1.1.7 is associated with significantly higher viral loads in samples tested by ThermoFisher TaqPath RT-qPCR. J Infect Dis. 2021 Feb 13. Available from: https://doi.org/10.1093/infdis/jiab082.

195. Davies NG, Jarvis CI, Edmunds WJ, Jewell NP, Diaz-Ordaz K, Keogh RH. Increased mortality in community-tested cases of SARS-CoV-2 lineage B.1.1.7. medRxiv. 2021 Mar 5. Available from: https://doi.org/10.1101/2021.02.01.21250959.

196. Kissler SM, Fauver JR, Mack C, Tai CG, Breban MI, Watkins AE, et al. Densely sampled viral trajectories suggest longer duration of acute infection with B.1.1.7 variant relative to non-B.1.1.7 SARS-CoV-2. medRxiv. 2021 Feb 19. Available from: https://doi.org/10.1101/2021.02.16.21251535.

197. Grint DJ, Wing K, Williamson E, McDonald HI, Bhaskaran K, Evans D, et al. Case fatality risk of the SARS-CoV-2 variant of concern B.1.1.7 in England. medRxiv. 2021 Mar 8. Available from: https://doi.org/10.1101/2021.03.04.21252528.

198. Challen R, Brooks-Pollock E, Read JM, Dyson L, Tsaneva-Atanasova K, Danon L. Risk of mortality in patients infected with SARS-CoV-2 variant of concern 202012/1: matched cohort study. BMJ. 2021;372:n579. Available from: https://doi.org/10.1136/bmj.n579.

199. Abdelnabi R, Boudewijns R, Foo CS, Seldeslachts L, Sanchez-Felipe L, Zhang X, et al. Comparative infectivity and pathogenesis of emerging SARS-CoV-2 variants in Syrian hamsters. bioRxiv. 2021 Feb 26. Available from: https://doi.org/10.1101/2021.02.26.433062.

200. Freitas ARR, Lemos DRQ, Beckedorff OA, de Góes Cavalcanti LP, Siqueira AM, de Mello RCS, et al. The increase in the risk of severity and fatality rate of covid-19 in southern Brazil after the emergence of the variant of concern (VOC) SARS-CoV-2 P.1 was greater among young adults without pre-existing risk conditions. medRxiv. 2021 Apr 19. Available from: https://doi.org/10.1101/2021.04.13.21255281.

201. Public Health England. SARS-CoV-2 variants of concern and variants under investigation in England. Technical briefing 14. London, UK: PHE; 2021 Jun 3. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/991343/Variants_of_Concern_VOC_Technical_Briefing_14.pdf.

202. Wang P, Nair M, Liu L, et al. Antibody resistance of SARS-CoV-2 variants B.1.351 and B.1.1.7. Nature. 2021 Mar 8. Available from: https://doi.org/10.1038/s41586-021-03398-2.

203. Brown JC, Goldhill DH, Zhou J, Peacock TP, Frise R, Goonawardane N, et al. Increased transmission of SARS-CoV-2 lineage B.1.1.7 (VOC 2020212/01) is not accounted for by a replicative advantage in primary airway cells or antibody escape. bioRxiv. 2021 Mar 1. Available from: https://doi.org/10.1101/2021.02.24.432576.

204. Wibmer CK, Ayres F, Hermanus T, Madzivhandila M, Kgagudi P, Oosthuysen B, et al. SARS-CoV-2 501Y.V2 escapes neutralization by South African COVID-19 donor plasma. Nat Med. 2021. Available from: https://doi.org/10.1038/s41591-021-01285-x.

205. Greaney AJ, Loes AN, Crawford KHD, Starr TN, Malone KD, Chu HY, et al. Comprehensive mapping of mutation sin the SARS-CoV-2 receptor-binding domain that affect recognition by polyclonal human plasma antibodies. Cell Host Microbe. 2021;29(3):463-76. Available from: https://doi.org/10.1016/j.chom.2021.02.003.

206. Bernal JL, Andrews N, Gower C, Gallagher E, Simmons R, Thelwall S, et al. Effectiveness of COVID-19 vaccines against the B.1.617.2 variant. medRxiv. 2021 May 24. Available from: https://doi.org/10.1101/2021.05.22.21257658.

207. Public Health Ontario. Lockdown duration and re-opening including considerations for COVID-19 variants of concern. Toronto, ON: Queen's Printer for Ontario; 2021 Jan 29. Available

from: https://www.publichealthontario.ca/-/media/documents/ncov/phm/2021/02/covid-19-environmental-scan-lockdowns-reopening-considerations-voc.pdf?la=en.

208. Grubaugh ND, Hodcroft EB, Fauver JR, Phelan AL, Cevik M. Public health actions to control new SARS-CoV-2 variants. Cell. 2021;184(5):1127-32. Available from: https://doi.org/10.1016/j.cell.2021.01.044.

209. Walensky RP, Walke HT, Fauci AS. SARS-CoV-2 variants of concern in the United States—challenges and opportunities. JAMA. 2021;325(11):1037-8. Available from: https://doi.org/10.1001/jama.2021.2294.

210. Public Health Ontario. Type of mask required or recommended for the public to control transmission of SARS-CoV-2 with consideration of variants of concern: rapid environmental scan Toronto, ON: Queen's Printer for Ontario; 2021 Feb 18. Available from: https://www.publichealthontario.ca/-/media/documents/ncov/voc/2021/03/covid-19-types-of-masks-public-variant-of-concern.pdf?la=en.

211. O'Keeffe J. Masking during the COVID-19 pandemic - an update of the evidence. Vancouver, BC: National Collaborating Centre for Environmental Health; 2020 May 20. Available from: https://ncceh.ca/documents/guide/masking-during-covid-19-pandemic-update-evidence.

212. Fontanet A, Autran B, Lina B, Kieny MP, Karim SSA, Sridhar D. SARS-CoV-2 variants and ending the COVID-19 pandemic. The Lancet. 2021 Feb 11. Available from: https://doi.org/10.1016/S0140-6736(21)00370-6.

213. Canadian Institute for Health Research, PHAC, CADTH. Best brains exchange – transmission routes for COVID-19: implications for public health. Ottawa, ON: CIHR; 2020. Available from: https://cihr-irsc.gc.ca/e/52238.html.

214. Anfinrud P, Bax CE, Stadnytskyi V, Bax A. Could SARS-CoV-2 be transmitted via speech droplets? medRxiv. 2020 Apr 6. Available from: https://dx.doi.org/10.1101%2F2020.04.02.20051177.

215. Tellier R. Aerosol transmission of influenza A virus: a review of new studies. J R Soc Interface. 2009 December 6, 2009;6(suppl_6):S783-S90. Available from: https://doi.org/10.1098/rsif.2009.0302.focus.

216. Sun S, Li J, Han J. How human thermal plume influences near-human transport of respiratory droplets and airborne particles: a review. Env Chem Lett. 2021 Jan 21. Available from: https://doi.org/10.1007/s10311-020-01178-4.

217. Jones NR, Qureshi ZU, Temple RJ, Larwood JP, Greenhalgh T, Bourouiba L. Two metres or one: what is the evidence for physical distancing in covid-19? BMJ. 2020;370:m3223. Available from: https://doi.org/10.1136/bmj.m3223.

218. US Centers for Disease Control and Prevention. Operational strategy for K-12 schools through phased prevention. Atlanta, GA: US Department of Health & Human Services; 2021 Mar 19. Available from: https://www.cdc.gov/coronavirus/2019-ncov/community/schools-childcare/operation-strategy.html#ref1.

219. Lyngse FP, Mølbak K, Træholt Frank K, Nielsen C, Skov RL, Kirkeby CT. Association between SARS-CoV-2 transmission risk, viral load, and age: a nationwide study in Danish households. medRxiv. 2021 Mar 5. Available from: https://doi.org/10.1101/2021.02.28.21252608.

220. Kemp SA, Collier DA, Datir RP, Ferreira IATM, Gayed S, Jahun A, et al. SARS-CoV-2 evolution during treatment of chronic infection. Nature. 2021 Apr 1;592(7853):277-82. Available from: https://doi.org/10.1038/s41586-021-03291-y.

221. Cevik M, Marcus J, Buckee C, Smith T. Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) transmission dynamics should inform policy. Clin Infect Dis. 2020 Sep 23. Available from: https://doi.org/10.1093/cid/ciaa1442.

222. National Academies of Sciences Engineering and Medicine. Rapid expert consultation on SARS-CoV-2 survival in relation to temperature and humidity and potential for seasonality for the COVID-19 pandemic (April 7, 2020). Washington, DC: The National Academies Press; 2020. Available from: https://www.nap.edu/catalog/25771/rapid-expert-consultation-on-sars-cov-2-survival-in-relation-to-temperature-and-humidity-and-potential-for-seasonality-for-the-covid-19-pandemic-april-7-2020.

223. Wang T, Lien C, Liu S, Selveraj P. Effective heat inactivation of SARS-CoV-2. medRxiv. 2020 May 5. Available from: https://doi.org/10.1101/2020.04.29.20085498.

224. Walker GJ, Clifford V, Bansal N, Stella AO, Turville S, Stelzer-Braid S, et al. SARS-CoV-2 in human milk is inactivated by Holder pasteurization but not cold storage. J Paediatr Child Health. 2020;56(12):1872-4. Available from: https://doi.org/10.1111/jpc.15065.

225. Moriyama M, Hugentobler WJ, Iwasaki A. Seasonality of respiratory viral infections. Annu Rev Virol. 2020;7(1). Available from: https://doi.org/10.1146/annurev-virology-012420-022445.

226. Zhao L, Qi Y, Luzzatto-Fegiz P, Cui Y, Zhu Y. COVID-19: effects of environmental conditions on the propagation of respiratory droplets. Nano Lett. 2020;20(10):7744-50. Available from: https://doi.org/10.1021/acs.nanolett.0c03331.

227. Biryukov J, Boydston JA, Dunning RA, Yeager JJ, Wood S, Reese AL, et al. Increasing temperature and relative humidity accelerates inactivation of SARS-CoV-2 on surfaces. mSphere. 2020;5(4):e00441-20. Available from: https://doi.org/10.1128/mSphere.00441-20.

228. Dabisch P, Schuit M, Herzog A, Beck K, Wood S, Krause M, et al. The influence of temperature, humidity, and simulated sunlight on the infectivity of SARS-CoV-2 in aerosols. Aerosol Sci Technol. 2020 Nov:1-12. Available from: https://doi.org/10.1080/02786826.2020.1829536.

229. Duan SM, Zhao XS, Wen RF, Huang JJ, Pi GH, Zhang SX, et al. Stability of SARS coronavirus in human specimens and environment and its sensitivity to heating and UV irradiation. Biomed Environ Sci. 2003 Sep;16(3):246-55. Available from: https://www.ncbi.nlm.nih.gov/pubmed/14631830.

230. International Ultraviolet Association. IUVA fact sheet on UV disinfection for COVID-19. Chevy Chase, MD: IUVA; 2020 Mar. Available from: https://www.iuva.org/IUVA-Fact-Sheet-on-UV-Disinfection-for-COVID-19.

231. Kowalski W. Ultraviolet germicidal irradiation handbook. New York, NY: Springer; 2009. Available from: https://link.springer.com/book/10.1007/978-3-642-01999-9.

232. Seyer A, Sanlidag T. Solar ultraviolet radiation sensitivity of SARS-CoV-2. Lancet Microbe. 2020;1(1):e8-e9. Available from: https://dx.doi.org/10.1016%2FS2666-5247(20)30013-6.

233. Blázquez E, Rodríguez C, Ródenas J, Navarro N, Riquelme C, Rosell R, et al. Evaluation of the effectiveness of the SurePure Turbulator ultraviolet-C irradiation equipment on inactivation of different enveloped and non-enveloped viruses inoculated in commercially collected liquid animal plasma. PLOS ONE. 2019;14(2). Available from: https://doi.org/10.1371/journal.pone.0212332.

234. Heßling M, Hönes K, Vatter P, Lingenfelder C. Ultraviolet irradiation doses for coronavirus inactivation – review and analysis of coronavirus photoinactivation studies. GMS Hyg Infect Control. 2020 May 14;15. Available from: https://dx.doi.org/10.3205%2Fdgkh000343.

235. Houser KW. Ten facts about UV radiation and COVID-19. LEUKOS. 2020;16(3):177-8. Available from: https://doi.org/10.1080/15502724.2020.1760654.

236. Rivers C, Martin E, Gottlieb S, Watson C, Schoch-Spana M, Mullen L, et al. Public health principles for a phased reopening during covid-19: guidance for governors. Baltimore, MD: John Hopkins Bloomberg School of Public Health, Center for Health Security; 2020 Apr 17. Available from: https://www.centerforhealthsecurity.org/our-work/publications/public-health-principles-for-a-phased-reopening-during-covid-19-guidance-for-governors.

237. US Centers for Disease Control and Prevention. Science brief: background rationale and evidence for public health recommendations for fully vaccinated people. Atlanta, GA: US Department of Health & Human Services; 2021 Mar 8. Available from: https://www.cdc.gov/coronavirus/2019-ncov/science/science-briefs/fully-vaccinated-people.html.

238. Eykelbosh A. Physical barriers for COVID-19 infection prevention and control in commercial settings. Vancouver, BC: National Collaborating Centre for Environmental Health; 2020 May 13. Available from: https://ncceh.ca/content/blog/physical-barriers-covid-19-infection-prevention-and-control-commercial-settings.

239. ASHRAE Epidemic Task Force. Commercial C19 guidance. Atlanta, GA: ASHRAE; 2021 Mar 22. Available from: https://www.ashrae.org/File%20Library/Technical%20Resources/COVID-19/ASHRAE-Commercial-C19-Guidance.pdf.

240. World Health Organization. Roadmap to improve and ensure good indoor ventilation in the context of COVID-19. Geneva, Switzerland: WHO; 2021 Mar 1. Available from: https://www.who.int/publications/i/item/9789240021280.

241. Nissen K, Krambrich J, Akaberi D, Hoffman T, Ling J, Lundkvist Å, et al. Long-distance airborne dispersal of SARS-CoV-2 in COVID-19 wards. Sci Rep. 2020;10(1):19589. Available from: https://doi.org/10.1038/s41598-020-76442-2.

242. Public Health Agency of Canada. COVID-19: guidance on indoor ventilation during the pandemic. Ottawa, ON: PHAC; 2021 Jan 18. Available from: https://www.canada.ca/en/public-health/services/diseases/2019-novel-coronavirus-infection/guidance-documents/guide-indoor-ventilation-covid-19-pandemic.html.

243. Bluyssen PM, Ortiz M, Zhang D. The effect of a mobile HEPA filter system on 'infectious' aerosols, sound and air velocity in the SenseLab. Build Environ. 2021;188:107475. Available from: https://doi.org/10.1016/j.buildenv.2020.107475.

244. Eykelbosh A. Indoor CO2 sensors for COVID-19 risk mitigation: current guidance and limitations. Vancouver, BC: National Collaborating Centre for Environmental Health; 2021 May 18. Available from: https://ncceh.ca/documents/field-inquiry/indoor-co2-sensors-covid-19-risk-mitigation-current-guidance-and.

245. O'Keeffe J. Air cleaning technologies for indoor spaces during the COVID-19 pandemic. Vancouver, BC: National Collaborating Centre for Environmental Health; 2020 Dec 10. Available from: https://ncceh.ca/content/blog/air-cleaning-technologies-indoor-spaces-during-covid-19-pandemic.

246. Chen T, O'Keeffe J. COVID-19 in indoor environments — air and surface disinfection measures. Vancouver, BC: National Collaborating Centre for Environmental Health; 2020 Jul. Available from: https://ncceh.ca/documents/guide/covid-19-indoor-environments-air-and-surface-disinfection-measures.

247. Walker CM, Ko G. Effect of ultraviolet germicidal irradiation on viral aerosols. Environ Sci Tech. 2007;41(15):5460-5. Available from: https://doi.org/10.1021/es070056u.

248. Bianco A, Biasin M, Pareschi G, Cavalleri A, Cavatorta C, Fenizia C, et al. UV-C irradiation is highly effective in inactivating and inhibiting SARS-CoV-2 replication. medRxiv. 2020 Jun 23. Available from: https://doi.org/10.1101/2020.06.05.20123463.

249. Simmons S, Carrion R, Alfson K, Staples H, Jinadatha C, Jarvis W, et al. Disinfection effect of pulsed xenon ultraviolet irradiation on SARS-CoV-2 and implications for environmental risk of COVID-19 transmission. medRxiv. 2020 May 11. Available from: https://doi.org/10.1101/2020.05.06.20093658.

250. US Centers for Disease Control and Prevention. Decontamination and reuse of filtering facepiece respirators. Atlanta, GA: US Department of Health & Human Services; 2020 [updated Apr 30]; Available from: https://www.cdc.gov/coronavirus/2019-ncov/hcp/ppe-strategy/decontamination-reuse-respirators.html.

251. Atci F, Cetin YE, Avci M, Aydin O. Evaluation of in-duct UV-C lamp array on air disinfection: a numerical analysis. Sci Technol Built Environ. 2020;27(1):98-108. Available from: https://doi.org/10.1080/23744731.2020.1776549.

252. Health Canada. Health product advertising incidents related to COVID-19. Ottawa, ON: Health Canada; 2021 Jun 10. Available from: https://www.canada.ca/en/health-canada/services/drugs-health-products/covid19-industry/health-product-advertising-incidents.html.

253. British Columbia Centre for Disease Control, British Columbia Ministry of Health. Tools and strategies for safer operations during the COVID-19 pandemic. Vancouver, BC: BC Centre for Disease Control and the BC Ministry of Health; 2020 Jul. Available from: http://www.bccdc.ca/Health-Info-Site/Documents/COVID19_ToolsStrategiesSaferOperations.pdf.

254. Eisenstein M. What's your risk of catching COVID? These tools help you to find out. Nature. 2021;589:158-9. Available from: https://doi.org/10.1038/d41586-020-03637-y.

255. Allen J, Cedeno-Laurent J, Miller S. Harvard-CU Boulder portable air cleaner calculator for schools. v1.3. Boston, MA: Harvard T.H. Chan Shool of Public Health; 2020 Nov 8. Available from: https://docs.google.com/spreadsheets/d/1NEhk1IEdbEi_b3wa6gI_zNs8uBJjlSS-86d4b7bW098/edit#gid=1882881703.

256. Khan K, Bush J, Bazant M. COVID-19 indoor safety guideline. Web app2021; Available from: https://indoor-covid-safety.herokuapp.com/.

257. Jimenez JL, Peng Z. COVID-19 aerosol transmission estimator. Boulder, CO: University of Colorado-Boulder; 2021 Mar 26. Available from: https://docs.google.com/spreadsheets/d/16K1OQkLD4BjgBdO8ePj6ytf-RpPMlJ6aXFg3PrIQBbQ/edit#gid=519189277.

258. Umwelt Bundesamt. Richtig Lüften in Schulen (In German) [Correct ventilation in schools]. Dessau-Roßlau: Umwelt Bundesamt; 2020 Feb 12. Available from: https://www.umweltbundesamt.de/richtig-lueften-in-schulen#was-nutzen-co2-ampeln-und-wie-setze-ich-sie-richtig-ein.

259. Public Health Agency of Canada. Risk mitigation tool for workplaces/businesses operating during the COVID-19 pandemic. Ottawa, ON: PHAC; 2020 Sep 28. Available from: https://www.canada.ca/en/public-health/services/diseases/2019-novel-coronavirus-infection/guidance-documents/risk-informed-decision-making-workplaces-businesses-covid-19-pandemic.html.

260. Workers' Safety and Compensation Commission. COVID-19 workplace risk assessment. Yellowknife, NT: WSCC; 2021 Feb. Available from: https://www.wscc.nt.ca/sites/default/files/documents/COVID-19%20Workplace%20Risk%20Assessment%20-%20EN.pdf.

261. Government of BC. Tools & resources for managing COVID-19 in the BC Public Service. Victoria, BC2020. Available from: https://www2.gov.bc.ca/gov/content/careers-myhr/managers-supervisors/covid-19-guidelines/tools-resources.

262. Small Business BC. COVID-19 safety planning. Vancouver, BC: Small Business BC; 2021. Available from: https://covid.smallbusinessbc.ca/hc/en-us/articles/360048313634-COVID-19-Safety-Planning.

263. WorkSafeBC. Reviewing and updating your COVID-19 safety plan: a guide for employers. Vancouver, BC: WorkSafeBC; 2020 Nov. Available from: https://www.worksafebc.com/en/resources/health-safety/books-guides/reviewing-updating-covid-19-safety-plans-guide-for-employers?lang=en.

264. Baron P. Generation and behavior of airborne particles (aerosols): US CDC, NIOSH; ND. Available from: https://www.cdc.gov/niosh/topics/aerosols/pdfs/Aerosol_101.pdf.

265. Luongo JC, Fennelly KP, Keen JA, Zhai ZJ, Jones BW, Miller SL. Role of mechanical ventilation in the airborne transmission of infectious agents in buildings. Indoor Air. 2016;26(5):666-78. Available from: https://doi.org/10.1111/ina.12267.

266. Qian H, Zheng X. Ventilation control for airborne transmission of human exhaled bio-aerosols in buildings. J Thorac Dis. 2018;10(Suppl 19):S2295-S304. Available from: https://doi.org/10.21037/jtd.2018.01.24.

267. Wei J, Li Y. Airborne spread of infectious agents in the indoor environment. Am J Infect Control. 2016;44(9):S102-S8. Available from: https://doi.org/10.1016/j.ajic.2016.06.003.

268. Zhu S, Jenkins S, Addo K, Heidarinejad M, Romo SA, Layne A, et al. Ventilation and laboratory confirmed acute respiratory infection (ARI) rates in college residence halls in College Park, Maryland. Environ Int. 2020 Apr;137:105537. Available from: https://doi.org/10.1016/j.envint.2020.105537.

269. Yang F, Sun Y, Wang P, Weschler LB, Sundell J. Spread of respiratory infections in student dormitories in China. Sci Total Environ. 2021;777:145983. Available from: https://doi.org/10.1016/j.scitotenv.2021.145983.

270. Du C-R, Wang S-C, Yu M-C, Chiu T-F, Wang J-Y, Chuang P-C, et al. Effect of ventilation improvement during a tuberculosis outbreak in underventilated university buildings. Indoor Air. 2020;30(3):422-32. Available from: https://doi.org/10.1111/ina.12639.

271. Pantelic J, Tham KW. Adequacy of air change rate as the sole indicator of an air distribution system's effectiveness to mitigate airborne infectious disease transmission caused by a cough release in the room with overhead mixing ventilation: A case study. HVAC&R Res. 2013;19(8):947-61. Available from: https://doi.org/10.1080/10789669.2013.842447.

272. Berlanga FA, Olmedo I, de Adana MR, Villafruela JM, José JFS, Castro F. Experimental assessment of different mixing air ventilation systems on ventilation performance and exposure to exhaled contaminants in hospital rooms. Energ Buildings. 2018;177:207-19. Available from: https://doi.org/10.1016/j.enbuild.2018.07.053.

273. Shajahan A, Culp CH, Williamson B. Effects of indoor environmental parameters related to building heating, ventilation, and air conditioning systems on patients' medical outcomes: A review of scientific research on hospital buildings. Indoor Air. 2019;29(2):161-76. Available from: https://doi.org/10.1111/ina.12531.

274. Eykelbosh A. High-humidity environments and the risk of COVID-19 transmission. Vancouver, BC: National Collaborating Centre for Environmental Health; 2020 Oct 16. Available from: https://ncceh.ca/documents/field-inquiry/high-humidity-environments-and-risk-covid-19-transmission.

275. Workers Health & Safety Centre. COVID-19 Enhanced ventilation: prudent actions to help control airborne virus transmission. Markham, ON: WHSC; 2020 Jun 18. Available from:

https://www.whsc.on.ca/Files/Resources/COVID-19-Resources/WHSC_Pandemic_Enhanced-Ventilation_June18-en.aspx

276. Nembhard MD, Burton DJ, Cohen JM. Ventilation use in nonmedical settings during COVID-19: cleaning protocol, maintenance, and recommendations. Toxicol Ind Health. 2020;36(9):644-53. Available from: https://doi.org/10.1177/0748233720967528.

277. Fitzpatrick M. German school finds DIY answer to anti-virus ventilation. Medical Xpress. 2020 Nov 13. Available from: https://medicalxpress.com/news/2020-11-german-school-diy-anti-virus-ventilation.html.

278. Pantelic J, Tham KW, Licina D. Effectiveness of a personalized ventilation system in reducing personal exposure against directly released simulated cough droplets. Indoor Air. 2015;25(6):683-93. Available from: https://doi.org/10.1111/ina.12187.

279. Cheshmehzangi A. Revisiting the built environment: 10 potential development changes and paradigm shifts due to COVID-19. J Urban Manag. 2021 Feb 27. Available from: https://doi.org/10.1016/j.jum.2021.01.002.

280. Chojer H, Branco PTBS, Martins FG, Alvim-Ferraz MCM, Sousa SIV. Development of low-cost indoor air quality monitoring devices: recent advancements. Sci Total Environ. 2020;727:138385. Available from: https://doi.org/10.1016/j.scitotenv.2020.138385.

281. Marques G, Saini J, Dutta M, Singh P, Hong W-C. Indoor air quality monitoring systems for enhanced living environments: a review toward sustainable smart cities. Sustainability. 2020;12:4024. Available from: https://doi.org/10.3390/su12104024.

282. Rodriguez K, Windwehr S, Schoen S. Bracelets, beacons, barcodes: wearables in the global response to COVID-19. Electronic Frontier Foundation. 2020 Jun 15. Available from: https://www.eff.org/deeplinks/2020/06/bracelets-beacons-barcodes-wearables-global-response-covid-19.

283. Giacomin J. What is human centred design? The Design Journal. 2014;17(4):606-23. Available from: https://doi.org/10.2752/175630614X14056185480186.