Public Health Ontario | Santé publique Ontario

SYNTHESIS

COVID-19 Transmission through Short and Long-Range Respiratory Particles

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Contents

Key Messages

- Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is transmitted from an infectious person (source or case) to a susceptible person (receptor or contact) across a spectrum of respiratory particle sizes and distances. Infectious respiratory particles are deposited on mucosal surfaces of individuals, or are inhaled by susceptible individuals. Evidence supports increased SARS-CoV-2 transmission risk as the source-to-receptor distance decreases, and respiratory transmission via particles of varying sizes can occur over short and long ranges.

- Respiratory transmission routes are not dichotomous. The relative contributions of larger respiratory droplets versus smaller aerosols in short- or long-range transmission to a specific case-contact interaction vary based on contextual factors that increase transmission risk: environmental characteristics (e.g., lower temperatures, lower humidity, poor ventilation) and host/source characteristics (e.g., forceful expulsions of respiratory particles, longer duration of exposure, inadequate distancing and lack of source control).

- Secondary attack rates can provide indirect evidence of transmission dynamics, assuming closer and longer duration contact occurs in household settings compared to non-household settings. Evidence consistently shows household secondary attack rates to be greater than non-household secondary attack rates, indicating SARS-CoV-2 transmission risk generally increases as the source-to-receptor distance decreases and duration of contact increases.

- Air sampling data supports that aerosol transmission is plausible at both short and longer distances; however, virus-laden aerosols may not reach infectious dose during transient or long distance exposures, reducing transmission risk in those scenarios.

- For variants of concern (VOC) such as Delta and Omicron, there is evidence for higher household secondary attack rates and epidemiological case studies demonstrate the potential for long-distance transmission.

- Several control measures applied together in a layered approach are necessary to mitigate SARS-CoV-2 transmission risk, including high vaccination coverage, appropriate self-isolation and other administrative measures, wearing a well-fitted mask, physical distancing, optimized ventilation, and hand hygiene. Avoiding the "3 C's" (closed spaces, crowded places and close contact) will reduce transmission risk.

Executive Summary

Background

This version replaces the May 20, 2021 version *COVID-19 Transmission through Respiratory Droplets and Aerosols…What We Know So Far*.[1] Traditionally, respiratory particles >5 micrometres (µm) or >10 µm have been termed droplets and were thought to impact directly on mucous membranes, while smaller particles (i.e., aerosols) were thought to be inhaled. This dichotomy of transmission routes has been applied to infection prevention controls within health care settings worldwide. However, these routes are not mutually exclusive. At short range within approximately 2 metres (m), infection can occur from both inhalation as well as deposition on mucous membranes, referred to as **short-range transmission** in this synthesis. Herein, we refer to what was traditionally called airborne transmission via inhalation of aerosols that have remained suspended for longer durations and distances as **long-range transmission**.[2,3] Three key elements influence all modes of transmission: the source, the pathway and the receptor.[4,5] The term 'receptor' in this document refers to people. Non-respiratory routes of transmission are out of scope of this document and have been reviewed in Public Health Ontario's (PHO) *Additional Routes of COVID-19 Transmission – What We Know So Far*.[6]

Methods

A rapid review methodology was employed, which is a knowledge synthesis approach where certain steps of the systematic review process are omitted in order to be timely.[7] Updated literature searches in MEDLINE, Embase (November 8, 2021), National Institutes of Health COVID-19 Portfolio (preprints) (November 16, 2021) and PubMed (December 22, 2021) were conducted, informed by the previous search strategy.[1] English-language peer-reviewed and non-peer-reviewed records that described respiratory droplet and aerosol routes of transmission for SARS-CoV-2 were included. We restricted the search to articles published after the previous search (April 22, 2021).

Results

Short-range Transmission

The available evidence supports that a spectrum of respiratory particle sizes is involved in short-range respiratory emissions and transmission. The relative contribution of droplets depositing on mucous membranes versus particles being inhaled would vary based on contextual factors including source/receptor and pathway characteristics. Evidence for short-range transmission did not rule out the potential for long-range transmission, but suggested there was a greater risk of infection as the distance from an infectious source decreased, especially without protective measures in place (e.g., during a conversation with inadequate distancing, no mask wearing).

Long-range Transmission

Certain conditions are more likely to lead to long-range transmission of SARS-CoV-2, and the relative contribution of short versus long-range transmission cannot be generalized across all SARS-CoV-2 transmission events. The evidence supporting long-range aerosol transmission has grown since the beginning of the pandemic, with more systematic reviews and primary studies supporting this route of SARS-CoV-2 transmission. The included studies support that long-range transmission via aerosols occurs, especially when source/receptor and environmental conditions are favourable, such as indoor settings, inadequate ventilation, prolonged exposure time, high viral load, certain activities (e.g., singing, exercising, yelling) and a lack of masking for source control by the index case.

Factors Affecting Short and Long-range Respiratory Particle Transmission

The primary environmental factors contributing to increased transmission are low temperatures, low humidity, poor ventilation, improper airflow (i.e., from potential sources to susceptible individuals), and low ultraviolet (UV) light. Across included studies, poor ventilation is often noted as a particularly important factor that contributes to increased SARS-CoV-2 transmission.[8-14] Inadequate ventilation can contribute to the spread of aerosols, where the buildup of infectious aerosols is inversely proportional to the number of air exchanges. Evidence related to the role of heating, ventilation and air conditioning (HVAC) systems in facilitating transmission between different areas of buildings or cruise ships was inconsistent. In addition, turbulent airflow (e.g., from an individual coughing, improper air flows creating areas of recirculated air) can increase transmission risk.

Decreased relative humidity can increase transmission risk compared to humid conditions due to evaporation contributing to respiratory particles reducing in size, leading to increased volume of potentially virus-laden molecules remaining suspended in the air. Increased humidity, increased temperature and increased UV light are associated with reduced SARS-CoV-2 transmission risk by reducing the amount of particles remaining suspended in the air, and by reducing virus viability. There is also evidence that the impact of these indoor environmental conditions have interacting effects, again pointing to the importance of implementing multiple layered measures rather than relying on a single prevention measure.

Important host/source factors that contribute to increased transmission are higher viral loads, higher concentration of SARS-CoV-2 in the air, smaller size of virus-laden particles and infectious dose. In terms of behaviour, lack of physical distancing, increased vocalization and expulsion of respiratory particles (i.e., coughing and sneezing compared to normal talking and breathing), and a lack of masking all contribute to increased risk of transmission.

Secondary Attack Rates: Setting and Disease State

In household settings where physical distancing, mask-wearing and disinfection of shared surfaces are potentially not feasible, there is a higher risk of infection compared to casual contact settings (17–43% vs. 1–13%, respectively). Secondary attack rates and risk of infection are greater for those exposed to symptomatic or presymptomatic cases, rather than asymptomatic cases. This indirect evidence does not provide clarity to the proportion of transmission events due to short or long-range transmission.

SARS-CoV-2 in Air Samples

The risk of SARS-CoV-2 transmission is highest near the source, as the likelihood of detecting SARS-CoV-2 RNA in air samples is greater as the source-receptor sampling distance decreases. Culturing of viable virus from air samples is relatively uncommon; however, unsuccessful culturing does not indicate an absence of viable virus. SARS-CoV-2 is present in a wide range of air particles sizes, particularly those less than 5 µm in diameter, implying that they remain in the air for longer periods and can travel further distances from the source patient. Overall, air-sampling data supports that aerosol transmission is plausible at both short and longer distances; however, virus-laden aerosols are relatively diluted and therefore less infectious during transient or distant exposures.

Increased Transmissibility of Variants of Concern

Previously, PHO assessed potential mechanisms for the increased transmission of VOCs; however, there is still no evidence for fundamentally different routes of transmission for Omicron or other VOCs.[15,16] Evidence has emerged that other VOCs, such as Delta, have higher aerosol and surface stability, meaning that Delta may be more easily transmitted via long-range aerosols and fomites, respectively.[15,17,18] While unknown for Omicron, there is a potential for greater aerosol and surface stability for Omicron given its high transmissibility. Household attack rates for Delta and Omicron are higher than ancestral SARS-CoV-2 or other VOCs. Recent research on Delta and Omicron transmission indicated that long-distance transmission through aerosols was possible.[19-22]

Conclusions and Implications for Practice

SARS-CoV-2 transmission occurs via a spectrum of respiratory particle sizes through direct deposition on mucous membranes and through inhalation at both short- and long-range. Dichotomizing SARS-CoV-2 transmission as either droplet or aerosol does not accurately reflect this spectrum. In fact, infection can occur by multiple routes and particle sizes depending on the context related to source, receptor and environmental conditions. There is a higher risk of SARS-CoV-2 transmission with close (<2 m), unprotected (lacking multiple prevention measures) and prolonged exposure to an infectious individual. The risk of transmission at longer distances increases when there is inadequate ventilation or ventilation with recirculation of unfiltered or untreated air, with activities involving increased expulsion of aerosols (e.g., shouting, coughing, exercising) and a lack of source control masking and physical distancing.[23-30]

The evidence emphasizes multiple contextual factors that affect transmission and the importance of multiple layers of prevention needed to mitigate transmission. An expert-based and interactive infographic developed by Rutter et al. (2021) provides a useful visualization of SARS-CoV-2 transmission routes and estimates the risk of infection based on a variety of source, receptor and environmental factors.[31] We recommend an approach that emphasizes the importance of optimizing layered measures to prevent SARS-CoV-2 transmission, with the aim of reducing morbidity and mortality. Several resources exist for community guidance (e.g., non-health care workplaces, public and private spaces) on how to reduce the risk of SARS-CoV-2 transmission through a layered approach of multiple public health measures designed to mitigate transmission.[32-34]

The cornerstone of a layered approach to preventing SARS-CoV-2 is a combination of measures to mitigate exposure particularly in settings with the "3 C's": closed spaces, crowded places, and close contact. The degree to which various mitigation layers are necessary or possible will depend on the setting and risk context, noting that not everyone can avoid the 3 C's. Transmission can be mitigated through: getting vaccinated; staying home if you have symptoms of COVID-19 or if you have been exposed to someone with SARS-CoV-2 infection; limiting the number and duration of contacts with individuals outside your household, particularly indoors; physical distancing and avoiding crowded, indoor spaces; improving indoor ventilation and/or filtration; wearing a mask (non-fit tested respirator, medical mask, or well-fitted 3-layer non-medical mask); and performing hand hygiene, respiratory etiquette and environmental cleaning.

The above measures are effective means of reducing risk of transmission irrespective of the relative contribution of respiratory particle size to transmission. Some controls will be more effective than others and it is the combination and consistent application of these controls that is most effective for reducing disease spread.

COVID-19 Transmission through Short and Long-Range Respiratory Particles

Introduction

Public Health Ontario (PHO) is actively monitoring, reviewing and assessing relevant information related to Coronavirus Disease 2019 (COVID-19). **This synthesis replaces the May 20, 2021 version COVID-19 Transmission through Respiratory Droplets and Aerosols…What We Know So Far.**[1] The updated version focuses on evidence from systematic reviews, meta-analyses and recently published primary studies, as the body of evidence concerning short and long-range transmission has increased since the last version. Transmission of SARS-CoV-2 can also occur by non-respiratory routes, such as touching mucous membranes with a hand contaminated with virus containing fluids; these routes are out of scope of this document and have been reviewed in PHO's *Additional Routes of COVID-19 Transmission – What We Know So Far*.[6]

Background

The diameter of microorganism-containing respiratory particles relevant for respiratory infections ranges from approximately 0.01 µm to greater than 100 µm.[35] Particles larger than about 100 µm play a role in respiratory infection transmission by depositing on mucosal surfaces, such as the nostrils, mouth and eyes. Smaller respiratory particles settle to the ground or remain suspended in the air as aerosols for various periods, and are affected by factors such as particle size (larger particles settling faster), gravity, air currents, temperature and humidity. These factors dictate how respiratory particles move, evaporate and remain suspended in the air;[27,36] they can be inhaled or deposited on mucosal surfaces of receptors.[27,36,37] Thus, three key elements influence the mode of transmission: the source, the pathway and the receptor.[4,5]

Traditionally, respiratory particles >5 µm or >10 µm have been termed droplets and were thought to impact directly on mucous membranes, while smaller particles (i.e., aerosols) were thought to be inhaled. This dichotomy of transmission routes has been applied to infection prevention controls within health care settings worldwide. However, these transmission routes are not mutually exclusive. At short range within approximately 2 m, infection can occur from both inhalation as well as deposition on mucous membranes, referred to as **short-range transmission** in this synthesis. Herein, we refer to what was traditionally called airborne transmission via inhalation of aerosols that have remained suspended for longer durations and distances as **long-range transmission**.[2,3]

We describe transmission through epidemiological studies, experimental or simulation of transmission studies, and statistical or mathematical modelling studies. Modelling shows what is possible, experimental studies what is plausible and epidemiologic studies observe what is actually occurring, and each type of evidence is subject to limitations. However, we can only infer exact routes of SARS-CoV-2 transmission in real-life scenarios based on the available data.

The purpose of this rapid review is to outline and update the evidence for respiratory particles in SARS-CoV-2 transmission. We have summarized the evidence supporting short- and long-range transmission, as well as the factors affecting the transmission of respiratory particles.

Methods and Scope

A rapid review methodology was employed, which is a knowledge synthesis approach where certain steps of the systematic review process are omitted in order to be timely.[7]

Updated literature searches in MEDLINE, Embase (November 8, 2021), National Institutes of Health COVID-19 Portfolio (preprints) (November 16, 2021) and PubMed (December 22, 2021) were conducted, informed by the previous search strategy[1] (strategy available upon request). English-language peer-reviewed and non-peer-reviewed records that described respiratory droplet and aerosol routes of transmission for SARS-CoV-2 were included. We restricted the search to articles published after the previous search (April 22, 2021). This rapid review concentrated on evidence from systematic reviews and meta-analyses, supplemented by primary literature where appropriate. We reviewed citations from included articles to identify additional research.

The updated search returned 3,529 records, which we screened for relevance. Given the increased evidence for airborne transmission occurring on a continuum rather than distinctly over short- versus long-ranges, results have been re-organized to more generally present evidence for short-range transmission, evidence for long-range transmission, factors affecting both short and long-range respiratory particle transmission, secondary attack rates (ARs) and SARS-CoV-2 detection in air samples.

Whole genome sequencing (WGS) studies were included as relevant; however, it is important to note a caveat around WGS studies as evidence supporting a link between cases and contacts. Identical or near-identical WGS results alone are not necessarily confirmation of direct epidemiological linkage between cases, and do not rule out multiple infectious sources. Other important contextual factors to consider when interpreting the epidemiology of transmission or outbreak events include the locally circulating SARS-CoV-2 strain, along with the behaviours and exposure histories of cases and contacts.

Out-of-scope for this document was a review of Infection Prevention and Control (IPAC) practices appropriate for individual transmission scenarios and settings. Application of a hierarchy of control measures for non-health care settings is briefly discussed in the conclusions. For additional information related to IPAC in health care settings, please see PHO's technical brief *Interim IPAC Recommendations for Use of Personal Protective Equipment for Care of Individuals with Suspect or Confirmed COVID-19* and *Interim Guidance for Infection Prevention and Control of SARS-CoV-2 Variants of Concern for Health Care Settings*.[38,39]

Prior to publishing, PHO subject-matter experts review all What We Know So Far documents. As the scientific evidence is expanding rapidly, the information provided in this document is only current as of the date of respective literature searches.

Short-range Transmission

Short-range transmission can occur from deposition of respiratory particles on mucous membranes as well as through inhalation of respiratory particles. We included a total of 13 primary studies, including five new studies added in this update; the studies employed epidemiological, experimental and modelling designs.

Main Findings

The available evidence supports that a spectrum of respiratory particle sizes is involved in short-range respiratory emissions and transmission. The relative contribution of droplets depositing on mucous membranes versus particles being inhaled would vary based on contextual factors including source/receptor and pathway characteristics. Evidence for short-range transmission did not rule out the potential for long-range transmission but suggested there was a greater risk of infection as the distance from an infectious source decreased, especially without protective measures in place (e.g., during a conversation with inadequate distancing, no mask wearing).

Primary Literature

MODES OF TRANSPORTATION

Transmission dynamics in the context of travel and modes of transportation were investigated in five epidemiological studies which assessed transmission or outbreak events during airplane,[40-42] bus[43] and train travel.[44] Overall, these studies support the risk of SARS-CoV-2 transmission being greatest in close proximity to an infectious case. For example, a study by Hu et al. (2021) investigated 177 airplanes travelling from Wuhan, China prior to the pandemic lockdown (January 2020) with 5,797 passengers and a total of 175 index cases.[42] Relative risk (RR) of SARS-CoV-2 infection and attack rates (AR) were greatest for passengers seated immediately adjacent to index cases (RR: 27.8, 95% confidence interval [CI]: 14.4–53.7; AR: 9.2%, 95% CI: 5.7–14.4). For passengers in the same row, RR was 10.6 (95% CI: 5.3–21.1). Upper bounds of ARs also increased as travel time increased.[42]

These findings are supported by other studies conducted in Japan, England and China, which similarly found ARs and odds of infection increased as distance from index cases decreased in the context of air and train travel.[40,41,44] Many people in an enclosed space, close contact, inconsistent or lack of masking, and inadequate hygiene and disinfection processes were also noted as factors facilitating short-range transmission.[41,43] It should be noted that all five of these modes of transportation studies assessed travel and outbreak events that occurred early in the COVID-19 pandemic before widespread vaccination coverage and before the emergence of VOCs. Also, while these studies do not conclusively rule out some contribution of long-range transmission, they consistently support infection risk being higher within short-range and over longer durations of exposure.

HEALTH CARE FACILITIES

Two studies conducted in Ireland and the United States (US) investigated SARS-CoV-2 infections associated with health care facilities which were concluded to be most likely caused by short-range transmission.[45,46] Lucey et al. (2020) investigated 50 cases of hospital-acquired SARS-CoV-2 between March and April of 2020 and reported that the majority of infections were among patients who required extensive and prolonged care by health care providers.[46] The authors concluded that the likely mode of transmission from health care workers to patients was through short-range transmission and close contact, rather than long-range transmission. Notably, the use of masks by health care providers was not universal and patients were not wearing masks.[46]

Klompas et al. (2021) investigated three short-range health care-associated transmission events in Massachusetts, US (November to January 2021) where short-range aerosol transmission was likely. Masks were worn by either the source or the contact and in two of three events, the contact was also wearing eye protection.[45] In all cases; however, there were long periods of close contact ($\leq$1 m) between infectious cases and contacts including a medical procedure, an oropharynx assessment and a face-to-face discussion.

SCHOOL AND SPORTS SETTINGS

Two epidemiological studies investigated SARS-CoV-2 transmission in elementary schools[47] and in an outdoor rugby league.[48] In an investigation of school-associated transmission, four student-to-student and one student-to-teacher transmission events were reported in 20 Salt Lake County, Utah, US elementary schools (December 2020 to January 2021).[47] Four transmission events involved unprotected, short-range (< 2 m) exposures, such as poor mask adherence or during lunch when masking was not possible. There was a lack of transmission to other students when a median physical distancing of 1 m was maintained during class, and in the context of other control measures implemented in the school. Overall, elementary school-associated transmission was found to be low.[47]

An analysis of SARS-CoV-2 infections in an outdoor rugby league in England indicated that no cases among players in the league could be linked to close-contact during the outdoor rugby games (July to October 2020).[48] Instead, transmissions were linked to other indoor short-range transmission events. While this study demonstrates examples where outdoor close-contact transmission did not occur, there were not enough close-contacts documented to provide evidence that close-contact transmission could not have occurred in the context of outdoor rugby.[48]

SETTING NOT SPECIFIED

One experimental simulation study[49] and three modelling studies estimated the risk of SARS-CoV-2 infection in the context of close proximity between case and contacts.[50-52] Overall, these studies support there being greater risk of infection at short- relative to long-range, and the contribution of both particle inhalation and deposition on mucous membranes to short-range transmission, which challenges the traditional dichotomous categories of respiratory transmission routes.

The modelling studies simulated scenarios involving various parameters; however, all consistently found that as distance between case and contact decreased, the risk of infection increased.[50-52] The experimental study by Fu et al. (2021) estimated the contribution of respiratory particle inhalation versus deposition on mucous membranes at short-range.[51] The authors simulated respiratory particle sizes of 1.0, 1.5, 2.5 and 5.0 µm, at a distance of 0.5 m between case and susceptible contact (thermal mannequins) over a 1 h period. A greater ratio of the smallest particles (1.0 µm, 1.5 µm) entered the respiratory tract of the contact (i.e., inhalation) compared to the larger particles (2.5 µm, 5.0 µm). The larger particles were more likely to deposit at the entrance of the susceptible mannequin (i.e., simulated deposition on mucous membranes) and less likely to be inhaled.

Long-range Transmission

Long-range transmission can occur through inhalation of respiratory aerosols emitted from an infectious source which remain suspended in the air for longer periods and travel further distances (typically beyond 2 m).

We included three reviews and 30 primary studies with epidemiological, experimental and modelling designs. This updated version added two new reviews and 16 new primary studies which investigated long-range transmission via aerosols as the likely route of transmission.

Main Findings

Certain conditions are more likely to lead to long-range transmission of SARS-CoV-2, and the relative contribution of short versus long-range transmission cannot be generalized across all SARS-CoV-2 transmission events. The evidence supporting long-range aerosol transmission has grown since the beginning of the pandemic, with more systematic reviews and primary studies supporting this route of SARS-CoV-2 transmission. The included studies support that long-range transmission via aerosols occurs, especially when source/receptor and environmental conditions are favourable, such as indoor settings, inadequate ventilation, prolonged exposure time, high viral load, certain activities (e.g., singing, exercising, yelling) and a lack of masking for source control by the index case.

Reviews

We included three reviews that supported long-range transmission as a contributing route of SARS-CoV-2 transmission. In these reviews, multiple routes of transmission at different source-receptor distances could not be ruled out.

Palmer et al. (2021) (preprint) conducted a rapid review of epidemiological outbreak/cluster investigation studies (search up to April 2021) related to airborne transmission in indoor community settings.[53] Of 13 included studies, four provided evidence for probable long-range transmission (>2 m), eight possible, and one study was unclear. Factors potentially increasing the risk of long-range transmission included closed indoor spaces, insufficient air replacement, recirculation of air flow and activities producing increased respiratory particles (e.g., singing and physically demanding work). In nine of the 13 studies, primary cases were asymptomatic, presymptomatic or very near the time of symptom onset. Overall, the certainty of the evidence was very low but supported the possibility of long-range transmission of SARS-CoV-2 in certain settings and conditions.[53]

Grudlewska-Buda et al. (2021) reviewed laboratory studies (search up to January 2021) and found that SARS-CoV-2 aerosol particles may remain viable for several hours, and aerosols in general were able to disperse over long-ranges. The authors reported that "super spreaders" of COVID-19 may produce many more aerosol particles than the average COVID-19 case, potentially creating greater risk of long-range transmission; however, this was not supported by empirical evidence.[54]

The review by Comber et al. (2021) (search up to July 2020) included eight epidemiological outbreak clusters investigating the contribution of aerosols to transmission, in settings such as restaurants, a shopping mall, a choir, a meat processing plant, buses, health care facilities, a cruise ship and public spaces. The authors concluded there was limited, low quality evidence, from a small number of epidemiological studies to suggest aerosol transmission of SARS-CoV-2. It was not possible to determine the relative contribution of aerosol transmission compared to other routes with any certainty.[55]

Primary Literature

We included 30 studies that concluded or hypothesized that long-distance aerosol transmission accounted for some or all transmission events. In most epidemiological studies, long-range transmission was inferred as the dominant route of transmission, given those infected were usually further than 2 m away from index cases. In addition, susceptible people were exposed to index cases for prolonged periods in indoor environments with inadequate ventilation or poor air movement patterns and, in some instances, with increased respirations (e.g., singing, yelling, exercising) and/or no face mask use (by case and/or contact).

As with most epidemiological studies on transmission events, it was difficult to exclude other contributing routes of transmission. We summarized these case studies, highlighting settings and contributing contextual factors to long-range transmission. Experimental and modelling studies found transmission at long-range was demonstrated to be possible but the overall finding was that risk of infection decreased as the distance from the infectious source increased.

SINGING VENUES

Four epidemiological studies investigated SARS-CoV-2 cases and outbreaks associated with indoor singing venues in Australia, Germany, the Netherlands and the US.[13,56-58] These studies supported the occurrence of long-range transmission in the context of group (i.e., choirs) and individual performers singing in indoor settings. This evidence does not completely rule out other routes of transmission and it is not expected that long-range transmission is the sole contributing route. However, across studies it concluded that short-range or fomite transmission did not reasonably explain the extent of SARS-CoV-2 transmission to susceptible contacts who were not in close proximity to the infectious case, indicating long-range respiratory transmission played a role through the accumulation of respiratory particles suspended in the air and being inhaled by susceptible contacts. All four studies described transmission events that occurred in 2020, early in the pandemic before widespread vaccination coverage and before the emergence of VOCs.

For example, 12 secondary cases of SARS-CoV-2 were linked to an index case, an 18-year-old chorister with high viral load who sang at four 1 h services in a church (New South Wales, Australia; July 2020).[56] The index case was seated at a piano raised approximately 3 m from the ground floor and faced away from the secondary cases. Secondary cases sat between 1–15 m (horizontal distance) from the index case, but did not have any close physical contact. Use of masks was not in place and there was minimal ventilation during the service. The authors suggested convection currents could have carried aerosol particles toward the seating areas. Additional studies report similar findings of transmission from infectious cases who sang indoors to contacts who were not in close proximity to the case.[13,57,58] One study found the AR in a choir group who practiced in an small indoor space with more participants (AR: 89%) was significantly greater than a similar choir who practiced in large indoor space with fewer participants (AR: 24%), suggesting certain indoor environments (small and crowded) may facilitate the accumulation of respiratory particles remaining suspended in the air more than others (larger and less crowded).[58]

MODES OF TRANSPORTATION

The contribution of long-range SARS-CoV-2 transmission on transportation vehicles was investigated in three epidemiological studies[59-61] and two modelling studies.[62,63] These studies involved buses,[60,61,63] patient transport vans[59] and a railway coach,[62] and were conducted in China[60,61,63] and the US.[59] It should be noted that most epidemiological evidence was from early in the pandemic.

In the epidemiological studies investigating transmission events on buses and patient transport vans, secondary cases were identified who were seated more than 2 m (up to 9.5 m) away from the index cases, suggesting the contribution of long-range transmission.[59-61] For example, Ou et al. (2021) investigated an outbreak involving two buses in Hunan Province, China in January, 2020, where one presymptomatic index case transmitted to 10 secondary cases (eight on Bus 1, two on Bus 2).[61] On Bus 1, long-range aerosol transmission likely occurred since the distance between the index case and farthest secondary case was 9.5 m. Short-range transmission potentially occurred on Bus 2 since the farthest distance from the index case was 2.3 m. Close contact was possible during boarding, de-boarding and luggage collection; however the authors posited the likelihood of infecting all secondary cases during these interactions was low and long-range transmission played at least a partial role.[61] A modelling study of this bus outbreak concluded that airborne transmission occurred on the bus, including both short-range and long-range transmission, and noted that transmission via fomites was negligible.[63]

Inadequate ventilation was consistently suggested as a factor facilitating long-range transmission in transportation settings, including ventilation rate below the recommended rate,[61] recirculating air without filtration or introducing fresh air,[60] and running fans with windows closed.[59]

The modelling study by Armant et al. (2021) (preprint) explored the possible dispersion of particles carrying SARS-CoV-2 from an individual not wearing a mask seated in an enclosed, ventilated railway coach with other passengers.[62] Coughing resulted in smaller particles (1 µm and 10 µm) moving and spreading according to air streams through the coach, and larger particles (100 µm and 1,000 µm) mainly settled on the source and the passenger seated opposite the source. Breathing resulted in airflow carrying small (1 µm) particles among the passengers closest to the spreader within approximately 2 min, and to the group of passengers on the same side of the coach and across the aisle in approximately 8 min. While ventilation directed particles out of the coach, breathing created a continuous source of particles, suggesting the possibility of long-range transmission in this scenario.

MULTI-STOREY APARTMENT BUILDINGS

Three epidemiological investigations involved SARS-CoV-2 transmission between vertically-aligned units in multi-storey apartment buildings in Hong Kong; Wuhan, China; and Seoul, South Korea.[64-66] These studies suggested the potential for long-range transmission of infectious aerosol particles being facilitated by common water drainage stacks and ventilation duct systems which connect apartments.

Wang et al. (2021) investigated an outbreak in two high rise buildings in Hong Kong, in which long-range transmission via contaminated stack aerosols was concluded as probable (January and February 2021).[66] Waste from toilets and sinks being flushed produces stack aerosols in vertical drainage stacks (i.e., chimney effect). In Building 1, 14 residents from six flats tested positive for SARS-CoV-2; in Building 2, nine residents from five flats were infected. The pattern of cases indicated they were aligned vertically and shared the same drainage stacks. Environmental samples were positive in some of the bathrooms and tracer gas experiments demonstrated leakage from pipes into vertically-aligned flats. The chimney effect created variable pressures in drainage stacks, creating an upward movement of aerosols and probable long-range transmission.[66]

Similarly, Lin et al. (2021) investigated an outbreak involving cases in vertically-aligned units in Wuhan, China (January and February 2020). An experiment with a tracer gas indicated that gas could spread from one storey to another via the drainage and vent systems, especially as the seals in U-shaped traps in the floor drains were dried out in some units and the use of exhaust fans could create a negative pressure in the pipeline system.[65] Finally, a similar situation was reported involving air ducts in a naturally ventilated apartment complex in Seoul, South Korea during August 2020 (Hwang et al. 2021).[64] There were no valves blocking air from entering the bathrooms from the shared natural ventilation shafts (not for building or apartment unit ventilation).[64]

RESTAURANTS

Four epidemiological studies[67-70] and one modelling study[71] investigated the role of long-range transmission in SARS-CoV-2 outbreaks in restaurant settings in China, South Korea and the US. Similar to the modes of transportation evidence described above, long-range transmission was indicated in these restaurant settings due to identification of secondary cases who were not in close proximity to the index case at the probable time of transmission.[67-70] The epidemiological studies investigated outbreaks that occurred in January and June of 2020, before widespread vaccination coverage and before the emergence of VOCs.

Zhang et al. (2021) investigated a restaurant outbreak in China involving three separate tables aligned with one another over a distance of approximately 6 m. Using video surveillance the authors ruled out close contact and fomite transmission for the secondary cases identified at the two tables the index case was not seated. The authors suggested that transmission was through long-range aerosols.[70] The studies assessing two other restaurant outbreak events report directional airflow as a key factor facilitating long-range transmission.[67-69] In South Korea, a restaurant outbreak involved an index case infecting two secondary cases who sat 4.8 m and 6.5 m away at different tables directly downwind from airflow originating near the index case.[69] In China, an outbreak involved three families at three separate tables, and an air conditioner running which is suggested to have created an “air column” flowing from the index case towards secondary cases who were 3 m away.[67,68] Additionally, it was determined due to cold weather the exhaust fans were closed, resulting in recirculated air indoors.[67,68]

Chaudhuri et al. (2021) (preprint), used mechanistic modelling to examine SARS-CoV-2 transmission by infectious aerosols using real-world occupancy data from full-service restaurants in ten large US cities (March 2020).[71] The authors noted a high degree of heterogeneity among individual levels of infection risk. The heterogeneity was due largely to varying viral loads in index cases and occupancy numbers, leading to overdispersion in numbers of secondary cases. The authors note that high overdispersion is indicative of aerosol transmission at short and long ranges.[71]

HEALTH CARE FACILITIES

Six epidemiological studies investigated SARS-CoV-2 outbreaks in health care facilities and concluded long-range transmission played a role.[72-77] The studies were conducted in Belgium,[77] the Netherlands,[73] South Korea,[75,76] Hong Kong[74] and Israel,[72] and assessed outbreaks that occurred in nursing homes[73,77] and hospitals.[72,74-76] Most studies assessed outbreaks that occurred in 2020,[73-77] one included evidence up to March of 2021,[76] and one did not report the date of the outbreak being studied.[72]

An outbreak in a Belgium nursing home was investigated by Vuylsteke et al. (2021), who reported that long-range aerosol transmission likely contributed to the outbreak originating from a cultural event where an external volunteer was determined to be the index case (tested positive the day after the event). The volunteer visited four units throughout the facility and for three of four participating units the residents gathered in a communal room for the event. Many residents did not wear masks, and an investigation using CO_2 sensors determined the event spaces to be poorly ventilated. Resident ARs differed by unit, with the highest rates around day 6 in the three units who participated by gathering in one room (84.5%, 92.1%, 77.8%), in contrast to the fourth unit which did not gather (52.5%). Staff sources could not be excluded, but this was deemed unlikely as most staff were confined to one unit and all tested negative 4 days before the event. Some residents not present at the event were also infected, the gathering rooms were connected by corridors where residents stroll and some residents who did not take part in the event took coffee in the same room shortly after the event. Aerosol transmission in the crowded and poorly ventilated spaces was reported as the most plausible explanation for the massive intra-facility spread.[77] One additional nursing home study similarly attributed a SARS-CoV-2 outbreak to poor ventilation which facilitated long-range aerosol transmission to 81% (17/21) of residents and 50% (17/34) of health care workers.[73]

Four hospital-based studies described various situations in which interactions between infectious cases and contacts were not considered to be close-contact or short-range, and transmission occurring despite the use of PPE, therefore indicating the likely contribution of long-range transmission. For example, an outbreak occurred in Seoul, South Korea in which 28% (10/36) of secondary cases did not have close contact with the index case and 72% (26/36) had close contact with the index case.[76] Non-close contact interactions included a short conversation while the index case was masked, shared space with the index case without any conversation while masked, and entering a space previously occupied by the index case.[76] Other studies posited unexpected airflow patterns,[72,75] inadequate ventilation[75] and small enclosed rooms[74] as likely facilitators of long-range transmission events observed in hospital units and rooms.

OTHER INDOOR SETTINGS

Eight included studies (four epidemiological,[78-81] one experimental[82] and three modelling[83-85]) investigated the role of long-range transmission in SARS-CoV-2 spread in various indoor settings including a courtroom,[81] exercise facilities,[79,80] travel and quarantine hotel,[78] plumbing systems,[82] a classroom,[85] and two modelling studies did not specify the indoor settings.[83,84]

The SARS-CoV-2 transmission events investigated in the four epidemiological studies took place in 2020.[78-81] All four noted poor ventilation as a likely factor contributing to long-range transmission in a courtroom, various exercise facilities and in a quarantine hotel.[78-81] Additional factors included mask removal while seated in the courtroom and in exercise facilities,[79,81] and in the quarantine hotel a commissioned review of the ventilation system found the hotel rooms exerted positive pressure relative to the corridor.[78] As with most included epidemiological studies, it was not feasible to completely exclude other routes of transmission; however, these studies consistently suggested that close contact and short-range transmission did not adequately account for all of the observed SARS-CoV-2 cases in these outbreaks due to distance or barriers between index and secondary cases, suggesting long-range transmission likely played at least a partial role.

An experimental study of aerosol particle production in plumbing systems conducted in the United Kingdom (UK) reported that 99.5% of particles emitted were <5 µm in diameter, with no particles >11 µm in diameter. The number of particles emitted from a toilet flush was equivalent to a person speaking loudly for 6.5 min.[82] The three modelling studies supported the possibility of infection due to long-range transmission of respiratory particles beyond 2 m distance from an infectious source.[83-85] These suggested that prevention measures beyond physical distancing are necessary to limit infection risk, such as mask wearing and reducing exposure time.

Factors Affecting Short and Long-range Respiratory Particle Transmission

We included five reviews and 27 primary studies that investigated factors affecting SARS-CoV-2 transmission through infectious respiratory particle deposition on mucous membranes and/or through inhalation. Three new reviews and 20 new primary studies were added in this update. Factors are grouped into environmental (indoor conditions) and host/source factors. Source immune status, as well as outdoor ambient climatic conditions, pollution, and particulate matter are out of scope.

Main Findings

The primary environmental factors contributing to increased transmission are low temperatures, low humidity, poor ventilation, improper airflow (i.e., from potential sources to susceptible individuals), and low UV light. Across much of the included evidence, poor ventilation is noted as a particularly important environmental factor that contributes to increased SARS-CoV-2 transmission.[8-14] Inadequate ventilation can contribute to the spread of aerosols, where the buildup of infectious aerosols is inversely proportional to the number of air exchanges. Evidence related to the role of HVAC systems in facilitating transmission between different areas of buildings or cruise ships was inconsistent. In addition, turbulent airflow (e.g., from an individual coughing, improper air flows creating areas of recirculated air) can increase transmission risk.

Decreased relative humidity can increase transmission risk compared to humid conditions due to evaporation contributing to respiratory particles reducing in size, leading to increased volume of potentially virus-laden molecules remaining suspended in the air. Increased humidity, increased temperature and increased UV light are associated with reduced SARS-CoV-2 transmission risk by reducing the amount of particles remaining suspended in the air, and by reducing virus viability. There is also evidence that the impact of these indoor environmental conditions have interacting effects.

Previously, we have noted that humidity seems to have less of an effect on SARS-CoV-2 viability in aerosols compared to the effect of sunlight or temperature.[86,87] The half-life of SARS-CoV-2 in aerosols is approximately 1 hour (h). Increasing temperature is associated with a reduction in the half-life of SARS-CoV-2 in aerosols.[55,88,89] Using a rotating drum experiment similar to other studies for viability of SARS-CoV-2, UV light (UVA/UVB) was applied to aerosolized virus through a window on the drum.[87] Results indicated 90% inactivation of virus within 20 min.

The most important host/source factors contributing to increased transmission are higher viral loads, higher concentration of SARS-CoV-2 in the air, smaller size of virus-laden particles and infectious dose. In terms of behaviour, a lack of physical distancing, increased vocalization and expulsion of respiratory particles (i.e., coughing and sneezing compared to normal talking and breathing), and a lack of masking all contribute to increased risk of transmission.

Reviews

A review by Dinoi et al. (2021) (search up to August 2021) reported that the most important viral and host factors that impact the risk of transmission over long-ranges are: 1) concentration and size of virus-laden particles; 2) fraction of viable virus in the air; and 3) the minimum dose of SARS-CoV-2 needed to cause infection in a susceptible person.[90] Environmental factors act primarily on virus concentration and survivability of virus in the air.[90]

Thornton et al. (2021) (preprint) conducted an overview of reviews (search up to January 2021) to investigate the impact of HVAC design features on transmission of viruses and included seven reviews published between 2007 and 2021.[91] Results indicated that transmission decreased with increasing temperature and relative humidity. One included review found inconsistent evidence related to the role of HVAC systems in the spread of SARS-CoV-2: three observational studies suggested HVAC contributed to spread, two studies of ship outbreaks did not support the role of HVAC in spread, and one study provided modelling evidence of the possibility of HVAC systems contributing to airborne transmission of SARS-CoV-2.[91]

Chen et al. (2021) conducted a systematic review and meta-analysis of 29 studies (search up to August 2020) and a modelling analysis to investigate the impact of respiratory viral load (rVL) on SARS-CoV-2 transmission.[92] The evidence review found that rVL tends to peak at approximately 1 day (d) from symptom onset, and rVL varies widely across cases suggesting some may pose higher risk of transmission (i.e., “super spreaders”). At peak infectiousness, cases with high rVL (i.e., 80th and 90th percentiles), compared to average rVL cases, emit aerosols (defined as $\leq$100 µm) and droplets (>100 µm) with significantly higher likelihoods of containing infectious particles. Modelling results also estimated talking, singing and coughing emitted comparable proportions of infectious particles in droplets (55.6–59.4%) and aerosols (40.6–44.4%), and breathing only emitted aerosols.[92]

Comber et al. (2021) conducted a rapid review of evidence (search up to July 2020) related to the airborne transmission of SARS-CoV-2 which included epidemiological, air sampling and virological primary studies.[55] The authors concluded that aerosol transmission over long-ranges may play a role; however, the contribution of aerosols was uncertain relative to short-range droplet and contact transmission. In a laboratory context, SARS-CoV-2 has been found to remain viable as an aerosol for 3 h and the median half-life is estimated to be 1.1 h (95% CI: 0.6–2.64). Experimental environmental conditions found to impact virus viability include simulated UV light (which de-activated aerosolized SARS-CoV-2) and using high temperature (200°C) in an air filter system to reduce SARS-CoV-2 suspended in the air.[55]

Goodwin et al. (2021) sought evidence (search up to May 2020) to determine which activities increase the risk of indoor SARS-CoV-2 transmission.[93] Results suggest that the number of respiratory particles emitted during respiratory activities increase in the following order: breathing, heavy breathing, speaking, singing, coughing and sneezing, with significant differences in the number of particles between each activity. The size of particles also differs between activities and therefore influences transmission risk. For example, breathing emits small particles that may be inhaled and sneezing emits large particles that may deposit on mucous membranes. Particles expelled by different activities are produced in different areas of the respiratory system and may contain different viral loads. There is consistent epidemiological evidence to indicate close and prolonged contact (e.g., sharing a bed, bathroom or meal; face-to-face contact) increases risk of transmission and supports short-range as the main route. The authors report that there is evidence to support the possibility of long-range transmission but at the time of the search (May 2020) was not conclusive.[93]

Primary Literature

ENVIRONMENTAL FACTORS

VENTILATION

Four epidemiological and nine modelling studies found that inadequate or poor ventilation was an important factor contributing to short and long-range transmission of SARS-CoV-2.[8,9,11,12,14,94-101] In epidemiological and modelling studies of indoor spaces, poor ventilation led to a build-up of respiratory particles that increased the risk of both short and long-range transmission. The primary literature supported short- and long-range transmission being on a continuum, and the concentrations of aerosols were greatest closest to the infectious source and decreased with greater distance.

Three epidemiological and experimental studies highlighted that poor ventilation contributed to long-range aerosol transmission in meat processing plants and a wholesale market (China, Germany, Ireland).[98,100,101] For example, a cross-sectional study by Pokora et al. (2021) investigated COVID-19 outbreaks in meat processing plants in Germany (22 plants, June to September 2020).[100] In seven plants with high case numbers, COVID-19 prevalence was 12.1%, and 16.1% specifically in deboning and meat cutting areas. The main factors related to increased risk of infection were: 1) working in areas with lower temperatures; 2) working in areas without outdoor airflow ventilation; and 3) inability to maintain at least 1.5 m distance from others while working.[100] A similar study in a meat processing plant in Ireland demonstrated that there was a gradual build-up of CO_2 and aerosols in the boning hall over the course of a shift, leading the authors to conclude that poor ventilation favoured aerosol transmission.[101] In the wholesale market in China, authors found while air was circulated, the air was unfiltered and there was very little fresh air, there was high humidity, low temperature, inadequate hygiene supplies and significant contamination of surfaces, all of which contributed to multiple possible modes of transmission including long-range transmission.[98]

In contrast, Xu et al. (2021) analysed the data of 197 symptomatic COVID-19 cases in the Diamond Princess cruise ship outbreak (January to February 2020) and concluded that long-range transmission did not occur between cabins based on the random distribution of symptomatic cases on all decks and the lack of spatial clusters of close contact (within cabin) infection.[99] The authors inferred that most transmission had occurred in public areas before the quarantine, possibly due to crowding and insufficient ventilation in those spaces.

Nine modelling studies assessed factors impacting SARS-CoV-2 transmission via respiratory particles, including ventilation, across a variety of scenarios and parameters.[8,9,11,12,14,94-97] Overall, results supported short- and long-range transmission being a continuum, and the concentrations of respiratory particles were greatest closest to the infectious source and decreased with greater distance. Ventilation was found to be an important measure to mitigate transmission in indoor spaces. For example, Li et al. (2021) investigated indoor short and long-range SARS-CoV-2 transmission via aerosols <50 µm in diameter, and the impact of ventilation on the same.[8] As distance between people decreased from 2 m, a significant increase in the room ventilation rate was required to control short-range aerosol exposure. The risk of infection from both short- and long-range transmission increased as ventilation decreased. Aganovic et al. (2021) used modelling methods to investigate the impact of indoor relative humidity and indoor ventilation on SARS-CoV-2 infection, and concluded that ventilation was a more important factor in reducing infection risk compared to humidity and should prioritized if modifying indoor environmental control measures.[97]

Several modelling studies noted the direction of air flow is an important factor.[11,12,14] Schade et al. (2021) found in a concert hall setting, fresh air flow moving from below seats up to exhaust vents at the ceiling resulted in minimal movement of aerosols to adjacent seats.[11] Ishak et al. (2021) conducted a modelling study to estimate the impact of humidity, air flow speed and masking on airborne transmission via droplets of various sizes (2–2,000 µm) produced by a source sneezing.[12] Air flowing from the area of the source in the direction of the susceptible contact was estimated to increase droplet deposition on humans, and decrease deposition on the ground, possibly increasing transmission risk.[12] de Oliveira et al. (2021) also commented that the direction of airflow can have a significant impact – upward air streams can maintain aerosols at face height significantly increasing infectious risk.[14] It was commonly noted across studies that other measures in addition to ventilation should be implemented to meaningfully reduce risk of transmission (e.g., vaccination, masking, distancing).

TEMPERATURE AND HUMIDITY

Six experimental and modelling studies investigated the impact of indoor environmental factors, including temperature and humidity, on respiratory transmission of SARS-CoV-2.[102-107] Overall, these studies indicated transmission risk was reduced in the context of higher temperature and increased humidity. For example, Liu et al. (2021b) modelled the impact of dry ambient conditions on small droplets which remain suspended in the air for longer times than larger droplets from a cough or sneeze. The authors concluded dry conditions, compared to humid, can increase the volume of airborne potentially virus-laden molecules due to rapid evaporation reducing amount of droplets falling from the air.[107] This finding was supported by other experimental and modelling studies.[103,105,106] Further, an experimental study by Schuit et al. (2021) found the influence of temperature interacted with the influence of humidity.[106] Increased relative humidity increased viral infectivity decay; increasing temperature to 20°C and 40% relative humidity did not significantly increase viral decay, but increasing temperature at 70% relative humidity resulted in significant viral decay.[106]

The initial sizes of respiratory particles influence their trajectory. Leiber et al. (2021) examined evaporation characteristics of saliva droplets.[105] Assessing droplets of different initial size, the final droplet diameter correlated to approximately 20% of the initial diameter. Large droplets (>150 µm) may contain substantial amounts of viable virus but have short lifespans as they quickly drop to the floor. Medium sized droplets (50–150 µm) were more impacted by ambient conditions with lower humidity and higher temperature increasing the airborne lifespan. These may remain in the air for minutes and due to their size may maintain high viable amount of the virus. Small saliva aerosols (<50 µm) may remain suspended in the air for hours, during which any viable virus is estimated to gradually decrease.[105]

One study by Canpolat et al. (2021) (preprint) experimentally investigated very high temperatures incorporated into an air filter system as an option to inactivate airborne SARS-CoV-2.[104] The average reduction in viral presence, compared to the stock virus suspension, at 150°C was 99.900%, and at 220°C was 99.999%. The authors concluded this provides a potential mitigation tool; however, practicality and feasibility would be need to be considered to implement such an approach.

HOST/SOURCE FACTORS

RESPIRATORY ACTIVITY AND BIOLOGICAL FACTORS

Issakhov et al. (2021) used modelling and simulations to study the transport and scattering of particles of various sizes (10^{-4} to 10^{-6}m) that occur when a person breathes, sneezes, or coughs.[108] During normal breathing, particles only travelled short distances; during sneezing or coughing, particles were transported over longer distances. Sneezing or coughing at 20 m/s led to particles travelling more than 3 m in 40 s. Sneezing propagation analysis showed a maximum impact zone of 4.8 m downstream, 1.1 m lateral and 1.8 m horizontal. In this study, host expiratory exertion had an impact on long-range transmission.[108]

Estimates for minimum infectious dose, amount of viable virus in aerosols and quantified exposure rates are lacking. One study assessed super spreading events related to long-range transmission in order to determine a minimum infectious dose for transmission.[109] The model used rate of aerosolized virus shedding based on data from other coronaviruses and a destabilization rate measured for SARS-CoV-2. They reported a critical exposure threshold for aerosol transmission of 50 virions.[109] A computational characterization of inhaled droplets by Basu (2021) reported an estimated inhaled infectious dose around 300 virions, which was similar to estimates of 500 virions for ferrets.[110] The author acknowledged that this estimate could vary widely depending on environmental and individual biological factors.[110]

DISTANCING AND MASKS

Five modelling studies demonstrated that increasing the source-receptor distance and wearing well-fitting masks reduced the risk of short and long-range SARS-CoV-2 transmission.[111-116] Tomshine et al. (2021) performed an experiment where aerosols were simulated using monodisperse polystyrene latex beads at a constant flow rate to mimic near-peak exhalation rates (2 µm diameter particles).[113] The greatest decrease in the number of aerosol particles transmitted from source to receptor is achieved by increased distancing, and masking: with 0.3 m between source and receptor, masking both reduced particles by >99.5%, masking only the source reduced by 99%, and masking only the receptor reduced by 62%. Increasing distance to 0.9 m and 1.8 m greatly reduced transmission even with no masks (84% and 97%, respectively) with the same pattern persisting with masking both or at least the source greatly reducing transmission compared to masking only the receptor.[113] A risk assessment of indoor SARS-CoV-2 aerosol transmission by Rocha-Melogno et al. (2021) used modelling to investigate influencing factors and transmission risk of one contagious person in a classroom, wedding and heavy exercise sessions.[112] Across all scenarios, risk of long-range aerosol transmission increased 309–332% if masks were not worn, and increased 424–488% if masks were not worn in a poorly ventilated room. Increasing ventilation rates and increasing relative humidity both reduced the risk of transmission.[112]

Secondary Attack Rates: Setting and Disease State

Secondary attack rates are useful for assessing the risk of infection based on relative frequency of close contact exposure based on index case-secondary case distance from one another. We use household settings as a proxy for closeness, where we assume there is relatively closer contact between people. In contrast, a proxy for relatively less closeness would be non-household settings such as retail spaces or workplaces. Secondary attack rates are not direct evidence for short- or long-range transmission; therefore, readers should use caution when interpreting these studies.

We examined five systematic reviews (with and without meta-analyses) and nine primary studies that investigated SARS-CoV-2 secondary attack rates in various settings, focusing on households. In this updated version, we included three new systematic reviews and nine primary studies. To ensure robust estimates, we limited included studies to those with >500 index and secondary cases.

Main Findings

In household settings where physical distancing, mask wearing and disinfection of shared surfaces are potentially not feasible, there is a higher risk of infection compared to casual contact settings (17–43% vs. 1–13%, respectively). Secondary attack rates and risk of infection are greater for those exposed to symptomatic or presymptomatic cases, rather than asymptomatic cases. This indirect evidence does not provide clarity to the proportion of transmission events due to short- or long-range transmission.

Reviews

In a systematic review and meta-analysis of 87 studies and 1,249,163 household contacts (search up to June 17, 2021), Madewell et al. (2021) reported that the household secondary attack rate was 18.9% (95% CI: 16.2–22.0).[117] Compared with studies from January to February 2020, the secondary attack rate from July 2020 to March 2021 increased (13.4% [95% CI: 10.7–16.7] vs. 31.1% [95% CI: 22.6–41.1]).[117]

In a systematic review and meta-analysis of 29 studies (search up to August 2020), Curmei et al. (2021) reported that the estimated pooled secondary attack rate for Singapore was 24% (95% CI: 20–28) and 31% (95% CI: 28–34) for Italy.[118]

In a systematic review and meta-analysis of 80 studies (search up to July 3, 2020), Qiu et al. (2021) reported that secondary attack rates varied according to disease state of the index case:[119]

- **Asymptomatic:** 1% (95% CI: 0–2, n=2,240 contacts)
- **Presymptomatic:** 7% (95% CI: 3–11, n=1,678 contacts)
- **Symptomatic:** 6% (95% CI: 5–8, n=50,505 contacts).[119]

In a systematic review of five studies (search up to August 12, 2020), Bulfone et al. (2020) reported that the odds of indoor transmission was 18.7 times (95% CI: 6.0–57.9) higher than outdoor settings, and less than 10% of infections occurred outdoors.[120] Researchers have identified few super-spreading events from exclusively outdoor exposures, likely due to important differences in ventilation, UV light, humidity and possible differences in behaviour.[120]

In a systematic review and meta-analysis of 45 studies (search up to July 6, 2020), Thompson et al. (2021) estimated that the household secondary attack rate was 21.1% (95% CI: 17.4–24.8, 29 studies). Non-household settings had lower secondary attack rates:[121]

- **Social settings with family and friends:** 5.9% (95% CI: 0.3–9.8)
- **Travel:** 5.0% (95% CI: 0.3–9.8)
- **Health care facilities:** 3.6% (95% CI: 1.0–6.9)
- **Workplaces:** 1.9% (95% CI: 0.0–3.9)
- **Casual social contacts with strangers:** 1.2% (95% CI: 0.3–2.1)

Primary Literature

Five epidemiological studies investigated secondary attack rates in various settings in China, Denmark, Japan, Norway and US.[122-126] The primary literature was in agreement with findings from reviews, highlighting that secondary attack rates are higher in household settings, where physical distancing is not always possible. For example, in a study of secondary attack rates among 4,550 contacts of confirmed cases in Japan (July 2020 to May 2021), Akaishi et al. (2021) reported that the highest secondary attack rates were in dormitories (27.5%), followed by households (12.5%).[125] In a national case-control study (317 cases, 300 controls) performed in Denmark (December 2020), Munch et al. (2021) reported that the primary determinants of infection were contact (OR: 4.9, 95% CI: 2.4–10) or close contact (OR: 13, 95% CI: 6.7–25) with a confirmed case.[124]

Four epidemiological studies (Bosnia and Herzegovina, China, US) investigated secondary attack rates from symptomatic and asymptomatic index cases.[127] These results indicated that secondary attack rates are higher when there are symptomatic index cases, which was in agreement with the review literature. In a population-based cohort study of 8,852 contacts of 730 index cases in Zhejiang Province, China (January to July, 2020), Ge et al. (2021) reported an increased risk of infection when contacts were exposed to index cases with mild disease (aRR: 4.0, 95% CI: 1.8–9.1) or moderate disease (aRR: 4.3, 95% CI: 1.9–9.7), compared to asymptomatic index cases.[127] Similar results for asymptomatic and symptomatic secondary attack rates were reported from additional studies, including an increased risk of transmission from symptomatic index cases: China (1.1% vs. 4.1%; OR: 3.8, 95% CI: 2.06–6.95), US (19.1% vs. 25.4%), Bosnia and Herzegovina (OR: 4.3, 95% CI: 1.60–11.63).[128,129]

SARS-CoV-2 in Air Samples

Air sampling for SARS-CoV-2 refers to the process of collecting volumes of air by a device to determine if they contain the virus. Collection can vary by aerodynamic particle size captured, duration of collection, volume per second collected, and media on which samples deposit. Air samples can then be tested by molecular methods such as reverse transcription PCR (RT-PCR) or droplet digital PCR (dd-PCR) to amplify viral nucleic acids and/or viral culture. RT-PCR cannot determine whether the microorganisms detected are viable. Viral culture is used to determine whether a sample contains live virus and is used as a proxy for measuring infectious virus.

We included five systematic reviews and 24 primary studies on testing of air samples for SARS-CoV-2 RNA or viable virus. In this updated version, we have included four new systematic reviews and seven new primary studies. To limit the volume of primary studies included in this review, we limited primary studies to those that tested at least 50 air samples, except where noted (studies attempting to culture viable virus from air samples).

Main findings

The risk of SARS-CoV-2 transmission is highest near the source, as the likelihood of detecting SARS-CoV-2 RNA in air samples is greater as the source-receptor sampling distance decreases. Culturing of viable virus from air samples is relatively uncommon; however, unsuccessful culturing does not indicate an absence of viable virus. SARS-CoV-2 is present in a wide range of air particles sizes, particularly those less than 5 µm in diameter, implying that they remain in the air for longer periods and can travel further distances from the source patient. Overall, air-sampling data supports that aerosol transmission is plausible at both short and longer distances; however, virus-laden aerosols are relatively diluted and therefore less infectious during transient or distant exposures.

Reviews

In the most recent systematic review and meta-analysis of 73 studies (search up to August 31, 2021), Dinoi et al. (2021) synthesized evidence investigating airborne SARS-CoV-2.[90] Viral concentrations were higher in health care settings compared to non-health care indoor settings, but both indoor settings had greater concentrations than outdoor settings. The authors concluded that in outdoor settings, virus particles were quickly dispersed and SARS-CoV-2 RNA is generally low or undetectable. Factors influencing indoor concentrations of SARS-CoV were room air volume, ventilation systems, distance from infectious patients, number of infectious patients, and the use of masks.[90]

- **Outdoor settings:** 33.3% (3/9) of studies reported at least one RNA-positive air sample, with a RNA positivity rate of 17.6%. The concentration range ranged from 0.1–23 copies/m^3, with an average of 7.9 copies/m^3 (median: 7.2).[90]
- **Indoor health care settings:** 60.3% (35/58) of studies reported at least one SARS-CoV-2-RNA-positive positive air sample, with a RNA positivity rate of 22.8% (median: 11.1). The median RNA concentration was 540 copies/m^3 (interquartile range [IQR]: 17.5–2,890). [90]
- **Indoor, non-health care indoor settings:** 30% (3/10) of studies reported at least one RNA-positive air sample positive (range: 11.1–64.3%). The average RNA concentration was 1,857 copies/m^3 (range: 14.5–3,700).[90]

In a systematic review and meta-analysis of 51 observational cross-sectional studies (search up to June 1, 2021), Ribaric et al. (2021) reported on air and surface contamination in hospital settings.[130] SARS-CoV-2 RNA was detected significantly more often in patient areas compared to non-patient areas (19.4% vs. 11.8%, p<0.001), with significantly more virus present (4.4 copies/L air vs. 0.7 copies/L air, p<0.001). The odds of detecting RNA in air samples decreased if samples were collected ≥2 m from patients (14.5%, n=276 samples), compared to <2 m from patients (20.9%, n=470 samples) (OR: 0.5, 95% CI: 0.43–0.96). 7.1% (7/98) of air samples had viable virus and included air samples collected from 2 m and

4.8 m away from patients. RNA positivity was significantly higher in fine aerosols (≤4 µm) compared to coarse aerosols/droplets (>4 µm) (18.3% vs. 11.6%, p=0.049). The odds of detecting RNA in air samples increased if taken in patient areas (vs. non-patient areas, OR: 1.8, 1.16–2.78) and where AGMPs were performed (vs. no AGMPs, OR: 2.6, 1.46–4.51).[130]

In a systematic review and meta-analysis of 25 studies of workplace settings (search up to December 24, 2020), Cherrie et al. (2021) reported a median SARS-CoV-2 RNA positivity of 6.6% (sample range: 2–135) in air samples.[131] Viable virus was cultured from air sample collected in 10% (1/10) of the primary studies. In 22 studies that performed both surface and air sampling, the positivity rate of surface samples increased as the positivity rate of air samples increased.[131]

Aghalari et al. (2021) conducted a systematic review of evidence investigating SARS-CoV-2 transmission through indoor air in 11 studies of hospitals (search up to October 1, 2020).[132] Seven studies reported at least one SARS-CoV-2-RNA-positive air sample, in which some positive samples were collected >1.5 m from patients. The authors concluded that the presence of SARS-CoV-2 in hospital air was affected by factors such as: indoor environmental conditions, sampling methods, sampling height and distance from patients, flow rate, sampling duration, efficiency and functionality of ventilation systems, the use of disinfectants and the amount of particles in the air.[132]

In a scoping systematic review and meta-analysis of 24 cross-sectional observational studies conducted in health care settings (search up to October 27, 2020), Birgand et al. (2020) reported that 17.4% (82/471) of air samples from patient environments were RNA positive (there was no difference in positivity at ≤1 m [2.5%] or 1–5 m [5.5%] distance from patients, p=0.22).[133] When culturing was attempted, viable virus was detected in 8.6% (7/81) of samples. Aerosol particle size peaked in the <1 µm fraction in patient rooms and PPE change rooms, compared to the >4 µm particle peak size in staff offices.[133]

Primary Literature

The primary literature was in agreement with results from reviews, noting that there is inconsistency in which particle size fractions contained the most SARS-CoV-2, detection of viable virus in air samples and the distance from patients at which SARS-CoV-2 RNA and viable virus were detected.

The majority of air samples collected air particles ≤5 µm in diameter (n=12 studies), followed by unknown (n=6), all particle sizes (n=6), ≤10 µm (n=5), >10 µm (n=2), >5 µm (n=1), <20 µm (n=1), and <100 µm (n=1) (multiple sizes investigated in several studies).[134-157] Due to the wide range of methods used among the studies, it was not possible to generalize which particle size fractions contain the most SARS-CoV-2 RNA, yet this observation in itself implies that SARS-CoV-2 likely exists on a wide range of particle sizes. In a study of 99 rooms (n=138 air samples) in health care and correctional settings (Ontario, Manitoba), Mallach et al. (2021) reported that there was no significant difference in RNA positivity among particle sizes (2.5 µm: 9.1% [6/66]; <10 µm: 13.5% [7/52]; all sizes >0.5 µm: 10.0%, [2/20]; p=0.74).[148] In an experiment measuring viral concentrations after breathing, talking and singing in 19 patients with COVID-19 in Singapore (February to April 2021), Coleman et al. (2021) reported that particles ≤5 µm in diameter comprised 85.4% of the total viral RNA load emitted by participants, compared to particles >5 µm in diameter.[149]

From the 11 primary studies with RNA positive air samples, the relationship between distance and positivity was inconsistent.[134,136,138,139,145,146,148,149,151,153,157] In a study performed in a hospital (Ahvaz, Iran), air samples collected 1 m or 3 m away from patient beds were SARS-CoV-2-RNA positive (11.8%, 6/51) (Baboli et al. 2021).[145] Four of the positive samples were collected from patient rooms and two were from hallways, possibly indicative of long-distance transmission. A study by Guo et al. (2020) in Wuhan, China (February to March 2020) detected SARS-CoV-2 RNA in 35% (14/40) of air samples in an ICU and 12.5% (2/16) of air samples in the general ward that managed patients with COVID-19.[136] Fifteen of the 16 RT-PCR-positive air samples were collected ≤2 m of patients, with one positive sample collected 4 m away from patients. In a study of air samples within a hospital (naturally ventilated open wards, mechanically-ventilated isolation wards) in Singapore (February to May 2020), Ang et al. (2021) reported that SARS-CoV-2 RNA was detected in 50% (6/12) of samples collected ≤0.9 m from patients, 54% (7/13) at 2.5–5.5 m, and 0% (0/2) at 9.8–13.3 m.[157]

Five studies failed to culture viable SARS-CoV-2 from RNA positive air samples when attempted,[141,146,148,149,157] while six studies successfully cultured viable virus from air samples.[134,135,142-144,146] In a study of SARS-CoV-2 RNA in size-fractioned aerosols from six patients (April 2020, Nebraska, US), Santarpia et al. (2021) reported RNA and viable virus was cultured from all fractionated samples: <1 µm (3/6 samples with viable virus), 1–4 µm (2/6), >4.1 µm (1/6).[144] Lednicky et al. (2021) detected viable SARS-CoV-2 from the front passenger seat of a car driven by a patient without cough symptoms (study date not reported, Florida, US).[142] The air sampler operated while the patient drove for 15 min with the windows up and air conditioner on, and for an additional 2 h. Viable virus was cultured only from the 0.25–0.5 µm fraction, which also had the highest quantity of detectable copies of viral RNA.

Increased Transmissibility of Variants of Concern (VOCs)

Previously, PHO assessed potential mechanisms for the increased transmission of VOCs; however, there is still no evidence for fundamentally different routes of transmission for Omicron or other VOCs.[15,16] Evidence has emerged that other VOCs, such as Delta, have higher aerosol and surface stability, meaning that Delta may be more easily transmitted via long-range aerosols and fomites, respectively. [15,17,18] There is evidence that Omicron has similarly higher surface stability, but aerosol stability remains unknown.[158]

Household attack rates for Delta and Omicron are higher than wild-type SARS-CoV-2 or other VOCs, as evidenced in three epidemiological studies (UK, Denmark) and a simulation study. [15,159-162] These studies demonstrated the increased transmissibility of Delta and Omicron and the increased risk of close-range transmission (households used as a proxy); however, these studies did not rule out long-range transmission. The UK Health Security Agency (2021) reported an increased risk of household transmission from Omicron index cases compared to Delta index cases (aOR: 3.2, 95% CI: 2.0–5.0).[162] There was an increased risk of a close contact becoming a secondary case (aOR: 2.1, 95% CI: 1.54–2.79) and the household secondary attack rate of Omicron was 21.6% (95% CI: 16.7–27.4), compared to Delta (10.7%, 95% CI: 10.5–10.8). In a simulation study, Mikszewski et al. (2021) estimated that more than twice as many Delta cases infected their close-proximity (0.8 m) contacts (64–69%) versus wild-type cases (29%).[160] In addition, the overdispersion parameter (k) was higher for Delta (0.49) compared to the wild-type strains (0.13) (high overdispersion is potentially indicative of long-range transmission).

Three epidemiology studies (Hong Kong, New Zealand) in quarantine facilities demonstrated potential Delta and Omicron long-range transmission through aerosols.[20-22] Gu et al. (2021) reported on the detection of SARS-CoV-2 Omicron in an asymptomatic, fully-vaccinated traveller (Case A) in a quarantine hotel in Hong Kong, China (November 2021), along with potential transmission to a fully vaccinated traveller (Case B) in a room across the corridor.[22] Hotel closed-circuit television footage confirmed neither case left their rooms during the quarantine period, and only opened their doors to pick up meals delivered to their rooms. The authors suggested that airborne transmission across the corridor was the most probable mode of transmission. Wong et al. (2021) reported on results of air flow tests performed at the quarantine hotel in Hong Kong mentioned above.[20] When Case A opened their door, air flowed from the room to the hall to Case B's room. In case B's room, environmental sampling (three days after transfer of case) detected the identical Omicron strain of Case B on a non-reachable portion of the ceiling (2 m height). The width of the hall was 1.5 m, but the distance between doors was not reported.[20] A similar study in New Zealand, demonstrated long-distance aerosol transmission (2 m) of Delta across a hall in a quarantine facility.[19]

Limitations of Included Studies

Epidemiological and contact tracing studies were limited by small samples sizes and the retrospective nature of the studies. In addition, not all contact and exposure between sources and receptors were known (mostly self-reported), meaning that there could have been other modes of transmission involved at different distances. In most epidemiological studies, researchers did not perform WGS, making it difficult assess transmission links and potential routes of transmission. Not all contacts of index cases were tested; therefore, there might be underestimation of attack rates. Much of the primary literature that attempted to document short or long-range transmission did not include index/secondary case behaviors (mask wearing, talking, coughing) or viral loads, both of which would affect transmission distance and risk. Due to recall bias, it was not always possible to determine the timing and location of exposures. In epidemiological studies, authors did not investigate all possible distances from sources and few investigated airflow or ventilation.

For experimental modelling studies, we should mention several limitations. In particular, there were uncertainties associated with several parameters used in these studies, such as infectious dose and viral loads emitted by sources. Simulating expiration of particles from a source is complicated and any model or simulation will not reflect real word complexities. In most cases, researchers simplified scenarios to test their hypotheses, while noting that future studies need to address some of the complexities in these types of studies.[163]

There were limitations to secondary attack rate studies, including self-reporting of data by index and secondary cases, such as symptom and contacts data. Studies used variable definitions of contact and close contact, likely impacting comparability between studies. There was likely recall bias in studies, with better recall for household contacts than non-household contacts or for symptomatic cases, which likely had a longer time to prepare for questions of exposures and contacts. There was likely misclassification of cases as index cases or secondary cases; e.g., if the index case has a long incubation period compared to contacts, cases could be misclassified. If there are a higher number of asymptomatic cases or cases not tested by RT-PCR in a given study, then authors might have missed these cases in their analyses and under-estimated secondary attack rates. Finally, most studies used samples of convenience; therefore, findings may not have been applicable across all populations.

In air sampling studies, there was no standardized method for quantifying SARS-CoV-2 RNA, making it difficult to compare results across studies. Quantifying RNA was further complicated in that most studies did not report a LoD and excluded quality controls. Detection of SARS-CoV-2 RNA used a variety of RT-PCR conditions and target genes (e.g., RNA-dependent RNA polymerase [RdRp], nucleocapsid 1 [N1], nucleocapsid 2 [N2], envelope [E], open reading frame 1ab [ORF1ab]). In addition, studies sampled a variety of volumes over variable periods, with different samplers with variable sensitivities (e.g., multi-stage impactor, centrifugal sampler, MD8 portable sampler) and filters (e.g., quartz fiber, polytetrafluoroethylene [PTFE], polycarbonate, gelatine). Future studies should standardize methodologies, using widely accepted samplers and sampling protocols with standard volume collection and duration of collection. Sampling protocols should collect a specified fraction of particle sizes, and report collection efficiencies with lower and upper size limits where appropriate. Recently, researchers have performed studies to standardize and optimize the collection of SARS-CoV-2 in air samples, including the detection of RNA and viable virus.[164,165]

Further research is needed to reconcile differences in viral RNA detection and virus viability in air samples. In most cases, correlation between C_t values and culture viability was study-specific, due to variable gene targets used and RT-PCR conditions. Differences may have been due to several factors, including: 1) air sampling devices potentially not capable of maintaining viability of captured virus; 2) timing of air sampling varies by time since onset of symptoms, severity of disease or viral load; and 3) the conditions of ventilation (engineering controls) reducing concentrations of viral aerosols to undetectable levels. Culturing SARS-CoV-2 is technically challenging and labour intensive; therefore, the lack of positive cultures does not necessarily indicate an absence of infectious virus.

Conclusions and Future Directions

As evidenced through epidemiological and experimental/modelling studies, SARS-CoV-2 transmission occurs via a spectrum of respiratory particle sizes through direct deposition on mucous membranes and through inhalation at both close and long range. As a result, dichotomizing SARS-CoV-2 transmission as either droplet or aerosol does not accurately reflect this spectrum. In fact, infection can occur by multiple routes and particle sizes depending on the context related to source, receptor and environmental conditions. Other respiratory viruses, like influenza, have similarly been described to demonstrate a spectrum of respiratory particle sizes contributing to transmission.[166,167]

There is a higher risk of SARS-CoV-2 transmission with close (<2 m), unprotected (lacking multiple prevention measures), and prolonged exposure to an infectious individual. The risk of transmission at longer distances increases when there is inadequate ventilation or with recirculation of unfiltered or untreated air, with activities involving increased expulsion of aerosols (e.g., shouting, coughing, exercising), and a lack of source control masking and physical distancing.[23-30] With more aerosol transmission, comes the need for the use of well-fitting medical masks or respirators, and optimized filtering efficiency.[23,24,168] Defining measures or cutoffs for inadequate ventilation were not possible based on the available descriptions of the contexts in which inadequate ventilation was reported to contribute to transmission. However, they included situations where air is circulated without filtration or exchange with fresh air, where there is no ventilation (e.g., windowless rooms without a ventilation system), and where the size of the room and ventilation rate relative to the quantity of infectious aerosols generated exceeds an unknown threshold of risk for infection. Some VOCs may be more effectively transmitted across all modes of transmission; however, there is no evidence that any VOC transmits by fundamentally different routes.[169-171]

The delineation of relative contributions of particle sizes and exposure routes to overall transmission patterns is complicated by dynamic source/receptor factors and pathway factors. For example, each infector/infectee interaction is affected by source activities and the source's viral load (e.g., forceful expulsion of respiratory particles during coughing or singing, timing in the course of illness), source/receptor adherence to preventative measures in place (e.g., physical distancing, mask-wearing, ventilation), and pathway factors (e.g., air flow, UV light, temperature, humidity).[172]

Rutter et al. (2021) developed an expert-based and interactive infographic that visualizes SARS-CoV-2 transmission routes and estimates risk of infection.[31] The infographic is scenario-based, allowing the user to modify a suite of factors for source and receptor, including activity (talking, coughing), location (indoor room, outdoors), distance between source and receptor (>2 m, <2 m), ventilation (on or off), physical contact (shared table, direct contact), surface type (metal, paper), face covering (surgical, cloth, FFP3) and hand hygiene (yes, no). This work complements the evidence of multiple contextual factors that affect transmission and the importance of multiple layers of prevention needed to mitigate transmission.

Studies related to identification of a specific mode of transmission are generally low quality. Moreover, different fields (e.g., epidemiology vs. modelling) can be at odds with respect to conclusions drawn about the role of different sized respiratory particles in short-range transmission and relative importance of long-range transmission events. Ongoing study is needed on the quantity of viral particles required to cause infection, along with the viability of SARS-CoV-2 in aerosols. Lastly, elucidation of setting-specific risk factors for transmission (e.g., differences between source/receptor and pathway factors in health care settings, residential buildings, schools, warehouses, transportation) may provide further insight into mechanisms of transmission and effectiveness of control measures.

The COVID-19 pandemic has identified the importance of interdisciplinary collaboration towards understanding and having a common lexicon for describing virus transmission.[173-175] When the analysis and interpretation of data are challenged by variable terminology used between and within public health, clinicians, aerosol scientists and the public, this can limit progress towards identification and application of appropriate mitigation measures.[173]

Implications for Practice

This document summarizes the evolving evidence on SARS-CoV-2 transmission through respiratory particles. The evidence supports the importance of incorporating multiple infection control layers to mitigate transmission. Translation of this information into recommendations for control measures also requires consideration of other evidence not reviewed in this document, on population-level effectiveness of control measures: 1) effectiveness of measures in isolation and in combination as layered mitigation; 2) effectiveness in the community versus health care settings; and 3) effectiveness considering the impact of implementation fidelity, which may vary widely across individuals and groups.

The bulk of disease transmission occurs in settings with crowded indoor conditions that have poor ventilation and where people are not wearing masks.[168,176,177] As SARS-CoV-2 transmits early in the course of infection, most commonly in the asymptomatic or presymptomatic period and within the first two days of symptom-onset, cases may not seek health care during their most transmissible phase.[178-182] In all settings it is necessary to utilize multiple control measures to mitigate the dynamic transmission factors and address potential routes of transmission. PHO previously made recommendations for IPAC measures in health care settings.[38,39] These documents integrate the existing evidence around different modes of transmission with jurisdictional experience with control measures and outbreak management to date, and recommends the use of the hierarchy of hazard controls to reduce the risk of transmission.

Until we have a better understanding of Omicron transmission, we recommend a cautious approach that underlines the importance of layered measures to prevent SARS-CoV-2 transmission, with the aim of reducing morbidity and mortality. Several resources exist for community guidance (e.g., non-health care workplaces, public and private spaces) on how to reduce the risk of SARS-CoV-2 transmission through a layered approach of multiple public health measures designed to mitigate transmission.[32-34]

The cornerstone of a layered approach to preventing SARS-CoV-2 is a combination of measures to mitigate exposure particularly in settings with the “3 C’s”: closed spaces, crowded places, and close contact. The degree to which various mitigation layers are necessary or possible will depend on the setting and risk context, noting that not everyone can avoid the 3 C’s. Irrespective of the relative contribution of respiratory particle sizes, transmission can be reduced through layered measures: getting vaccinated; staying home if you have symptoms of COVID-19 or if you have been exposed to someone with SARS-CoV-2 infection; limiting the number and duration of contacts with individuals outside your household, particularly indoors; physical distancing and avoiding crowded, indoor spaces; improving indoor ventilation and/or filtration; wearing a mask (non-fit tested respirator, medical mask, or well-fitted 3-layer non-medical mask); and performing hand hygiene, respiratory etiquette and environmental cleaning.

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