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Understanding transmission of SARS-CoV-2 in the ongoing COVID-19 pandemic

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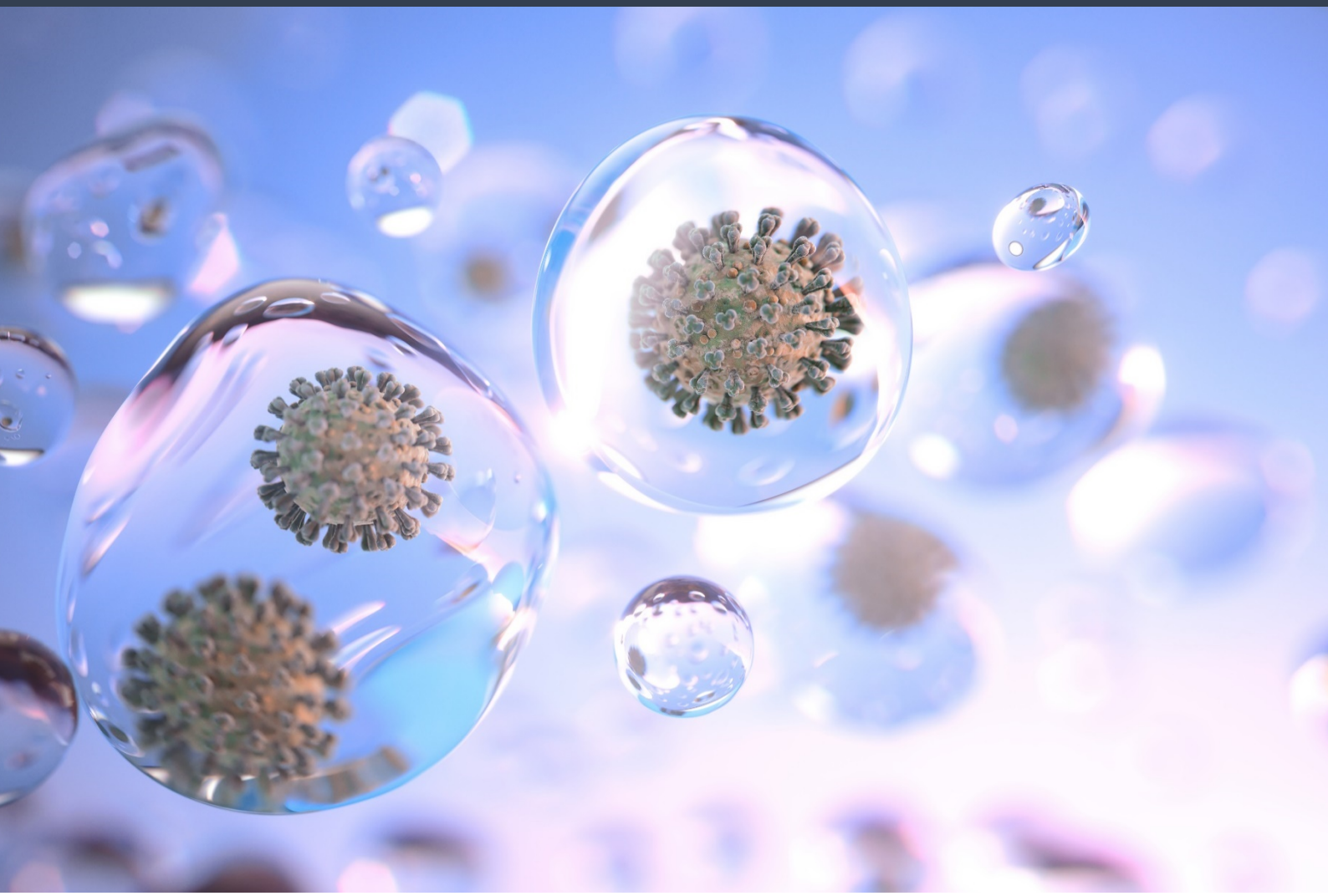

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Introduction

The emergence of a novel coronavirus in late 2019, identified as SARS-CoV-2, has resulted in a global pandemic accompanied by an unprecedented public health response. This review of the properties of SARS-CoV-2 and how it is transmitted outlines some of the evidence that currently forms the basis of the ongoing public health response.

This document has been updated from previous versions published in 2020 (April, July, and November) previously titled "An introduction to SARS-CoV-2", and in January and March 2021, titled "The basics of SARS-CoV-2 transmission". This update reflects new findings and additional information about the virus available at the time of writing that may be relevant to the public health response. The evidence presented below is based on current knowledge and characteristics of the dominant variants of the virus known to be circulating globally and will continue to be updated as new evidence and interpretations emerge.

Key Messages:

- The originally circulating strain of the SARS-CoV-2 virus is no longer prevalent in Canada, with the Delta variant of concern (VOC) being the dominant strain since mid-2021, and the highly transmissible Omicron VOC gaining prevalence since emergence in late 2021.
- Continued surveillance for emerging variants is needed to detect those that are more transmissible, more virulent, evade natural or vaccine-related immunity, evade detection by available tests, or are less responsive to treatment.
- The increase in transmissibility of currently circulating variants means a susceptible person may be infected more efficiently than before. Infection may result from a short but intense exposure or following prolonged or repeated exposure to a smaller dose over time.
- While the rates of transmission for VOC have increased, the routes of transmission remain the same, with exposure to the respiratory emissions of an infected person being the primary route.
- Most people infected with SARS-CoV-2 will experience symptoms at some point, but transmission can occur in the absence of symptoms, with infectiousness being highest just before, or at, the time of symptom onset.

- The estimated proportion of asymptomatic persons and their relative contribution to transmission varies widely in the literature. Asymptomatic transmission is more common among close contacts and is more likely to result in asymptomatic secondary cases than transmission via symptomatic index cases.
- Currently circulating VOC do not appear to be more persistent in the environment compared to previous strains, and generally persist better under cool, dry, low ultraviolet (UV) conditions.
- The range and frequency of COVID-19 symptoms experienced for VOC infections is similar to non-VOC infections but may be more severe and persist for longer.
- Rates of transmission among children are higher where the level of community transmission is high, and the level of community vaccination is low.
- Vaccination is associated with a lower likelihood of infection and transmission to others. For breakthrough cases, vaccination reduces the incidence and duration of symptoms and significantly reduces the risks of severe illness, hospitalization, and death due to COVID-19.
- Increased transmissibility of VOC, particularly the Omicron variant, implies that risks from all routes of transmission may be heightened and there is a need to continue to apply public health measures that reduce transmission by the known routes, with layering of public health measures and pre-emptive strategies to reduce transmission.

SARS-CoV-2 and genetic variants

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is responsible for the illness COVID-19. Coronaviruses are genetically distinct from viruses that cause influenza. They are enveloped, single-stranded RNA viruses, the surfaces of which are covered by a halo of protein spikes, or "corona." Other coronaviruses that have caused significant and lethal outbreaks in the past 20 years include SARS-CoV-1 and MERS-CoV that cause SARS and Middle East respiratory syndrome (MERS), respectively.

Phylogenetic (evolutionary) analysis has helped to establish that the original (wild-type) strain of SARS-CoV-2 emerged in the human population in November 2019. Since then, continued analysis of the genome in COVID-19 cases from around the world has been used to track the evolution of the virus. The rate of mutation observed for SARS-CoV-2 is significantly lower than for influenza, but similar to other coronaviruses.[1-3] Thousands of mutations in the SARS-CoV-2 genome have emerged over the course of the pandemic. Not all mutations proliferate, and many lineages will die out, but the increasing frequency of some variants indicates that they have a selective advantage such as increased transmissibility (e.g., spreads more quickly), or virulence (e.g., causes more severe disease).[4-8] The most concerning variants

may be more transmissible, more virulent, evade natural or vaccine-related immunity, evade detection by available tests, or are less responsive to treatment.[9]

Naming SARS-CoV-2 variants

Monitoring has been ongoing to inform how variants are spreading geographically and whether new variants that emerge are a cause for concern.[10-14] The Public Health Agency of Canada (PHAC) defines **variants of interest (VOI)**, or **variants of concern (VOC)** as described in Box 1.[15] VOI have the potential for impact, whereas VOC have demonstrated impact.[3] A new naming convention was established by the WHO in May 2021 using the Greek alphabet for VOI and VOC.[16]

Box 1: PHAC definitions of variant of interest (VOI) and variant of concern (VOC):

Variant of Interest (VOI) (e.g., Eta, Iota, Kappa, Lambda)

- has a genome with mutations associated with changes in epidemiology, antigenicity, or virulence, or changes that potentially have a negative impact on available diagnostics, vaccines, therapeutics, or public health measures;

  and
- is known to cause community transmission/multiple COVID-19 cases/clusters in Canada or has been detected in multiple countries;

  or
- is otherwise assessed to be a VOI by the World Health Organization (WHO) or the Canadian SARS-CoV-2 Variant Surveillance Group (CSVSG)

Variant of Concern (VOC) (e.g., Alpha, Beta, Gamma, Delta, Omicron)

- A SARS-CoV-2 variant is a VOC if, through a comparative assessment, it has been demonstrated to be associated with one or more of the following:
  - increased transmissibility or detrimental change in COVID-19 epidemiology;
  - increased virulence or change in clinical disease presentation;
  - decreased effectiveness of available diagnostics, vaccines, therapeutics, or public health measures;

  or
- is otherwise assessed to be a VOC by the WHO or the CSVSG.

The US Centre for Disease Control and Prevention (US CDC) has an additional category of **variants of high consequence (VOHC)**, which includes VOC that may be less susceptible to control by prevention or medical countermeasures compared with previous variants.[9] These variants may evade detection by diagnostic tests, demonstrate significantly reduced vaccine effectiveness, have reduced susceptibility to

therapeutics, or cause more severe disease. At the time of writing there have been no variants designated as VOHC. Some VOC may be de-escalated when they are no longer circulating or having an impact on the epidemic, such as the previous VOC Alpha, Beta, and Gamma in the US, which, at the time of writing had been reclassified as **variants being monitored (VBM)** by the US CDC.[9,17]

Processes that give rise to SARS-CoV-2 variants

The greater the number of active SARS-CoV-2 infections globally, the greater the potential for new mutations with some of the characteristics of VOI or VOC to arise.[3] More than one mutation may be contributing to the competitive advantage of a VOC, but not all variants that increase in frequency are necessarily more harmful. Some may spread more rapidly by chance among a particular group (e.g., those with a large number of contacts or high activity levels) or geographical location, and can be affected by travel between regions.[3]

Immunocompromised persons and those with underlying health conditions are at greater risk of developing severe illness from SARS-CoV-2 infection and may have a prolonged course of infection and maintain a higher viral load. This can favour mutation of the virus, and the virus can evolve rapidly in immunosuppressed patients who suffer from persistent SARS-CoV-2 infection.[18-20] This has implications for heightened precautions for care of immunocompromised persons in hospital to prevent transmission in the community.[19] Broad-coverage vaccination has been shown to significantly reduce the incidence of infection with currently circulating variants and, by association, can reduce the opportunity for new mutations to arise. While some variants show weaker inhibition by neutralizing antibodies, mRNA vaccines recognize different parts of the spike protein, such that a single mutation will not necessarily result in substantially reduced protection.[3] Modelling has indicated that a rapid rate of vaccination can decrease the probability of vaccine-resistant variants emerging, but relaxation of non-pharmaceutical interventions too early, before vaccination roll-out is near complete, may undermine this effect.[21]

SARS-CoV-2 transmission dynamics

Rate of transmission

The basic reproduction number for a contagious disease, or the R_0 value, estimated at the beginning of an outbreak, indicates the number of secondary cases that can be infected by a primary case in a population with no underlying immunity, vaccine, or preventive measures. Where R_0 is greater than 1, the number of infected persons is likely to increase. Over time, the effective reproductive number (R_t) changes as more people are infected and public health measures are implemented or as new variants with different levels of transmissibility emerge. The goal of public health interventions is to bring the R_t below 1, which would indicate that the outbreak is declining and will eventually die out.[22] The R_t at any

point in time is an average and can vary depending on the patterns of local transmission.[23,24] The estimates of R_t are improved where there is widespread testing. Monitoring the change in R_t can help to evaluate the effectiveness of public health measures, including vaccination.[25]

For SARS-CoV-2, the preliminary WHO estimate of R_0 was 1.4–2.5[26] with subsequent research estimating the mean R_0 at 3.28 for the originally circulating virus.[27] All circulating VOC have a higher R_t in comparison to the original strain of the virus.[28-30] The R_t of the Delta variant is much higher than previously circulating VOC, and is estimated to be approximately double that of the original strain (e.g., approximately 6–7).[31-33] The R_t of the Omicron variant is being investigated, however initial indications suggest in may be even more transmissible than Delta. Mutations that allow the virus to enter the cell more efficiently and begin replicating sooner and faster can lead to higher rates of transmission.[32,34,35] An increased rate of transmission is faciliated by:

- **Shorter incubation time** (time between exposure and the beginning of infection): The incubation period for VOC Alpha and Delta has been estimated to be about two days shorter (e.g., 3–4 days)[32,36-38] compared to non-VOC (5–6 days),[39,40] meaning infected persons can potentially start transmitting the disease earlier.
- **Shorter serial interval** (time between symptom onset in successive cases in a chain of transmission): The serial interval for Delta has been estimated in one study to be approximately 2.5 days compared to 4 days for the previously circulating strain, suggesting chains of transmission progress faster.[34]
- **Higher viral load** (the quantity of viral particles per unit of bodily fluid in the infected person)**:** Higher viral loads have been observed tor Delta cases compared to non-VOC infections, with one study estimating these to be up to 1260 times higher.[32,36] This increases the dose of virus to which a susceptible person may be exposed.

The incubation time and serial interval for Omicron are still under investigation, but initial evidence of a greater level of transmissibility for Omicron suggests these may be shorter. The impact of Omicron infection on viral load is also still under investigation.

Infectious dose

Exposure to a few viral particles is unlikely to result in infection, but the precise dose needed to cause infection is unknown and may vary from person to person. Experimental studies in non-human primates and rodents show a range of estimates that may differ by the route of transmission (e.g., inhalation versus intranasal or ocular inoculation) and the particle size.[33,41] Based on these findings, and experimental studies on humans for other coronaviruses, a median dose between 10 and 1000 viral particles (plaque-forming units, PFU) has been proposed, with estimates from primate research indicating that approximately 36-179 viral particles is required to cause infection via inhalation.[33] Modelling based on five superspreading events (pre-Delta variant) estimated the number of virions required to cause an infection to be between 300-2000 viral copies, similar to Influenza A.[42] The likelihood of infection can depend on the viral load of the source, the route of infection, and the immune response of the exposed

person.[41,43-47] An infectious dose may result from a short but intense exposure to a high concentration of virus or following prolonged or repeated exposure to a smaller dose over time.[42] Exposure to a higher dose can result from both the duration and the type of contact with an infected person.[48] Mutations that allow for more efficient entry of the virus into host cells, or result in a higher viral load in infectious people, may reduce the time needed to receive an infectious dose. There is also some evidence to suggest that severity of disease may be influenced by the magnitude of the exposure dose.[48-50] Human challenge trials are being conducted in the UK to determine the minimum dose needed to cause infection, but no results have been reported to date.[51]

Infection risks are greatest for individuals who are elderly, obese, smokers, immunosuppressed, or have a pre-existing condition such as diabetes, hypertension, heart disease, or cancer, as these individuals are at the greatest risk of requiring hospitalization or dying from COVID-19.[33,52-54] Persons with conditions that involve multiple comorbidities may be at heightened risk of COVID-19-related hospitalization or death.[55] While pregnant women do not appear to be at heightened risk of SARS-CoV-2 infection compared to the general population, those who do experience symptomatic infection have higher risks of serious outcomes and may experience pregnancy impacts.[56,57] Evidence suggests that these effects are more severe with Delta variant infection compared to previous variants.[57] Some groups may also be disproportionately affected by COVID-19 as a result of existing health inequities related to socioeconomic factors.[58]

Timing of transmission

Most people infected with SARS-CoV-2 will experience symptoms at some point; however, an infected person can transmit the virus to others both before they show any symptoms (pre-symptomatic) and when they are symptomatic. Peak infectiousness is thought to occur about one day before symptom onset, when viral load is at its highest,[33,59,60] but infected persons can potentially infect others several days before and after symptom onset,[59,61,62] with most transmission occurring during the early stages of symptomatic disease.[63-67] Ge et al.[62] estimated that the transmission potential between index patients and close contacts was greatest in the first two days before and three days after symptom onset (non-VOC). The period of infectiousness may be slightly longer for VOC. Kang et al.[32] estimated that for the Delta variant, infectiousness peaked about 2.1 days before symptom onset; however, high viral loads were maintained between four days before symptom onset to seven days after. The period of infectiousness may be shorter for children.[68]

Viral loads are generally higher in symptomatic compared to asymptomatic people (infected persons who never display symptoms), suggesting symptomatic transmission is more efficient.[68] Persons with a high viral load generally have more severe disease and shed virus over a longer period than mild cases. There is some variability in measured viral load among individuals, however, which can vary by age, and some individuals with high viral load may experience no symptoms.[69,70]

Evidence from pre-VOC studies indicated that most cases are not infectious beyond eight to ten days after symptom onset.[71-76] In a small number of severe to critical cases, infectious virus has been detected for more than 30 days.[72] Persons who have been infected with COVID-19 may continue to shed virus beyond the period of infectiousness and after symptoms have resolved.[71,73,74] Persistent shedding of viral RNA may be responsible for some patients testing positive again after an apparent negative RNA test.[74,77] Reinfection with SARS-CoV-2 is possible, and genomic analysis has been used to distinguish between persistent shedding due to the original infection and the presence of a new infection, which has occurred in a small number of cases.[78,79] While reinfection remains rare, there is evidence that those who have recovered from previous SARS-CoV-2 infection have an increased risk of reinfection with the Delta variant compared to Alpha, for previous infections that occurred ≥ 180 days earlier.[80,81]

As infection progresses, the quantity of virus contained in droplets and aerosols expelled by an infected person will vary by the viral load in various parts of the respiratory tract and the stage of the disease. In the early stages of the disease, viral load is found to be higher in sputum than in the throat.[63,82] The range and frequency of symptoms experienced for VOC infections (for VOC identified to date) is similar to non-VOC infections,[33,66,83-85] but may be more severe and persist for longer.[86] A comparison of VOC versus non-VOC cases found that Delta variant infections had higher odds of oxygen requirements, admission to intensive care, and death.[86] Viral loads were significantly higher for Delta and persisted longer than for the wild-type strain, with more virus shed for a longer period, increasing the likelihood of transmission to others.[86] Compared to the Alpha variant, Delta appears to be more transmissible and results in more severe outcomes, with the risk higher for those with more comorbidities.[87,88] The impact of Omicron on severity of illness is still under investigation, particularly in highly vaccinated populations. *For information on duration of illness and long-term symptoms, see Box 2.*

Box 2: Duration of COVID-19 illness and long-term sequelae[33,89-100]

The duration of illness generally ranges from about two weeks for mild cases to between three and six weeks in severe cases, or longer for patients admitted to critical or intensive care. Long-term symptoms (sequelae) that persist beyond six weeks have been observed in some patients, referred to as “long Covid” or Post-Acute Sequelae of SARS-CoV-2 infection (PASC). PASC may last from weeks to months or longer. Age, chronic health conditions, obesity, and severity of illness are significant predictors of persistent symptoms, and those who have been hospitalized may experience symptoms for longer.

Persistent symptoms can include many of those experienced during the initial COVID-19 illness as well as new or additional symptoms including damage to the heart muscle, scarring of the alveoli, endocrinological and metabolic dysfunction, neurological effects, strokes, and seizures. Most people with PASC experience more than one symptom.

The proportion of COVID-19 cases experiencing PASC is still being investigated as more people become infected and recover from the illness. Chevinsky et al. estimated that 7.0% of inpatient and 7.8% of outpatient cases were diagnosed with new post-COVID conditions 31-120 days

following their initial illness. Seeßle et al. reported that in a study of German COVID-19 cases with initial disease severity ranging from mild to critical, only 22.9% of patients were completely free of symptoms after 12 months. A longitudinal cohort study of hospitalized COVID-19 patients in China by Huang et al. found that 68% of patients experienced at least one sequela after six months, and 49% after 12 months. After 12 months, 12% had not yet returned to their original work and life.

There has been significant interest in the proportion of transmission that occurs in the absence of symptoms, because infected persons may be unaware they are transmitting the virus, and the transmission routes may be different due to the absence of symptoms such as coughing and sneezing.[101-105] Transmission via smaller respiratory aerosols released during breathing, speaking, laughing, or singing may be more important.[106] The occurrence of pre-symptomatic and asymptomatic transmission was recorded from the outset of the pandemic in various locations around the world.[61,105,107-111] Modelling by Johannsen et al.[112] estimated that at least 50% of transmission could be from infected persons without symptoms, but some of these will later go onto develop symptoms. The proportion of cases who never display symptoms is difficult to quantify as some infected persons may never be tested. Those who are tested and recorded as asymptomatic at the time of testing may go on to develop symptoms but may be lost to follow-up.[67]

The estimated proportion of asymptomatic persons and their relative contribution to transmission varies widely in the literature.[113-115] A review of studies by Buitrago-Garcia et al.[67] estimated that about 20% of infections remain asymptomatic during follow-up (prediction interval of 3-67%). Sah et al.[116] estimated the percentage of asymptomatic cases to be about 35%. For asymptomatic spread, the period of transmission is still being investigated.[82,117] Current evidence suggests that asymptomatic transmission is more likely to occur following prolonged close contact, such as in family settings.[103,107,111] The ratio of symptomatic to asymptomatic cases varies by age. Older patients are less likely to be asymptomatic compared to children (*for more information on COVID-19 and children, see Box 3*). Persons with underlying comorbidities, are also less likely to be asymptomatic than those with no underlying conditions.[116] Asymptomatic cases have also been found to have lower secondary attack rates (SAR) (the proportion of exposed susceptible persons that develop infection) among close contacts compared to symptomatic cases,[64,104] and secondary infections are more likely to be asymptomatic.[62,64]

Box 3: COVID-19 in children[118-137]

COVID-19 was less prevalent among children as compared to adults in the initial stages of the pandemic, and children infected with SARS-CoV-2 generally experienced less severe symptoms. This may be associated with lower viral loads measured among symptomatic children compared to symptomatic adults, and a faster clearance of the virus in children.[68] The incubation period for the virus seems to be longer in children compared to adults, and children are more likely to be asymptomatic. In jurisdictions where cases in the community are rising rapidly due to more transmissible variants, cases of COVID-19 among children and adolescents also increase substantially, although current evidence does not suggest children and adolescents disproportionately experience more severe illness compared to adults from VOC to date.

Children account for a lower proportion of hospitalizations, ICU admissions and deaths as compared to adults, although very young children, and those with underlying conditions may experience more severe illness than other children. Among children, the reported symptoms are similar to those of adults but may be less severe, and abdominal symptoms and skin changes or rash may be more commonly reported. Children also report fewer symptoms per person compared to adults. In a study of children (0 – 19 years) admitted to hospital with COVID-19 in Canada (prior to VOC dominance), the most common symptoms reported were fever (70.0%), vomiting (34.7%) and cough (34.4%). Data from UK school aged children (5 – 17) between March 2020 and February 2021 show that the most commonly reported symptoms among child with a positive COVID-19 test were fatigue (66%) and headache (62.2%), with a median duration of illness of six days. In rare cases, children with COVID-19 have developed pediatric multisystem inflammatory syndrome in children (MIS-C), which can include symptoms of fever and inflammation, and can affect cardiac, renal, respiratory hematologic, gastrointestinal, dermatologic, or neurological systems

A small proportion of children studied pre-Delta variant have been found to experience COVID-19 symptoms beyond one to two months. Long-COVID appears to be possible but less prevalent among children, although there is limited study of long- term symptoms among this group.

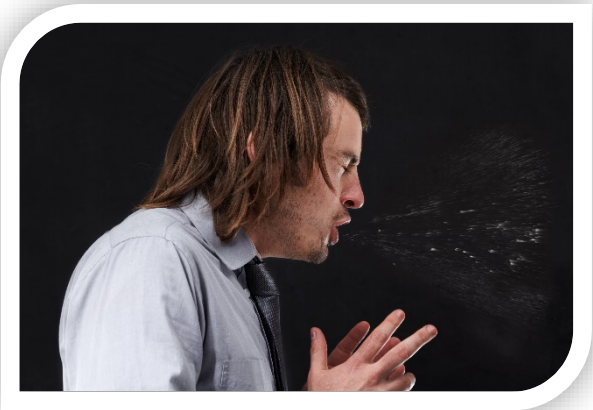
Routes of transmission

While the rate of transmission for VOC has increased, there does not appear to be evidence that the currently circulating strains are more persistent in the environment or that the routes of transmission

have changed. SARS-CoV-2 is thought to infect a host cell by binding to ACE-2 receptors that are present in the epithelial cells of the upper and lower airways.[66,138] The main route of entry is via the upper respiratory tract or mucous membranes of the face, and once a person is infected, the virus replicates predominantly in the tissues of the upper respiratory tract.[73,138] Various physical and biological mechanisms influence how the virus is emitted from an infected person and how a secondary case is subsequently infected. Most transmission appears to be due to exposure to the respiratory droplets and aerosols of an infected person.[139-141] Other routes (e.g., fomites) may be possible but are not considered to be major routes of transmission.

Most COVID-19 outbreaks have been linked to close contact interactions indoors. These are most often associated with interactions in the home environment, including shared accommodation or other indoor spaces where there is a high density of people and a period of prolonged contact.[142-146] This includes workplaces with close proximity of work stations where there is prolonged contact between workers throughout the duration of a shift, such as in manufacturing and food processing plants.[147,148] This is evidenced by higher SAR among people who spend extended duration in close contact with each other. The effect is more pronounced as contact time increases, (e.g., sharing accommodation, riding in a vehicle, or engaging in verbal interactions),[149-151] and in settings where mask-wearing is variable (e.g., during shared meals).[64,151-156] SAR for people in the same household is estimated to be approximately 20%,[157,158] and is much higher than for close contacts from non-household settings and low-risk casual contact with strangers.[159] Research on SAR for VOC indicates that it is slightly higher than SAR for non-VOC, but is lower in households with vaccinated index cases compared to unvaccinated households.[60,158,160] The Delta variant has a higher SAR compared with Alpha and is more easily transmitted in both high-risk settings and households.[161]

Transmission via respiratory emissions



Replicated virus can accumulate in the mucous, saliva or other respiratory emissions of an infected person and subsequently be released during coughing, sneezing, singing, laughing, shouting, talking, or breathing. Forceful respiratory actions (e.g., coughs and sneezes) release bursts of respiratory particles intermittently, which range in size from large droplets (e.g., > 100 µm diameter) to smaller aerosols (e.g., < 5 µm diameter). Breathing or speaking tends to be less forceful but occurs more frequently, producing fewer particles per event, which tend to be smaller.[162-164] Shouting or singing can produce more respiratory emissions than breathing or quiet speaking, and the quantity of particles released can vary with loudness, phonation, and articulation, with some people (e.g., "super-emitters") emitting many more particles than others.[162,164-166] In a small study of persons infected with SARS-CoV-2 (VOC, VOI and wild-type), Coleman et al.[167] measured viral loads in coarse (>5 µm) and fine

(<5 µm) respiratory particles released during breathing, talking, and singing. Of 22 participants, 13 had detectable viral RNA in their respiratory emissions, which may have varied by stage and severity of illness. Most viral copies were emitted by singing (53%), followed by talking (41%) and breathing (6%), but this varied by participant. Most virus released during talking and singing was detected in the fine particles (93.1% and 83.2%, respectively). Overall, fine particles constituted 85.4% of the total viral RNA load detected in the study.[167]

Transmission via respiratory emissions can occur over a short-range or long-range. Particles can deposit direction on mucous membranes or be inhaled into the respiratory tract.

- **Short-range transmission** refers to transmission resulting from close contact with an infected individual. PHAC defines close contact as interactions between individuals within two metres, and prolonged contact as interactions of more than 15 minutes over a 24-hour period.[168] Close contact results in a greater likelihood of encountering virus-laden particles, either via deposition on mucous membranes or inhalation of concentrated aerosols. Transmission over a short-range is likely to be more efficient than indirect transmission over longer distances, due to direct exposure to a larger dose and potentially more concentrated bursts of respiratory emissions when near the source.[44,45,169,170]
- **Long-range transmission** refers to transmission beyond two metres from the source. Modelling has shown that most large droplets do not travel beyond two metres, hence transmission over longer distances is more likely to be associated with dispersed respiratory emissions that do not settle (e.g., aerosols). Respiratory emissions from an infected person that remain suspended and are circulated by ambient air currents may contain virus that remains viable for several hours.[101,171-176] These emissions are more likely to accumulate in settings where an infected person spends a long duration and where lack of ventilation prevents clearance of accumulated particles and dilution with fresh air. Several experimental studies have sought to measure SARS-CoV-2 in the air in healthcare settings with COVID-19 patients[176-182] and some public settings.[183-186] Detection of SARS-CoV-2 RNA in the air has been variable, and viable virus is only occasionally detected.[187] This may be due to variation in sampling techniques, but also implies that virus does not always remain aloft long enough or in sufficient quantity to be detected and that ventilation assists in clearing suspended aerosols.[188-192] The quantity of virus detected may also be influenced by the source load of viral emissions, the duration over which infected persons are emitting, and when the emission occurred relative to the timing of sampling.

Indoor spaces with a high density of people and extended duration of contact increase the opportunities for both **short-range** and **long-range** transmission to occur.[144,170,193] Clusters and outbreaks in indoor spaces have been reported widely throughout the pandemic in fitness centres and classes,[169,194-197] restaurants,[198,199] public transport,[200] choirs and music rehearsals,[201-203] nightclubs,[193,204,205] offices,[206] and religious venues.[207,208] In many of these examples, multiple factors may have contributed to transmission such as a poor clearance of aerosols (e.g., enclosed and poorly ventilated spaces), the

absence of masking, activities that generated a higher proportion of aerosol (e.g., vigorous exercise, loud speech or singing), and a long duration of time spent in the space (e.g., > 15 min).

There have been a small number of cases that suggest transmission may have occurred over a longer range via vertical natural ventilation shafts,[209] or plumbing stacks[210] in high rise buildings, and one case where it is difficult to determine how infection passed between occupants in adjacent rooms of a quarantine hotel.[211] Some studies have reported the presence of SARS-CoV-2 RNA on ventilation grates, ducts or filters; however, there does not appear to be evidence of transmission via HVAC ducts recirculating air to other parts of buildings.[212,213]

- See more from the NCCEH on transmission risks in different settings including indoor spaces, outdoor spaces, multi-unit residential buildings, choir or performing arts settings, encampments, shared laundry facilities, outdoor dining, outdoor urban spaces, public transport and carpools.
- See more from the NCCEH on measures for reducing transmission risks via respiratory emissions including masks, face shields, physical barriers, air cleaning technologies, air and surface disinfection, ventilation and CO_2 sensors.

Transmission via contact with surfaces

Contact with contaminated surfaces (**fomites**) followed by touching of the eyes, mouth or nose is a possible mode of SARS-CoV-2 transmission, although it is not considered to be the main route. Fomites can become contaminated by direct deposition of viral particles or by cross-contamination by touching an object with contaminated hands. Frequently touched surfaces, such as door handles or faucets, may be more important in fomite transmission than less frequently touched objects or surfaces. Experimental studies have indicated that the virus persists longer on smooth hard surfaces such as stainless steel, plastic, glass, and ceramics, as compared with more porous surfaces such as paper and textiles.[214] Observational studies have detected viral RNA on a wide range of surfaces in settings where persons with COVID-19 have been present, such as hospitals or quarantine rooms,[215] as well as in public settings.[216,217] These studies indicate that high-touch surfaces such as door handles, garbage cans, bed rails, shopping trolleys, crosswalk buttons, taps, and toilet seats can be contaminated with SARS-CoV-2 RNA.[178-180,182,183,189,216-219] Viral RNA has also been detected on many untouched surfaces in healthcare settings such as floors, walls, door frames, shelves, ceiling exhaust and window sills.[180,220-222] These studies imply that virus-laden particles can be transported on air currents, in many cases more than two metres from the source; however, reporting on the viability of detected virus is variable. In a study of supermarket surfaces, viral load on surfaces with detectable viral RNA was low, indicating the concentration of virus that could potentially

be transferred via fomites was also low.[216] Another study performing touch transfer tests of SARS-CoV-2 from surfaces such as bank notes, coins, PVC and stainless steel indicated that risk of transmission of viable virus via these surfaces is likely to be low.[223]

Tracing fomite transmission, particularly in public spaces, where people who are unknown to each other and share many common surfaces, is extremely difficult, but it does not appear that fomite transmission is a major route of transmission based on current evidence.[214] The presence of virus in the community underscores the relevance of continuing to observe good hand hygiene, surface cleaning, and disinfection practices, and these practices may have contributed to reducing incidence of fomite transmission more widely.

- See more from the NCCEH on fomite transmission, hand sanitizers, cleaning and disinfection of household surfaces, air and surface disinfection measures, use of disinfectants and sanitizers in food premises, nanomaterials as disinfectants, and disinfectant chemical exposures and health effects.

Transmission via other routes

Viable SARS-CoV-2 virus has been detected in bodily fluids other than respiratory particles, such as blood, feces, and urine of infected persons, but current evidence does not indicate that these contribute to major routes of transmission.[114,224-226] For example, conjunctival transmission through the eyes or tears and **vertical transmission** (from a mother to a fetus) may occur but are likely to be uncommon.[41,114,227-229] For **ocular transmission**, there is some evidence that eye-protection has resulted in reduced infection rates when implemented in high-risk environments such as healthcare settings, but ocular transmission does not appear to be a major source of community transmission.[230,231] Food-borne transmission, sexual transmission, and transmission via other bodily fluids including blood, urine, and breast milk are unlikely to occur based on current evidence.[33,226,232] SARS-CoV-2 is known to be shed via feces, and patients with more severe COVID-19 have higher concentrations of SARS-CoV-2 in their stool.[233-235] Only a few studies have identified infectious virus associated with feces.[179,234,236-239] One study reported that patients with a higher viral load in their stool were also more likely to have measurable infectious virus, and were at a higher risk of dying.[235] There are few examples of possible transmission by **fecal-oral** (e.g., transmission of virus in fecal particles from one person to the mouth of another, or fecal contamination of food) or **fecal-aerosol** transmission (e.g., transmission via inhalation of aerosolized infectious fecal particles), but no investigations have definitively identified that transmission via feces occurred.[209,210,240]

- See more from the NCCEH on public washrooms in the time of COVID-19 and wastewater-based epidemiology

Experimental studies have shown that several mammal species including ferrets, cats, and dogs, can become infected with SARS-CoV-2, and the virus has been detected in some companion animals, zoo animals, and farmed mink.[33,241-245] Evidence of **zoonotic transmission** of SARS-CoV-2 from animals to humans is scarce, apart from cases related to mink farms around the world that have been impacted by extensive outbreaks among the mink, and possible transmission back to humans.[246-248] In most cases, the

evidence suggests that SARS-CoV-2 was transmitted between humans working at the farms and from humans to mink, but not from the animals back to humans in most cases.[249,250] An investigation of mink farms with COVID-19 outbreaks in the Netherlands identified high levels of SARS-CoV-2 RNA in the air and on surfaces inside the farms, up to several metres from the infected animals; however, no spillover infections to the surrounding community were detected.[244] Continued identification and surveillance of cases of zoonotic transmission is ongoing to understand transmission pathways and the risk to humans.

- See more from the NCCEH on SARS-CoV-2 and mink

Sensitivity of SARS-CoV-2 to environmental factors

Research is ongoing to understand how environmental conditions affect the persistence of SARS-CoV-2, with various studies investigating the effect of different levels of temperature, humidity, and ultraviolet (UV) light and combinations of different conditions. Generally, cool, dry, low-UV conditions favour the survival or persistence of SARS-CoV-2 in the environment. Environmental factors may likewise modulate the ability of the human hosts to resist or succumb to infection.

Temperature

Experiments have found that high temperatures are more effective for deactivating the SARS-CoV-2 virus, and the virus is more persistent at colder temperatures. Experiments using viral suspension found minimal reduction over 14 days at 4°C, but detected no viable particles after four days at 22°C, within one day at 37° C, less than 30 minutes at 56°C and less than five minutes at 70°C.[251-253] This is generally consistent with more recent studies on heat inactivation, for virus dried on stainless steel or suspended in culture medium.[254,255] Studies of persistence of SARS-CoV-2 on various surfaces (skin, currency and clothing) also found that the virus remained stable for much longer at 4°C compared with experiments at 22°C and 37°C.[256] A study of persistence of SARS-CoV-2 in milk found that pasteurization temperatures of 56°C and 63°C for 30 minutes resulted in no viable virus. At colder temperatures no reduction was detected after 48 hours stored at 4°C, and only a minimal reduction after 48 hours stored at -30°C.[257] One study noted high temperature resistance of SARS-CoV-2 in suspension at 80°C for up to 30 minutes, which was attributed to the formation of viral aggregates in response to heat. However, this is not likely to affect real-world exposures. As noted by Biryukov et al.,[254] the generally low heat tolerance of SARS-CoV-2 means that heat experienced on a warm summer day (e.g., on playground equipment or in the interior of a car) is likely sufficient to quickly reduce the amount of active virus on non-porous surfaces.

Although temperature affects inactivation of the virus, few studies have investigated the influence of temperature on transmissibility. Evidence on originally circulating variants suggested that the spike protein of the virus had increased affinity to ACE-2 receptors at low temperatures; however, more recent

evidence from Prevost et al.[258] suggests that a common mutation in circulating VOC (N501Y) reduces this effect, allowing the virus to bind more easily, regardless of temperature.

Relative humidity (RH)

Humidity may influence viral transmission by affecting how droplets move and their rate of evaporation and settling.[259] Higher RH[a] indoors reduces the rate of evaporation of liquid contained within respiratory droplets, reducing aerosol formation and allowing droplets to fall to the ground or settle on surfaces more readily.[260] In contrast, warm, dry environments could enhance evaporation of droplets, resulting in a greater number of aerosols being dispersed.[261] Aerosol transmission may thus be facilitated in low RH environments compared to very humid ones.[262]

Humidification of the air has also been proposed as a means to accelerate settling, as the introduction of moist air may help to adsorb smaller desiccated aerosolized virus and bear them to the ground.[263] The feasibility of applying humidification to reduce transmission has not been proven in practice, and could increase the risk of fomite transmission (if deposited virus remains viable), or expose occupants to other indoor air quality hazards, such as mould. It may also be ineffective compared to other interventions. A recent modelling study found that increasing RH to the upper end of the comfortable range (~53%) resulted in only a modest decrease (7%) in the modelled infection rate. In comparison, increasing ventilation from 0.5 air changes per hour (ACH) to 6 ACH resulted in a 54% decrease in the modelled infection rate.[264]

RH also affects the concentration of solutes within the droplet, which impacts chemical reactions leading to virus inactivation. At low RH, the evaporation of water out of the droplet and subsequent crystallization of solutes protects the virus from chemical reactions that would lead to its inactivation.[260] Thus, under low RH conditions, virus survival is primarily determined by temperature-dependent inactivation. Decreased SARS-CoV-2 inactivation at lower RH conditions has been demonstrated experimentally in both aerosols and on surfaces.[265,266] As RH increases past a critical point, the rapid dissolution of those crystallized solutes results in a concentrated solution that strongly favours virus inactivation at moderate RH values. In contrast, a droplet held at high RH will experience a lower rate of evaporation from the droplet and maintain a more dilute solution within it, leading to a lower inactivation rate. Thus, RH appears to have a U-shaped effect on virus viability, with low viability at both low RH as well as extremely high RH.[260]

[a] Relative humidity (RH) refers to the amount of water vapor currently in the air versus that which could be present at the current temperature. RH is thus tied directly to air temperature, but may have effects on viruses that are not directly related to temperature-dependent decay of viral proteins, RNA, etc.

Humidity can affect the susceptibility of respiratory systems to viral infection, with dry conditions reducing the effectiveness of the mucosal lining of the respiratory tract to prevent infection.[259] It has been recently proposed that masking may decrease the risk of transmission, not only by reducing the number of viruses reaching the respiratory tract, but also by preventing dehydration of the mucosal lining by capturing and returning exhaled moisture.[267]

- See more from the NCCEH on high humidity environments and the risk of COVID-19 transmission

Light and ultraviolet (UV) irradiation

UV light induces virucidal effects at wavelengths between 200-320 nm, which covers the range of UV produced by natural sunlight (UV-B, 280-320 nm) and UV produced by lamps for specific applications (UV-C, 200-280 nm). Disinfection using UV-C is more efficient than UV-B, and UV-C is effective for inactivation of double-stranded, enveloped RNA viruses.[268-271]

In laboratories and hospitals, UV-C irradiation has been studied for decontamination of personal protective equipment (PPE)[272] and to inactivate virus in clinical samples.[273] Initial results suggest that UV-C is particularly effective at deactivating SARS-CoV-2 by inducing genome damage without damaging other morphological characteristics or protein structure.[274] To date, research conducted using several SARS-CoV-2 variants, as well as other human and animal coronaviruses, has shown that UV irradiation remains highly effective across viral lineages, regardless of whether the virus is present on surfaces, in liquid suspensions, or in aerosols.[270,275,276]

Because UV-C irradiation is effective for disinfection, there is interest in using UV devices for disinfecting indoor air, in both healthcare and non-healthcare settings. UV-C irradiation carries some risk, as exposure to UV-C can be harmful to human skin and eyes.[277] Studies of far-UVC, which applies a shorter wavelength (e.g., 222 nm), have demonstrated disinfection potential without causing acute harm to skin.[278,279] Further study is needed to determine the optimum dose for inactivation of SARS-CoV-2, and how UV-C could be safely applied in real-world conditions in public indoor settings.

In outdoor environments, solar UV may help to inactivate SARS-CoV-2 settled on surfaces or released in respiratory emissions, decreasing the risk of outdoor transmission. Solar UV overall is expected to have a weaker virucidal effect compared to UV-C, but it can provide a disinfectant effect under a high UV-index over a sustained period.[280] Studies using artificial sunlight have observed good results for viral inactivation within minutes,[281] and suggest that UV illuminance may have a greater effect than temperature on viral inactivation.[282] Karapiperis et al.[283] examined the role of seasonal UV radiation in size- and socioeconomically-matched nations in the northern vs. southern hemispheres, finding that UV levels were strongly associated with trends in epidemiological data (daily national COVID-19 case rates), event after accounting for the effect of public health interventions such as lockdowns and decreased human mobility.[283]

UV treatment may be more effective on smooth surfaces such as steel as compared to fabrics or porous materials.[284] In addition, the matrix in which the virus is found may affect inactivation time, with previous studies showing that inactivation occurs more slowly in mucus or when the surface is dirty, due to shielding effects.[282,285,286] Even so, simulated sunlight rapidly deactivated virus contained in artificial saliva-derived aerosols at a rate of approximately 38% per minute.[281,287]

- See more from the NCCEH on UV disinfection in COVID-19 in indoor environments – Air and surface disinfection measures and Air cleaning technologies for indoor spaces

Vaccination and COVID-19

Currently available vaccines in Canada have been effective against SARS-CoV-2 infection and severe outcomes associated with COVID-19. Vaccination reduces both transmission of the virus in the community and the virulence of the virus for breakthrough cases.

Influence of vaccination on transmission of SARS-CoV-2

Several studies have reported on the high level of vaccine effectiveness against infection with SARS-CoV-2, and unvaccinated cases are more likely to become infected and subsequently transmit the virus compared with fully vaccinated people.[32,288,289] Vaccines reduce the risk of both asymptomatic and symptomatic infection.[290] This has been observed for originally circulating strains and good protection against VOC thus far.[288,291] Although some partially and fully vaccinated people may become infected with the virus (breakthrough cases), this represents a small proportion of the overall vaccinated population, and transmission from unvaccinated cases is a more important driver of community spread. Breakthrough cases are more prevalent among older people, immunosuppressed individuals, and persons with underlying comorbidities (e.g., diabetes, hypertension, cardiovascular disease) compared to unvaccinated groups.[292-294]

Reporting on the measurement of viral loads (using cycle threshold (Ct) value as a proxy) in breakthrough cases versus unvaccinated infections has led to some confusion surrounding the impact of vaccination on transmission risks. Some studies have estimated that the viral load in vaccinated breakthrough cases is lower (as indicated by a higher Ct) compared to unvaccinated cases.[288,289] Other studies have reported that breakthrough cases of the Delta variant have a similar viral load to unvaccinated persons.[295,296] Only a few studies have reported on proportion of measured viral load that represents viable virus. A study of

healthcare workers (HCW) in the Netherlands found that while Ct values were similar among infected HCW, infectious virus was less likely to be found among vaccinated breakthrough cases compared to unvaccinated HCW. Viral loads were also higher in symptomatic compared to asymptomatic breakthrough cases.[296] Viral loads in vaccinated persons also decline quicker, thereby reducing the duration of shedding and infectiousness and subsequent onward transmission.[290,295,297,298] Studies of household contacts of HCW in Finland[299] and the UK[300] have reported lower rates of secondary infection among household contacts of vaccinated versus unvaccinated HCW, demonstrating the effect of vaccination on reducing onward transmission. Shah et al.[300] noted the effect of vaccination for reducing secondary transmission was strongest among HCW with patient-facing roles, most at risk of exposure.

Community vaccination rates influences infection rates among children and adolescents.[136] Siegel et al.[137] observed that emergency room visits and hospitalizations for persons aged 0–17 were between 3.4 to 3.7 times higher in US states with the lowest vaccination rates, compared to states with the highest vaccination rates. Transmission among children in the school setting appears to be related to both the level of transmission of SARS-CoV-2 in the community, and the implementation of mitigating measures to reduce transmission in schools, including measures to reduce transmission between students and from teachers to students (e.g. masking and vaccination).[301,302] It does not appear that transmission in schools is a primary driver of transmission in the community, particularly where community rates of transmission are low and mitigation measures are in place.[303-305]

Influence of vaccination on virulence of SARS-CoV-2

While vaccination is highly effective at preventing infection, where breakthrough cases do occur, vaccinated persons have better outcomes compared to unvaccinated persons. Vaccination has been highly effective against both symptomatic disease and serious outcomes including hospitalization and death due to COVID-19.[86,288,292,297,306] This effect has been demonstrated for originally circulating strains and currently circulating VOC, and stronger for fully vaccinated compared to partially vaccinated persons.[307] In a study in China, breakthrough infections of the Delta variant were more likely to be asymptomatic compared to unvaccinated persons (28.2% vs. 9.2%) and those who were symptomatic had fewer symptoms.[297] In an analysis of COVID-19 cases in California between May and July 2021, Griffin et al.[306] reported that the median age of death among unvaccinated persons due to COVID-19 was much lower than among fully vaccinated persons that succumbed to the disease (63 vs. 78 years old respectively). Thomson et al.[289] found that in a prospective cohort of nearly 4000 HCW, partial and full vaccination was associated with a lower likelihood of infection, lower viral load, shorter duration of detectable viral RNA, a lower incidence of febrile symptoms, and significantly fewer days experiencing symptoms compared to unvaccinated participants. Some of the reasons for better outcomes include higher levels of neutralizing antibodies, lower mean measures of systemic inflammation, a faster decline in viral load, and fewer days with detectable viral RNA among vaccinated versus unvaccinated people with COVID-19.[292,297]

Concluding remarks

The information provided in this document is based on current understanding and interpretations of the literature at the time of writing. Many knowledge gaps remain in understanding aspects of transmission and progression of the disease, including the impact of emerging variants on transmission patterns. Increased transmissibility of VOC implies that risks from all routes of transmission may be heightened and there is a need to continue to apply public health measures that reduce transmission by the known routes, and potentially adapt these as needed to emerging VOC with new or strengthened measures.[308] Layering of public health measures, and pre-emptive rather than reactive strategies, remain the most effective approaches to reducing transmission.[309,310]

Additional COVID-19 related resources to support environmental health can be found on our regularly updated Environmental health resources for the COVID-19 pandemic topic page.

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