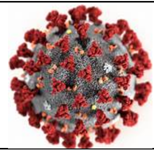
National COVID-19 Science Task Force (NCS-TF)



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The role of Aerosols in SARS-CoV-2 Transmission

Executive summary

It is now generally recognized that aerosols play a role in the transmission of SARS-CoV-2. While the role of aerosols in overall transmission remains difficult to quantify, superspreading events point to aerosols as an important transmission mode in indoor situations with poor ventilation, particularly when associated with activities that result in large aerosol emission rates (e.g. speaking, singing, shouting, physical activity). As the colder season approaches and more activities will occur indoors, the role of aerosols in transmission may increase.

The well known measures of physical distancing, hand hygiene and mask wearing should continue to be implemented broadly. Physical distancing is valuable for both droplet-based and aerosol-based transmission, since the concentration of both decreases with distance from the source. Mask wearing has value for both droplet-based and aerosol-based transmission, and should be considered also when distances in indoor environments are above 1.5 m, particularly in poorly ventilated environments in conditions of prolonged exposure. In addition to these measures, measures that will specifically help diminish aerosol transmission are (i) ensuring proper ventilation of indoor environments with fresh or appropriately filtered air, (ii) avoiding overcrowding of indoor environments, (iii) reducing the duration of stays in poorly ventilated, indoor environments, (iv) limiting or cancelling high-emission activities, particularly in poorly-ventilated indoor environments.

Main text

1. What are aerosols?

The currently known modes of transmission of SARS-CoV-2 are through direct and indirect contact with infected people via mouth and nose secretions (i) through contaminated surfaces, also referred to as fomites; (ii) through larger droplets, also referred to as ballistic route; and (iii) through smaller droplets, also referred to as aerosols. This policy brief focuses on the role of aerosols in the transmission of SARS-CoV-2.

The reason that a distinction is made between larger droplets and smaller droplets is that

- **larger droplets fall rapidly to the ground by gravity**, because of their larger size and thus weight, and can travel ‘ballistically’ (i.e., like little cannonballs) through air towards eyes, nostrils and mouth; whereas

- **smaller droplets remain suspended in air for longer periods of time**, up to several hours, and do not travel in direct paths.

It is important to highlight that **“larger” and “smaller” droplets are part of a continuum of droplet sizes.** There is thus no clearly defined cut-off in size that distinguishes two separate classes of droplets. Rather, the effect of gravitational settling (i.e., falling to the ground) increases with increasing droplet size, whereas the effect of evaporation (which shrinks the droplet size) increases with decreasing droplet size. In practice a size cut-off is often used, below which droplets behave more like “aerosols” (we call these just ‘aerosols’ here) and above which they behave more ballistically (we call these ‘large droplets’ here). This size cut-off for the droplet diameter was traditionally set at 5 µm and this is how aerosols are still defined in most cases. More recently, support has been growing for the use of a value of 100 µm (Prather et al. 2020; COVID-19 Aerosol Transmission FAQ) as ‘this size more effectively separates their aerodynamic behavior, ability to be inhaled, and efficacy of interventions’ (Xie et al. 2007). It is important to highlight that in most studies on the effect of aerosols on transmission, the contribution of different size fractions (i.e., how different sizes contribute to transmission) is not given, largely due to the challenges in resolving this. Whereas size distributions at emission are often known (Johnson et al. 2011), the load of infectious viruses as a function of droplet size remains unknown, making it difficult to firmly establish which droplet sizes most contribute to transmission.

Both types of droplets are emitted, in different amounts, during breathing, talking, singing, coughing, sneezing, shouting and other forms of vocalization or exhalation. **An important question is then the extent to which larger droplet vs. smaller droplets contribute to transmission.** The different physics governing the emission and the motion of larger and smaller droplets have direct consequences on the concentration of droplets of a given size in the air and thus on the probability of transmission through larger compared to smaller droplets.

An additional concept that is important for understanding the role of aerosols and protective measures against aerosol transmission is that, during the course of its (short) lifetime, **a large droplet can become an aerosol**, **because evaporation shrinks the size of a droplet over time.** When evaporation is strong, as occurs in conditions of low relative humidity and/or high temperature, droplets shrink more rapidly in size and thus more of them become aerosols before settling to the ground.

The distribution of aerosols, like the distribution of larger droplets, depends on the distance from the source of the aerosols. The highest concentrations of both larger droplets and aerosols occur in the vicinity of the source and decay with distance from the source. For aerosols, this decay is driven by dilution, and is thus stronger outdoors, or in large and ventilated environments. Physical distancing is thus central for droplet-based transmission, but important, although not sufficient, also for aerosol-based transmission.

The distribution of aerosols, but to a much lesser extent the distribution of larger droplets, depends strongly on the movement of the air, including currents and turbulence. Air movement can both (i) dilute aerosol concentration, by mixing contaminated air with fresh air (hence the importance of ventilating a closed environment); and (ii) rapidly carry aerosols considerable distances from the source (hence the potential for long-range transmission, i.e., transmission at larger distances). In outdoor environments, the dilution effect typically dominates, due to the large volumes of air and its often turbulent state, which tends to make aerosol transmission outdoors of small concern provided physical distance is respected. In indoor environments, the dilution effect is much smaller except if aided by adequate ventilation, and air currents (nearly always present) can rapidly transport aerosols across rooms, creating the potential for transmission.

2. Evidence for aerosol-based transmission

Our understanding of the role of aerosols in the transmission of SARS-CoV-2 is still evolving. Early on in the pandemic aerosols were largely dismissed as having a negligible role in transmission. Over the past months, new evidence and in-depth analysis have changed this view. The prevailing view is now that aerosols play a role in the transmission of SARS-CoV-2. However, there is still debate on whether this role is important or even dominant (Prather et al. 2020; COVID-19 Aerosol Transmission FAQ) or whether it is minor (Conly et al. 2020; Klompas et al. 2020). **We argue below that the quantitative role of aerosols on the *overall* transmission remains difficult to ascertain with precision, but that the evidence is sufficient to conclude that aerosols can play an important role in transmission in certain settings and situations, thus identification of those settings and design of appropriate mitigation measures is urgently needed.**

For historical context, we note that this challenge is not a new one in a pandemic, particularly in the initial phases of the pandemic: measles and tuberculosis were classified as spreading by droplets and/or surfaces for decades, before it was realized that they can spread by aerosols (COVID-19 Aerosol Transmission FAQ, point 1.3).

Aerosols are emitted and inhaled in large numbers, and viruses on aerosols remain infectious for a few hours. In a study that used laser light scattering observations, Stadnytskyi and colleagues showed that loud speech can emit thousands of oral fluid droplets per second and inferred that 'these observations confirm that there is a substantial probability that normal speaking causes airborne virus transmission in confined environments' (Stadnytskyi et al. 2020). Similar conclusions were reached by Asadi and colleagues (2019). Using a mathematical model, Li and colleagues have shown that one is far more likely to inhale aerosols than droplets (Li et al. 2020). In a study in which aerosols enriched in SARS-CoV-2 viruses were generated in the laboratory, Van Doremalen and colleagues showed that SARS-CoV-2 viruses on aerosols remain infectious for up to 3 hours (Van Doremalen et al. 2020).

Using a box model for the exposure estimation, Zhang and Wang (2020) quantified the infection risk via transmission by airborne droplet nuclei after evaporation of the volatile part. For a 1 hour exposure in a room of 10m x 10m x 3m, ventilated using the typical ventilation rate for offices, they find the median risk (3.7×10^{-5}; 95% confidence interval: 3.5×10^{-6} to 4.4×10^{-4}) to be more than three orders of magnitude lower than the risk due to contact at a distance of 1 m. For a room that is 10-fold smaller in area, the risk increases by approximately one order of magnitude. While this work is not yet published in a peer-reviewed journal, it supports the fact that aerosol transmission over large distances in large, well ventilated rooms poses a significantly lower risk than close contact, and that the risk increases for smaller rooms and poor ventilation. This study highlights that 'with prolonged exposure duration and large exposed population, the infection caused by aerosol transmission could be considerable, thus it is necessary to be cautious for the potential aerosol transmission risk in such situations'.

Epidemiological investigations supporting transmission by aerosols

It is difficult to ascribe any given transmission definitively to either aerosols or droplets. Many clinical and epidemiological investigations and reports support the predominance of transmission occurring by closer contact and/or larger particles, yet their detailed discussion is beyond the scope of this policy brief (Conly et al. 2020). **Early evidence already pointed at aerosol-based transmission as an important contributor to several notable superspreader events** (Kupferschmidt 2020). Examples include choirs in closed environments, call centers, abattoirs, gyms, and restaurants, as detailed below.

In a study carried out in a hospital room (limited to two patients), aerosols containing infectious viruses have been isolated up to 4.8 m away from patients (Lednicky et al. 2020). In a recently developed indoor scenario simulator, a model based on a simulation of droplet generation and assumptions of indoor conditions revealed that in typical situations, such as moderately ventilated offices, small shops, trains, buses, or carpool, very high emitters (99th percentile and above) not wearing masks are likely to cause concentrations with an elevated risk of infection via aerosols (Riediker and Monn 2020).

In a choir rehearsal in the state of Washington, USA, one symptomatic index case infected 53 out of 61 people in attendance, of which 2 died (Miller et al. 2020). The authors conclude that 'Transmission by the aerosol route is likely; it appears unlikely that either fomite or ballistic droplet transmission could explain a substantial fraction of the cases'. This conclusion was based on the detailed reconstruction of the activities of the choral members during the rehearsal, including the interactions of the members with the single member who attended the event with cold-like symptoms and was subsequently tested positive for COVID-19. The reconstruction took into account the spatial arrangement of chairs during the event, the use of bathrooms and snacks during the intermission; in particular, person-to-person contact and touching of surfaces was consciously limited during the event, and hand sanitizer was used. Similarly, carnival activities, which contributed to a superspreading event in a small German town, were linked with virus emission during loud talking and singing (Streeck et al. 2020).

In a meat processing complex in Germany, an index case was found to have transmitted the virus to co-workers at a distance of more than 8 meters during work-shifts on 3 consecutive days (Günther et al. 2020). The authors conclude that 'the facilities' environmental conditions, including low temperature, low air exchange rates, and constant air re-circularization, together with relatively close distance between workers and demanding physical work, created an unfavorable mix of factors promoting efficient aerosol transmission of SARS-CoV-2 particles. It is very likely that these or similar factors are also responsible for current worldwide ongoing outbreaks in other meat or fish processing facilities or abattoirs.

Animal model studies provide inconclusive results on the role of aerosols on transmission, often because a clear distinction between transmission by larger droplets and by aerosols is not made or because the experimental setting does not allow distinguishing between the two (Kim et al. 2020; Richard et al. 2020; Sia et al. 2020). **The strongest evidence from animal model studies points at aerosol transmission being possible but requiring prolonged exposure to high viral doses:** Bao and colleagues performed an experimental simulation of three transmission modes, including close-contact, respiratory droplets and aerosol routes in Human Angiotensin-Converting Enzyme 2 (hACE2) Mice (Bao et al. 2020). They found that SARS-CoV-2 can be highly transmitted via close contact and by respiratory droplets. hACE2 mice could not be experimentally infected via aerosol inoculation until continued up to 25 minutes with high viral concentrations, indicating that aerosol transmission is possible but requires prolonged exposure to high viral doses. These authors do not explicitly define the size of aerosols they used in their study, however based on the bioaerosol generator they employed, one can conclude that the aerosols in their study were in the range of 1 to 7 µm.

Factors contributing to superspreading events

Superspreading events may be related to factors associated with the infected host such as the variability of individual emission rates of droplets and aerosols and the viral load, specific behaviors promoting emission of virus (i.e. speaking, singing, shouting, touching etc.) and specific settings (crowded environments, short poor ventilation)

Variability in individual emission rates of aerosols may be one factor accounting for the occurrence of superspreading. For example, during speech, the rate of particle emission increases with the loudness of vocalization, as one would expect, but additionally 'a small fraction of individuals are 'speech superemitters', consistently releasing an order of magnitude more particles' than others (Asadi et al. 2019). What makes someone a speech superemitter remains unclear.

Considerations regarding the basic reproduction number

It is relevant here to briefly address an argument often brought against the role of aerosols in transmission, based on the idea that the basic reproduction number R_0 of SARS-CoV-2 is much lower than that of viruses known to spread by aerosols, such as measles (Klompas et al. 2020). While a high R_0 typically suggests aerosol transmission, one cannot exclude aerosol transmission for infectious diseases with a lower R_0 (COVID-19 Aerosol Transmission FAQ, point 1.3). For example, aerosol transmission has been shown to play a role in the transmission of SARS-CoV (R_0 = 3, Lloyd-Smith et al. 2005), MERS-CoV (R_0 = 0.5, Kucharski and Althaus 2015), and influenza (R_0 = 1.8, Biggerstaff et al. 2014, Tellier et al. 2019), which all have a considerably lower contagiousness than that of measles (R_0 = 16, Lloyd-Smith et al. 2005). **The evidence thus converges towards aerosols being an important mode of transmission of SARS-CoV-2.**

We highlight that the potential for superspreading of SARS-CoV-2, that is characterized by a large variance (overdispersion) in the number of secondary infections generated by one infected individual (Riou and Althaus 2020), underlines the likely contribution of aerosol-based transmission as it has also been described (albeit to a larger extent) for the related viruses SARS-CoV (Lloyd-Smith et al. 2005) and MERS-CoV (Kucharski and Althaus 2015). It should not be concluded from this evidence that aerosol-based transmission is limited to superspreading events. The reason for this is that only for such superspreading events is it possible to attribute transmission to aerosols with reasonably large confidence, whereas for regular-spreading events it remains difficult to distinguish between the large-droplet and the aerosol mode. It appears likely that a fraction of the close-proximity infections are caused not just by larger droplets, but also by aerosols, or by a combination of the two. In this latter case, the distinction between large droplets and aerosols does not substantially affect the required prevention measures.

3. Implications

The importance of ventilation

Large transmission events have typically occurred in indoor settings (Leclerc et al. 2020). As we highlighted in our previous writing on aerosols ('Response to FOPH questions on masks and aerosol transmission', Jun 2020), **ventilating indoor environments is an important measure that can substantially reduce aerosol-based transmission**. Wherever possible, outdoor alternatives should be preferred, yet in the many instances in which this is not possible, sufficiently strong ventilation should be ensured through either opening windows or through central air circulation systems. Mathematical modeling also shows that ventilation can have a substantial positive effect (Smieszek et al. 2019). **With the increase in the numbers of events and interactions that will occur indoors over the colder season months, the issue of ventilation will grow in importance.** Some countries are already taking substantial action in this respect, with Germany for example recently investing 500 million Euro to improve ventilation systems to stop the spread of SARS-CoV-2 (BBC News October 2020).

Ensuring sufficiently frequent air exchanges, so that the fraction of rebreathed air remains low, is critical to maintain low the concentration of aerosols in the air. In general, the higher the ventilation, the higher the dilution effect on aerosol concentrations, the lower the risk of transmission. The higher the fraction of outside (i.e. fresh) air brought to a room during ventilation, the more effective the ventilation is at reducing aerosol concentrations. Ventilation equipment that uses a large fraction of recirculated air can represent a danger, unless filtration is adequate (though appropriate filtration equipment is typically limited to specialized facilities such as operating rooms of hospitals and airplanes and trains that use HEPA filters). There is evidence that a SARS-CoV-2 outbreak in an industrial production facility can be traced back to the use of a larger fraction of recirculated air (Günther et al. 2020). Two documents from the Robert Koch Institute provide useful further details on ventilation and its practical implementation, one in buildings overall (Umwelt Bundesamt 2020a) and one specifically in schools (Umwelt Bundesamt 2020b).

Of note in this respect is also **the value of using CO2 sensors as sentinels to trigger or evaluate ventilation**. These inexpensive devices (often <100 CHF) measure the CO2 concentration in a room: an increase of the CO2 concentration (e.g. to >800 or 1000 ppm) from the ambient concentration (e.g., 410 ppm) indicates the need to ventilate, and is often associated with a simple-to-operate 'traffic light' system (turning from green to yellow to red as conditions worsen). While there are some limitations to the use of CO2 as a proxy for the need to ventilate, this is generally recognized as an effective approach (Umwelt Bundesamt 2020b) and, for other respiratory infections, 'it has been shown that the risk of indoor transmission of infection by the airborne route can be estimated using a CO2-based risk equation' (Rudnick and Milton 2003).

Ventilation is thus an effective and often simple-to-implement measure to minimize the risk of aerosol-based transmission.

Physical distancing and mask wearing in indoor environments

Whereas outdoors the diluting effect of air currents is typically sufficient to abate the concentration of aerosols in the vicinity of a source, so that a 1.5 m or 2 m physical distancing is effective, **in indoor environments there might not be a universally safe distance.** This is because exposure also depends on the duration of the interaction, which increases the concentration of aerosols in the room, and on ventilation. **Larger distances are generally better and the 1.5 m rule should definitely be applied also in indoor environments**, because aerosol concentrations like larger droplets also decrease with distance from the source, **however aerosols can carry viruses further than this distance**, due to typically unavoidable air currents in indoor environments.

Wearing a mask has been shown to protect against the transmission of respiratory diseases, including SARS-CoV-2 (Chu et al. 2020; Liang et al. 2020). The filtration capacity of droplets and aerosols depends on the type of mask. While certified FFP masks retain >94% of <0.45 µm particles, community masks retain >70% of 1 µm particles (based on the criteria proposed by the Swiss National Science Task Force and further detailed in the policy brief "Recommendations on minimal specifications for community masks and their use") and certified surgical masks of Type II retain >98% of 3 µm particles (differences in particle diameter between these performance requirements are only a result of differences in the standards used in certification of masks, which differ by mask type). The majority of particles produced during different physical activities fall into a range of 0.8 and 5 µm, depending on the activity performed (Prather et al. 2020). In addition to filtration capacity, the fit of the mask plays an important role in terms of protection from aerosols: the better the fit (i.e., the fewer the gaps between the mask and the face of the wearer), the lower the risk of transmission by smaller particles. Masks do not guarantee absolute protection, but their filtration capacity reduces the risk of infection, particularly if everyone wears one, as the mask works in both directions. **Masks do not only protect the wearer, but also, importantly, have a source control effect by retaining the particles exhaled by the wearer, including larger droplets**. (Morawska et al. 2009; Ueki et al. 2020). For recommendations on the use of masks for healthcare workers we refer to the swissnoso guidelines "Interims Vorsorgemassnahmen in Spitälern für einen hospitalisierten Patienten mit begründetem Verdacht oder mit einer bestätigten COVID-19 Infektion" (https://www.swissnoso.ch/fileadmin/swissnoso/Dokumente/5_Forschung_und_Entwicklung/6_Aktuelle_Erreignisse/201023_Vorsorgemassnahmen_COVID-19_Spital_V8.4_DE.pdf).

The basic prevention measures of physical distance, hygiene and mask wearing are only sufficiently effective in indoor settings when coupled with sufficient ventilation (Umwelt Bundesamt 2020a). In poorly ventilated environments, particularly small ones, the probability of transmission increases also beyond a distance of 1.5 m, particularly when an individual with high viral load is present (Riediker and Tsai 2020). In a modeling study of a room of 50 m^3, the size of a small office or medical examination room, Riediker and Tsai found that 'the estimated infectious risk posed by a person with typical viral load who breathes normally was low, and only few people with very high viral load posed an infection risk in a poorly ventilated closed environment', concluding that '**strict respiratory protection may be needed when there is a chance to be in the same small room with an individual [with a high viral load], whether symptomatic or not, especially for a prolonged period'** (Riediker and Tsai 2020)**.** We highlight that the chance that an asymptomatic individual has a high viral load cannot be estimated a priori, which expands this recommendation to all prolonged interactions in small rooms.

Along the same lines, in its summary of current evidence, the RKI concludes that 'for stays of extended duration in small, poorly or not ventilated rooms, the probability of transmission increases also beyond a distance of 1.5 m, in particular when an infectious person emits particularly many aerosols and spends a large amount of time in the room'. Due to the resulting enrichment and redistribution of aerosols in the room, maintaining a minimum physical distance may not be sufficient to prevent transmission.

Type of activities

The available evidence indicates that certain activities, associated with higher viral emission rates, represent greater danger compared to others. Among the more dangerous activities are singing, shouting, and heavy breathing such as that associated with intense physical activity. These activities should be avoided, particularly in indoor environments that are poorly ventilated, or at a minimum associated with appropriate safety measures, including physical distancing (even beyond the 1.5 m), mask-wearing, limitation of the duration of exposure, and adequate ventilation of the environment.

Conclusions

Given the evidence in favor of aerosol transmission in certain settings, and in line with calls from international experts, we propose that 'following the precautionary principle, we must address every potentially important pathway to slow the spread of COVID-19' (Morawska and Milton 2020). At the same time, current evidence indicates that aerosol-based transmission occurs primarily in either (i) confined, poorly ventilated settings, where there is long-duration exposure to a high-load emitter, even at distances beyond 1.5 m; or (ii) as part of close-range (<1.5 m) interactions, where it is difficult to distinguish from droplet-based transmission.

The well known measures of physical distancing, hand hygiene and mask wearing should continue to be implemented broadly. Physical distancing is valuable for both droplet-based and aerosol-based transmission, since the concentration of both decreases with distance from the source. Mask wearing also has value for both droplet-based and aerosol-based transmission, and should be considered also when distances in indoor environments are above 1.5 m, particularly in poorly ventilated environments in conditions of prolonged exposure. In addition to these measures, measures that will specifically help diminish aerosol transmission are (i) ensuring proper ventilation of indoor environments with fresh air or appropriately filtered (HEPA filter) air, (ii) avoiding overcrowding of indoor environments, (iii) reducing the duration of stays in poorly ventilated, indoor environments, (iv) minimizing high-emission activities in poorly-ventilated indoor environments.

Systematic ventilation is all the more important in the colder season when windows tend to be closed, indoor spaces are heated, and more social activities occur indoors. In many environments, briefly opening windows at intervals of time (including in the colder season) is the simplest form of ventilation, and protocols for window opening in different situations are available (Umwelt Bundesamt 2020b).

Finally, clear communication of the situations in which aerosols can contribute to transmission (and where they tend not to) and of these measures that one can take to protect themselves will contribute to acceptance and compliance in the population, in particular because the much-talked-about topic of aerosols harbors complications (all these droplets are invisible and the physics are non-trivial) that are prone to creating confusion.

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