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VIEWPOINT

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Airborne Transmission of Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2): What We Know

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We examine airborne transmission of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) potential using a source-to-dose framework beginning with generation of virus-containing droplets and aerosols and ending with virus deposition in the respiratory tract of susceptible individuals. By addressing 4 critical questions, we identify both gaps in addressing 4 critical questions with answers having policy implications.

Keywords. SARS-CoV-2; COVID-19; airborne transmission.

From the coronavirus disease 2019 (COVID-19) pandemic's start, modes of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) transmission—direct contact, indirect contact involving fomites, large droplet spray, and aerosol inhalation— have been debated and investigated, given implications for infection control. Infected individuals release virus into the air while breathing, speaking, singing, coughing, and sneezing. Successful airborne transmission requires that infectious virus reach the respiratory tract (and possibly the eyes) of susceptible individuals at doses sufficient to initiate infection. This perspective examines the potential for airborne transmission of SARS-CoV-2 using a source-to-dose framework that begins with generation of virus-containing droplets and aerosols and ends with the virus depositing in the respiratory tract of a susceptible individual. Intermediate steps include transport of droplets and aerosols through the air and possible loss of infectivity of the virus over time. Human behavior affects dose as well, including physical distancing and use of masks. Contextual factors overlay this sequence, such as the built environment, occupational exposure, and the upstream drivers of race, ethnicity, and income. This framework leads to 4 critical questions (Table 1). In this perspective, we draw on a 2-day workshop of the National Academies of Science, Engineering, and Medicine (NASEM) [1] that addressed these questions.

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We adopt terminology newly proposed to harmonize discussions about transmission of respiratory pathogens [2]. In the context of infectious disease transmission, "droplets" are particles emanating from the respiratory tract larger than 100 μm in aerodynamic diameter that typically fall to the ground in seconds and within 6 feet (2 meters) of the source. "Aerosols," also particles, are smaller than 100 μm and can remain suspended in air from seconds to hours. The definitions preserve the general meaning of these words in infectious disease transmission—droplets are sprayed onto the mucus membranes, a form of contact transmission, while aerosols are inhaled into the respiratory tract—while aligning their physical behavior with route of exposure.

Concepts of respiratory virus transmission have long been grounded in the 1930s work of Wells [3]. He described generation of respiratory droplets of all sizes by coughing and sneezing, some being sufficiently large to fall to the ground quickly and others remaining suspended in air and dehydrating to form so-called droplet nuclei or aerosols—small enough to remain airborne for extended time periods. The Wells transmission model underlies the proposition that distancing by at least 6 feet protects against droplet infection. Wells also recognized that particles smaller than 100 μm would evaporate faster and decrease in size while settling toward the ground and thus could remain in the air and "convey such infection long distances." Reflecting the tools of his time, Wells and contemporaries were unaware of the enormous numbers of aerosols produced during expiratory activities.

For the first question, the evidence is clear: people produce droplets and aerosols that cover a broad size range [4]. Droplets can travel beyond 6 feet, and there is now visual documentation that the respiratory tract generates millions of aerosols that are

Table 1. Four Critical Questions on Airborne Transmission and What We Know

Critical Question	What We Know
CQ1. What size particles are generated by people, and how do they spread in air?	• Individuals generate aerosols and droplets across a large range of sizes and concentrations. There is great variation among individuals and across activities. • Respiratory plumes, containing a continuum from small aerosols to large droplets, are an important determinant of exposure at short-range distances, up to about 1.5 m. • At longer-range distances (>1.5 m), smaller aerosols that can remain airborne for longer time periods dominate exposure.
CQ2. Which size particles are infectious and for how long?	• Humans infected with SARS-CoV-2 produce particles smaller than 5 µm that contain virus. • Viral half-life in aerosols is approximately 1 hour, but viruses can persist much longer.
CQ3. What behavioral and environmental factors determine personal exposure to SARS-CoV-2?	• Masks (face coverings) reduce the amount of virus emitted in aerosols and droplets and reduce the wearer's exposure to them. • Masks (face coverings) reduce community transmission. • Ventilation can reduce room-based exposure and filtration is an effective supplement to ventilation for reducing aerosol concentrations indoors.
CQ4. What do we know about the infectious dose and disease relationship for COVID-19?	• Human and animal studies on different coronaviruses have demonstrated that viral infectivity is dependent on host and environmental factors. • The role of infectious dose remains to be characterized while individual characteristics are important determinants of SARS-CoV-2 disease severity.

Abbreviations: COVID-19, coronavirus disease 2019; SARS-CoV-2, severe acute respiratory syndrome coronavirus 2.

highly concentrated at the source and can travel for distances well beyond 6 feet, the span generally proposed for protection against droplet transmission. Experiments show that aerosols outnumber droplets by more than 100:1 during speaking and 20:1 during coughing; generation of droplets and aerosols increases with loudness and length of speech. We also know that smaller aerosol particles can stay suspended for hours, accumulate over time, and be carried long distances by air currents in indoor spaces. However, more studies are needed on the sizes of virus-containing droplets and aerosols that are generated by different activities.

Addressing the second question, studies have shown that SARS-CoV-2 is present and infectious in small aerosols. Samples of airborne particles <5 µm in diameter contain viral RNA, although the presence of RNA does not establish that infectious virus is present. Using a sampling technique that maintains viability, airborne infectious virus was detected at >6 feet from patients. Laboratory experiments suggest that SARS-CoV-2 in aerosols remains viable for up to 16 hours, with a half-life for viability of 0.5–3.3 hours in one study [5].

In the source-to-dose framework, exposure constitutes virus-laden droplets contacting an individual's mucus membranes or virus-laden aerosols being inhaled into the respiratory tract. Both environmental and behavioral factors affect exposure of people. For airborne transmission, exposure can occur by proximity to an infected person's respiratory plume and by occupancy of spaces, usually indoors, contaminated with virus-laden aerosols. Longer-range transmission of aerosols, particularly in closed and poorly ventilated spaces with crowds, likely produces superspreading events, as observed during a choir practice in Skagit, Washington. In tightly packed groups, transmission by droplets is also plausible. Droplets and aerosols may become resuspended following surface deposition, reinforcing a need for cleaning floors and other surfaces.

Because exposure is affected by environmental and behavior factors, modifications to these factors can reduce airborne transmission of SARS-CoV-2. Infection risks can be diminished by increasing building ventilation, the exchange of indoor air with outdoor air, and by air cleaning using filtration and ultraviolet light in appropriate environments (Table 1). Limiting the number of people within spaces reduces the chances of an infected person being present, and distancing them reduces exposures to respiratory plumes. Because aerosols contribute substantially to transmission, what is the role of masks in reducing risk? Reduction of risks by wearing masks has been assessed by mechanistic, experimental research with more limited evidence available from population studies [6]. Nonetheless, evidence is sufficient to conclude that masks reduce emissions that expose others and also reduce exposure to airborne virus for wearers (Table 1).

For viral infections generally, little is known about the dose-response relationship between the inhaled number of virions and infection risk and the relationship between the site of deposition within the respiratory tract and the clinical phenotype and severity of illness. For SARS-CoV-2, evidence related to the fourth critical question is lacking, although useful animal models now exist and have demonstrated that aerosols transmit infection in some species. Contributions of host sex, age, and genetic features complicate studies to define the human infectious dose and should be included in future studies to link pathogenesis to source and concentration of virus-laden aerosols or droplets.

The gaps in addressing the 4 critical questions highlight the necessity of an organized interdisciplinary research agenda. The pandemic quickly launched such research, resulting in the new but still incomplete findings presented at the NASEM workshop. These findings document the critical role of aerosols in transmission of SARS-CoV-2. Further studies are needed to refine understanding of the relative contributions of the modes of transmission in distinct settings. Strong and immediate precautionary actions should be taken based on the demonstrated significance of this transmission mode, particularly as the pandemic surges. Strategies need to be developed that assure sufficient ventilation and that add air cleaning and perhaps ultraviolet light in appropriate settings.

Conclusions based on the state of evidence for the 4 questions have immediate policy implications. The correct blend of policy measures and transmission-reducing behaviors is needed. Assuring adequate ventilation of indoor spaces is requisite, and air cleaning, including perhaps ultraviolet light in appropriate settings, may help. However, and most critically, the public needs to understand the importance of airborne transmission and its implications for how we can best protect ourselves. The scientific evidence is clear on the importance of layered interventions in reducing the spread of SARS-CoV-2: using face coverings, maintaining distancing, and avoiding large gatherings that have the potential to become superspreading events.

Key authoritative agencies, the Centers for Disease Control and Prevention, and the World Health Organization should more fully acknowledge the critical role of aerosols and offer strong recommendations for controlling this dominant mode of transmission.

Note

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