Airborne Transmission of SARS-CoV-2: Proceedings of a Workshop in Brief (2020)

DETAILS

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Proceedings of a Workshop

IN BRIEF

October 2020

AIRBORNE TRANSMISSION OF SARS-CoV-2

Proceedings of a Workshop—in Brief

INTRODUCTION AND WORKSHOP OBJECTIVES

With the rapidly evolving coronavirus disease 2019 (COVID-19) pandemic, researchers are racing to find answers to critical questions about the virus that causes the disease severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). Understanding how the virus[1] is transmitted is among the most important questions, as it will inform efforts to stop its spread. For example, can the virus be transmitted via speech and exhaled breath? How long can aerosols[2] containing the virus linger in the air? How far can these aerosols travel? Is the amount of virus in these aerosols enough to cause infection?

These questions and more were the subject of an August 26–27, 2020, National Academies of Sciences, Engineering, and Medicine virtual workshop (see Statement of Task in Box 1) that convened experts in aerosol science and atmospheric chemistry, building engineering, epidemiology, environmental health, infectious disease, pulmonary medicine, public health, and virology to explore the evidence on airborne transmission of SARS-CoV-2. The workshop was organized by the Environmental Health Matters Initiative (EHMI)[3] to address the state of the science (what we know, what we need to know, and what research is needed) around these four critical questions:

1. What size aerosol particles and droplets are generated by people and how do they spread in air?
2. Which size aerosol particles and droplets are infectious and for how long?
3. What behavioral and environmental factors determine personal exposure to SARS-CoV-2?
4. What do we know about the relationship between infectious dose and disease for airborne SARS-CoV-2?

These four questions are reflected in the framework shown in Figure 1. Also important are contextual factors—housing quality, income, and race and ethnicity, among others—that were not the focus of this workshop. Each critical question was the subject of a session chaired by a member of the planning committee, with several short presentations followed by a moderated panel discussion. The session chairs provided a synthesis of the main points at the end of the workshop. The discussion of each of the critical questions is captured below, organized according to the session chair's main points, highlighting the key thinking contributed by speakers and panelists. The workshop was informed by, and contributes to, a larger body of COVID-19-related work at the National Academies.[4]

This Proceedings of a Workshop—in Brief provides the rapporteurs' high-level summary of the topics discussed at the workshop itself. Additional details and ideas can be found in materials available online,[5] including videos of the presentations. The reader is encouraged to use this document to gain insights into what was discussed during the workshop by presenters and views of individual experts, but should not view the ideas as consensus conclusions or recommendations of the National Academies.

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[1] SARS-CoV-2 is also referred to as "the virus" throughout this Proceedings of a Workshop—in Brief.

[2] The aerosol and droplet terminology adopted in this Proceedings of a Workshop—in Brief is detailed in Table 1. Because the terminology evolved over the course of the workshop, the archived presentations and recordings may not reflect the terminology adopted in this document.

[3] EHMI chair Thomas Burke, Johns Hopkins University, explained that the EHMI organized this workshop because of its ability to rapidly convene experts and because environmental factors, some of which were covered in the workshop, are important in thinking about the SARS-CoV-2 pandemic broadly, as well as the pandemic's disparate effects on different American populations.

[4] See https://www.nationalacademies.org/topics/covid-19-resources.

[5] See https://www.nationalacademies.org/event/08-26-2020/airborne-transmission-of-sars-cov-2-a-virtual-workshop.

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BOX 1 Workshop Statement of Task

The science around transmission of SARS-CoV-2, the virus that causes COVID-19, is complex and evolving quickly. For example, questions about how long infectious particles linger in the air and how far they travel have been the subject of debate because of the implications for interventions.

The National Academies of Sciences, Engineering, and Medicine will organize a workshop on transmission of SARS-CoV-2 by exploring the potential paths from the generation of these particles by infected people to the viable transmission of these particles to others. The workshop will cover the latest scientific evidence about airborne transmission of SARS-CoV-2 and discuss critical research gaps to inform prevention policies. Participants will include experts from a range of scientific disciplines including aerosol and atmospheric science, virology, infectious disease, and epidemiology.

Questions to consider may include:

- How is consideration of SARS-CoV-2 transmission as either respiratory droplets or aerosols supported by the science?
- What are the size range and characteristics of infectious particles generated by infected people?
- What are the concentrations of infectious particles in different size ranges?
- What factors (e.g., environmental and host factors) determine personal exposure to infectious particles?
- What do we know about the relationship between viral load and infection for SARS-CoV-2?

The workshop will not produce conclusions or recommendations. A brief proceedings capturing the presentations and discussions will be prepared in accordance with institutional guidelines.

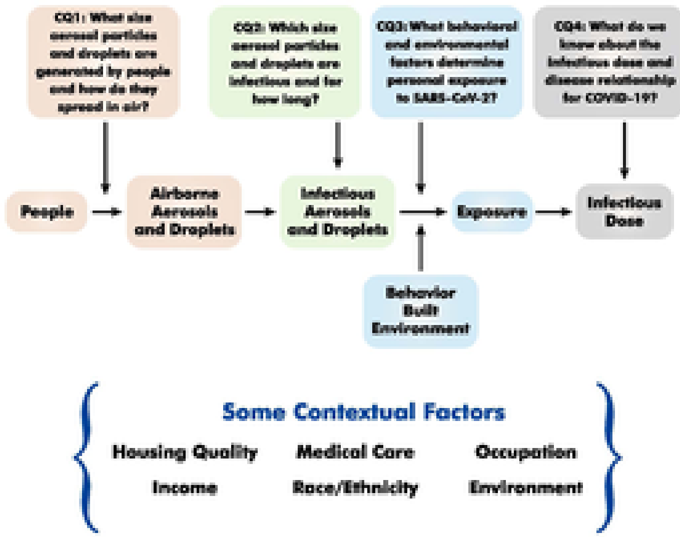

FIGURE 1 Framework for organizing the workshop. NOTE: This framework is consistent with the National Academies' series of reports on *Research Priorities for Airborne Particulate Matter*. SOURCES: NRC 2004; Samet 2020a.

IMPORTANCE OF UNDERSTANDING AIRBORNE TRANSMISSION: LESSONS FROM THE FIELD

Anthony Fauci, National Institute of Allergy and Infectious Diseases; Jay Butler, Centers for Disease Control and Prevention (CDC); Jonathan Samet, Colorado School of Public Health; and Linsey Marr, Virginia Tech, provided an overview of why it is important to understand airborne transmission for SARS-CoV-2, including what is known based on epidemiologic and outbreak data.

Understanding the mode of transmission of the virus is necessary to inform action to stop its spread. As Fauci mentioned, transmission information is needed to inform the use of interventions, such as the use of masks, ventilation, cleaning and disinfecting, and physical distancing. (See Figure 2 for four general categories of interventions and their potential impact on transmission.)

SARS-CoV-2 is a respiratory virus that has been detected on surfaces for up to 48 hours or longer, but the role of inanimate objects (fomites) in transmission is not entirely clear. Research has also found the virus in a variety of body fluids. Speakers noted that in terms of assessing transmission, perhaps the most troublesome aspect is that 40–45% of individuals who are infected are without symptoms. Transmission of SARS-CoV-2 by asymptomatic individuals has now been clearly documented; such transmission makes it extremely challenging to conduct contact tracing and fully assess modes of transmission.

- **Source control:** Source control can greatly reduce, if not completely eliminate, the number of aerosols released into the air
- **Ventilation/filtration:** With effective ventilation/filtration, the number of viral aerosols can be greatly reduced
- **Distance and personal protective equipment:** These interventions can offer some protection by reducing a person's exposure
- **Hygiene:** Research indicates that the highest viral loads or positive samples can be found on the floor. Cleaning the floor can reduce the possibility of resuspension

FIGURE 2 Interventions to reduce the spread of SARS-CoV-2. Four basic categories of interventions, described by Marr (2020), can result in a significant reduction in the risk of airborne transmission of SARS-CoV-2.

The science on SARS-CoV-2 is rapidly evolving. As Butler, Marr, Fauci, and others noted, while SARS-CoV-2 is genetically similar to other respiratory viruses, these similarities have not necessarily translated in terms of transmission dynamics. Also, experts' understanding about the infectiousness of the virus has changed over time. For example, Butler, an infectious disease doctor, noted that initially CDC and others believed, based on phylogenetic similarities, that the period of infectiousness for SARS and SARS-CoV-2 were similar. However, once it was understood that SARS-CoV-2 was quite different in that it can be spread by asymptomatic individuals, the agency revised its recommendation on mask use to include everyone who goes into public places.

As Butler noted, the transmission of SARS-CoV-2 was initially thought to be primarily through respiratory droplets produced when an infected person coughs, sneezes, or talks—droplets that can then inoculate mucus membranes of people who are nearby or within 6 feet. However, he said that current understanding about how the virus spreads continues to evolve. Butler reiterated the importance of "stay[ing] agile in our views as additional data become available because airborne spread of SARS-CoV-2 is also plausible, and our approaches need to be data based and not dogma based."

Epidemiologic Studies of Transmission of SARS-CoV-2

Epidemiologic patterns inform experts' understanding of SARS-CoV-2 transmission. Butler provided an overview of current epidemiologic research, which has indicated that outbreaks of COVID-19 resulting from a point source (one infected person transmitting to others) have most often occurred in settings where there is crowding or people who are exposed indoors for extended periods of time (e.g., long-term care facilities, correctional facilities, homeless shelters, and bars).

In describing the spread of the virus, epidemiologists often cite the basic reproduction number, also known as R_0 or "R naught." This value represents the average number of immunologically naïve people that one infectious person infects. It is important to recognize that R_0 is not an absolute; instead, it varies over time and circumstances. A significant challenge for researchers is understanding "super-spreading events."[6] Butler cited instances of super-spreading events that he said suggest, but do not confirm, airborne spread (Hamner et al. 2020). Several other meeting participants referred to subsequently published analysis by Miller and colleagues (2020) as being more strongly indicative of airborne transmission.

Community epidemiologic studies also indicate that secondary attack rates—the probability that an infection occurs among susceptible people within a specific group—are generally greatest among household contacts. The risk appears to be lower among other interpersonal contacts, such as sharing a meal, and even lower for passing interactions, such as grocery shopping. Data also indicate that of those infected with SARS-CoV-2, a higher percentage of this group had eaten in a restaurant (where masks are removed to eat) during the 14 days prior to onset (Fisher et al. 2020). Additionally, data have suggested that mask wearing in the community slows the spread of the virus; the number of daily cases was lower in states where mask mandates were implemented (Lyu and Wehby 2020).

Butler clarified that droplet and airborne transmission are not mutually exclusive. Roy and Milton (2004) outlined a paradigm for classifying airborne transmission as *obligate* (infection occurring only via aerosol deposition), *preferential* (predominant aerosol deposition and mode-dependent clinical presentation), and *opportunistic* (non-airborne transmission is most common but aerosols[7] may transmit infection under favorable conditions). As alluded to in EHMI chair Thomas Burke's

[6] For more description of super-spreader events, see Galvani and May (2005).

[7] The phrase "fine-particle aerosols" was used by Butler and in the referenced paper. Such aerosols fall within the term "aerosols" as used in this document.

opening comments on the epidemiologic triangle (see Figure 3), there are a number of environmental and other variables (continuous exposures during the infectious period, a lack of protective measures like face coverings, and air characteristics) that can affect the relative importance of droplet versus airborne transmission. Butler said their relative importance is something public health officials need to determine as they try to limit both transmission and non-health effects of the pandemic.

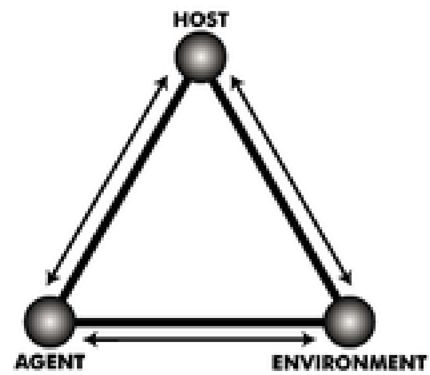

FIGURE 3 Epidemiologic triangle denotes the relationship among agent, host, and environment. The agent, or microbe, causes disease; the host, or organism, harbors disease; and the environment, or external factors, causes or allows disease transmission. SOURCE: Burke 2020.

OVERVIEW OF AEROSOLS AND TRANSMISSION OF RESPIRATORY VIRUSES

After the opening talks, Marr, an aerosol scientist specializing in viruses, provided a general overview of aerosols and droplets, and their role in the transmission of respiratory viruses. An understanding of the basic principles and terms is important to inform understanding of the SARS-CoV-2 situation and enable communication among experts with different technical backgrounds. Transmission of respiratory viruses can occur through direct person-to-person contact, indirect contact, large droplet spray, aerosols, or a combination of these. Infectious disease practitioners traditionally describe large droplet sprays as comprising material >5 μm and occurring at close range (<2 m or 6.6 feet), while aerosols that transmit disease are described as involving material <5 μm. These terms, and others that describe size and behavior of viruses (e.g., droplets, droplet nuclei) have been used differently by infectious disease practitioners than by aerosol scientists, creating challenges in moving the science forward (see Table 1).

TABLE 1 Terminology for Particles Involved in Airborne Diseases

Terms	Traditional Thinking (based on longstanding misconceptions, *not* informed by aerosol science)	Updated Descriptions (informed by aerosol science and exposure pathways)		
		Definition and Typical Size	Behavior in Air	Exposure Pathways
Aerosol[a]	Particle <5 μm	Stable suspension of solid and/or liquid particles in air, smaller than about 100 μm	Can remain airborne for extended time. Concentration is highest near source. Concentration decreases with distance from source but can travel farther than about 2 meters or 6 feet and build up in a room	Inhaled into respiratory system
Droplet	Particle >5 μm	Liquid particle, larger than about 100 μm	Settles quickly to the ground or on to a surface. Travels less than about 2 meters or 6 feet, except when propelled (e.g., sneezes and coughs)	Exposure via eyes, nose, or mouth at close range

[a] Aerosol is used here as a shorthand for "aerosol particle," reflecting common usage. When the physical attribute of the particle is described in this document, the term aerosol particle is used.

NOTES: The table illustrates how differences in language can contribute to confusion and prevent a shared understanding of the science. Several workshop leaders proposed terminology informed by aerosol science and emphasizing exposure path to improve communication and understanding. This table is based on concepts presented by Linsey Marr and others at the workshop.

As Marr notes, there has been widespread conception that aerosols and droplets >5 µm settle within about 6 feet of the infected person generating them due to gravity. However, the use of 5 µm as a cutoff for these definitions is not supported by modern aerosol science, stated Marr, and has hampered the understanding of the transmission by creating a false dichotomy between what is considered a droplet and what is considered an aerosol. Importantly, despite its lack of grounding in science, this dichotomy has guided decision-making about controlling transmission, for example, underpinning guidance around infectious disease control in hospitals.

The exposure path of the virus is critical to understanding transmission, stated Marr. Droplets are sprayed on to the body and its mucus membranes, a form of contact transmission, while aerosols are inhaled into the respiratory system. As mentioned above, this distinction currently drives control strategies, infectious dose, and severity of disease. At close range, both contact and inhalation transmission routes are possible, but at a longer range, once droplets have settled quickly, transmission by inhalation is the important route. Aerosol science indicates there is no 5 µm "cutoff," so aerosols >5 µm spread further than 6 feet and are subject to inhalation. Marr noted, as discussed by Ristenpart below, that aerosols can also be formed from resuspension of settled dust or aerosols.

To address the challenges created in terminology and the incorrect understanding that there is a 5 µm cutoff that dictates how viruses spread, Marr and other workshop participants proposed terminology usage that is informed by aerosol science and exposure path (see Table 1). Their suggestion was that the term aerosol be used to describe the stable suspension of solid and/or liquid particles in air, smaller than about 100 µm (some said ~30 µm or 60 µm, noting that this detail is less important than the fact that size is about an order of magnitude more than 5 µm). In contrast, a droplet (sometimes referred to as a spray droplet) is a liquid particle, larger than about 100 µm. This terminology is adopted in this Proceedings of a Workshop—in Brief, even when it differs from the actual words used by presenters and discussants.

What size aerosols and droplets contain viruses? This is discussed in more detail in later sections and in Table 1, but Marr noted that viruses, in general, have been observed in respiratory fluid or saliva that forms aerosol and droplet sizes ranging from 0.2 µm to 100 µm. These aerosols and droplets are produced by breathing, talking, and coughing, with talking associated with aerosols and the fast-settling droplets with coughing.

CRITICAL QUESTION 1: WHAT SIZE DROPLETS AND AEROSOLS ARE GENERATED BY PEOPLE AND HOW DO THEY SPREAD IN AIR?

This session focused on the source of droplets and aerosols and how they spread in the air. Kimberly Prather, Scripps Institution of Oceanography, University of California, San Diego, chaired the session and presented a synthesis of Critical Question 1 at the end of the workshop. That synthesis is reflected in boldface; the full synthesis can be found in workshop recordings and slides.

Prather stated that **individuals generate aerosols and droplets across a wide range of sizes and concentrations.** The size distribution is multimodal, said Lidia Morawska, Queensland University of Technology, reflecting the origin of aerosols and droplets in different regions of the respiratory tract and production via different mechanisms. The smallest aerosols are probably generated from bronchial fluid film burst and laryngeal vibrations associated with speaking and singing. Larger aerosol particles and droplets are associated with specific oral speech articulation movement, as well as coughing and sneezing.

The vast majority of aerosols observed in human breath are <10 µm. Breathing, talking, and singing produce ~100–1,000× more aerosol particles (<100 µm) than droplets (>100 µm). Marr showed that exposure to aerosols far exceeds exposure to droplets, except for coughing and at distances less than 0.5 meters (see Figure 4). She pointed out that a large fraction of transmission of SARS-CoV-2 involves asymptomatic individuals who are not coughing or sneezing, suggesting that exposure to aerosols is an important transmission pathway.

Aerosol production varies widely for different people and activities. For example, William Ristenpart, University of California, Davis, noted that louder talking produces a larger number of aerosols than softer talking or whispering. Activities that involve deeper breathing (e.g., singing) produce more aerosol particles from the lower respiratory tract. Further research is needed into these variations in where in the respiratory tract aerosols are generated, and which activities are most conducive to aerosol generation, said Ristenpart.

Donald Milton, University of Maryland School of Public Health, said that better understanding of the physiological factors that contribute to aerosol generation could improve understanding of the potential role of super-spreading events, in which one individual has infected many others. He noted that about 20% of people produce 80% of the aerosols in a room, and that about 10% of COVID-19 cases have led to about 80% of the infections. Improved understanding of production mechanisms and fluid composition that lead to different sizes and numbers is needed to explain variability in production of infectious aerosols.

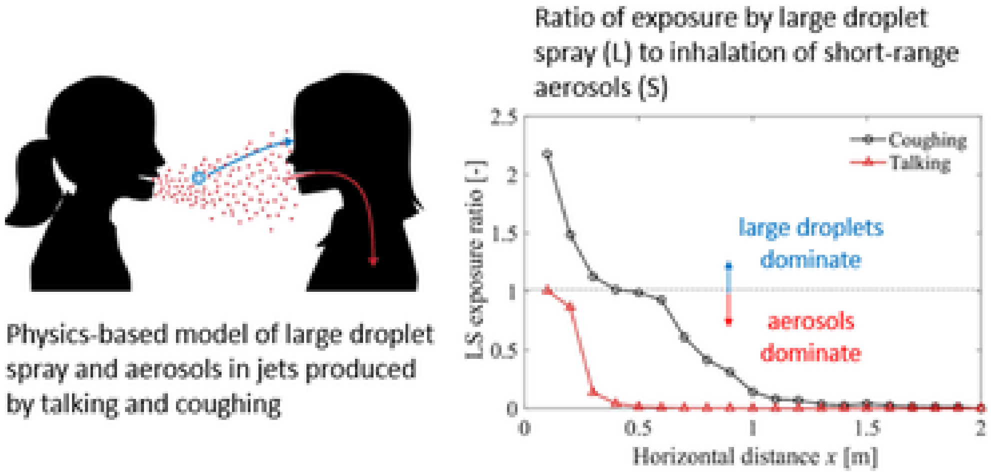

FIGURE 4 Droplets versus aerosols during coughing and talking. Aerosols dominate as the distance from the source increases, for both coughing and talking related exposure. SOURCE: Chen et al. 2020.

After being breathed out, aerosols and droplets immediately begin to shrink due to evaporation of the water and other fluids in them, said Morawska. This rapid evaporation results in aerosol particles that are ~30–50% of their initial size (Nicas et al. 2005). Milton also noted that the virus within the aerosol or droplet is subject to biologic decay from exposure to ultraviolet (UV) light, desiccation, or other factors.

Droplets settle rapidly, while aerosols can be carried over further distances, stated Lydia Bourouiba, Massachusetts Institute of Technology. These aerosols are transported by exhalation gas flows emitted by a person, which can then be transported over large distances rapidly. As the exhaled cloud that carries them slows down, the background ventilation airflow takes over to disperse the remaining particles in the air in the indoor space. Eventually, these particles land, or "deposit," on surfaces. If they land on susceptible cells (e.g., in the bronchia, distal lung, eyes) they can then cause infection, said Milton. It is not yet known how many infectious aerosols or droplets are needed to cause infection (see discussion in Critical Question 4).

All exhalations—breathing, talking, singing, sneezing, and coughing—create a continuum of aerosols and droplets suspended in a multiphase turbulent gas cloud of exhaled air, said Bourouiba. The exhaled cloud, along with aerosols and droplets of all sizes, can travel up to 8 meters in the case of sneezes (Bourouiba 2020).[8] All exhalations—from breathing, talking, singing, coughing, and sneezing—can emit the same regimes of high-momentum clouds with contaminated droplets within, but the ranges (distance) they reach differ, and the aerosol and droplets within them differ in size, Bourouiba said. To further understanding, Bourouiba called for a unified methodology for quantification of respiratory flow emissions across studies. She also suggested a need for the development of multiscale models (coupling of models at different scales) that account for physical processes associated with transmission dynamics, which would enable better risk assessment and understanding of transmission pathways.

Resuspension of virus-containing dust or aerosol particles that have settled on the floor, clothing, or other surfaces, as well as aerosolization of fomites, could be another transmission pathway, said Ristenpart, noting up to half of the aerosols in a room may be attributed to resuspension by walking on floors. Rubbing a contaminated tissue has been shown to create thousands of aerosol particles, and guinea pigs have been shown to transmit viruses via their fur (Asadi et al. 2020). The potential for resuspending the virus into air has implications for cleaning protocols and the handling of used personal protective equipment, leading Ristenpart to call for more research to determine the importance of these pathways.

In her synthesis, Prather pointed out that the speakers and panelists each indicated that **aerosols represent an important transmission pathway for SARS-CoV-2.** She noted that this view is supported by several lines of evidence:

- Aerosols can contain infectious SARS-CoV-2, remain suspended in air for hours, and be transported many meters from the source.
- Asymptomatic individuals emit mostly aerosols with sizes <10 μm and produce very few droplets.
- Super-spreading events are more readily explained by aerosol transmission.
- Aerosols are more concentrated at close range and can spread and accumulate in a room, leading to both close and long-range exposure.
- Transmission in outdoor settings has been much less common than indoors.

[8] Other experts, such as Marr, said sneezes are not a significant factor in SARS-CoV-2 transmission.

Definitively proving the aerosol transmission pathway is challenging and will require more research, according to Milton and William Lindsley, National Institute for Occupational Safety and Health. In particular, Milton and Lindsley noted that methods that can sample different sizes and large volumes of air while not damaging the virus are needed. Milton also emphasized the need for more measurements of how the size of aerosols and droplets generated varies by activity. Research on airborne transmission pathways for SARS-CoV-2 transmission may not yield definitive results for some time, as has been the case for other airborne diseases, most notably measles and tuberculosis, said Milton. Thus, given the available evidence pointing to airborne transmission as a potential pathway, a prudent public health strategy would be to take measures to limit this pathway, said Robert Schooley, University of California, San Diego.

The speakers and panelists addressed many audience questions about various interventions to limit the spread of SARS-CoV-2. The recurring theme of their responses, according to Prather, was that current evidence suggests that **multiple transmission pathways for SARS-CoV-2 can occur, supporting the need for layered interventions.**[9] Schooley emphasized that masks limit bidirectional transfer of infectious aerosols and droplets, protecting the wearer and those surrounding the wearer. Bourouiba added that, even with the mask, indoor activities should be limited, and distances maintained because of local leakage from the masks, accumulation of aerosols indoors, and the importance of accounting for the breathing zone in addition to overall indoor airflow. Marr noted that ventilation and filtration can have a major effect on aerosol concentrations. Ristenpart pointed out that plexiglass barriers and face shields reduce droplet transmission, but do not limit aerosols because they are transported in the air currents.

CRITICAL QUESTION 2: WHICH SIZE DROPLETS AND AEROSOL PARTICLES ARE INFECTIOUS AND FOR HOW LONG?

This session addressed factors that influence the infectivity and transport of SARS-CoV-2, including which size droplets and aerosol particles may be infectious, and for how long. The session also focused on what is known about how well masking provides source control. John-Martin Lowe, University of Nebraska Medical Center, chaired the session and presented a synthesis of Critical Question 2 at the end of the workshop. That synthesis is reflected in boldface; the full synthesis can be found in workshop recordings and slides.

Humans infected with SARS-CoV-2 can produce infectious aerosols that may be able to transmit the disease after sufficient exposure, stated Lowe. Josh Santarpia, University of Nebraska Medical Center, said the aerosol spread of SARS-CoV-2 between humans is supported by studies finding that hospital rooms of COVID-19 patients have widespread contamination in the air and on surfaces, detected via RNA positive samples (Chia et al. 2020; Ong et al. 2020; Santarpia et al. 2020). Although these RNA positive samples indicated the possibility of infectious virus, cell culture results were inconclusive except in sub-micron-sized particles (Santarpia et al. 2020). However, an important and more recent study using a "gentler" collection method was able to measure infective virus (Lednicky et al. 2020). Taken together these studies indicate that COVID-19 patients can produce aerosols with intact virions capable of replication in cell culture.

Viral half-life in aerosol is approximately 1.1 hours, said Emmie de Wit, Rocky Mountain Laboratories. She described research on the impact of environmental conditions on the infectivity of SARS-CoV-2 in aerosols. The Goldberg drum is used to keep artificially generated aerosols in suspension and to measure infectious virus stability. With this approach, her laboratory found the half-life of SARS-CoV-2 was a little over an hour (van Doremalen et al. 2020). Others have also found infectious aerosols after 16 hours in the Goldberg drum, demonstrating virus stability (Fear et al. 2020).

UV light greatly decreases virus stability, and lower temperatures and humidity may increase stability, de Wit said (Schuit et al. 2020). With high humidity, the half-life of the virus decreased to 55 minutes in one study; other studies have also shown half-life decreases with increasing humidity (Morris et al. 2020). Studies show that the virus loses infectivity faster in warmer temperatures. The effect of sunlight on the virus was examined using simulated UV light to mimic spring, fall, and summer sunlight. These studies showed the half-life of SARS-CoV-2 decreased to less than 6 minutes, or 10% of what is seen in dark environments.

de Wit discussed studies of the stability of SARS-CoV-2 in respiratory secretions. In one laboratory experiment that used simulated saliva (Schuit et al. 2020), the virus was found to be less stable than in tissue culture at high relative humidity, while another study showed the opposite (Smither et al. 2020). She noted that while there are no data with real human respiratory secretions, SARS-CoV-2 in mucus and sputum transferred to surfaces had a shorter half-life than SARS-CoV-2 in tissue culture medium (Matson et al. 2020), suggesting stability in aerosols from the respiratory tract may be lower than in laboratory studies using culture medium.

Available evidence for face coverings (masks) consistently indicates a reduction of community transmission, said Ben Cowling, The University of Hong Kong. He discussed research on the effectiveness of face masks for reducing the spread of COVID-19, which is described in further detail in Box 2.

[9] The effectiveness of masks and other interventions was discussed throughout the workshop and is thus captured in several places within this Proceedings of a Workshop—in Brief.

During the discussion, panelists identified challenges in studying and understanding the dose required for infection, the topic of Critical Question 4 below. Milton noted that in experimental studies done in the 1960s on influenza, the infectious dose was far lower via aerosols than drops. Santarpia and Catherine Noakes, University of Leeds, noted the need to study the infectiousness of exhaled breath from all forms (breathing, talking, and coughing). The panel noted the biologic plausibility of airborne transmission of the disease, despite difficulty in segregating aerosols from droplets in samples. This is further supported by studies that demonstrate that the virus can remain infectious on surfaces and in air for hours.

Lowe's synthesis of the discussion included several areas where he noted panelists' alignment on the need for future research, including:

- Characterization of human-generated infectious SARS-CoV-2 aerosols. This includes research on variability in production rate of infectious aerosol from person to person; production of infectious aerosol over the course of illness; and the relationship between aerosol dose and response through the aerosol route. There is also a need to devise aerosol collection devices that optimize preservation of intact virus.
- How long human generated aerosols last in different environments and how to characterize these environmental factors in high-risk settings (e.g., long-term care facilities, dental offices, bars, restaurants, and schools).
- Effect of temperature, humidity, and sunlight on stability of the virus in actual respiratory secretions.
- Characteristics of optimal face covering, to support source control.
- Greater understanding of effective face covering strategies in different environments to inform clear public guidance.

CRITICAL QUESTION 3: WHAT BEHAVIORAL AND ENVIRONMENTAL FACTORS DETERMINE PERSONAL EXPOSURE TO AIRBORNE SARS-COV-2?

This session addressed a range of factors that affect how much individuals are exposed to SARS-CoV-2. Exposure to infectious aerosols and droplets can be influenced by human behaviors, characteristics of the built environment, interventions intended to mitigate exposure risk, and other factors. Volckens chaired the session and presented a synthesis of Critical Question 3 at the end of the workshop. That synthesis is reflected in boldface; the full synthesis can be found in workshop recordings and slides. The discussions focused almost exclusively on indoor environments, where risk of exposure to SARS-CoV-2 is greatest.

Respiratory plumes containing a continuum of small aerosols to large droplets are an important determinant of exposure at short-range distances (<1.5 meters or ~5 feet) from infected individuals, said Yuguo Li, The University of Hong Kong. Sharing of respiratory plumes is modulated by distance between individuals, behaviors (e.g., gestures, face touching),

BOX 2 Effectiveness of Face Coverings (Masks)

Julian Tang, University of Leicester, said masks reduce both emissions and intake of aerosols and droplets by the wearer. In his research with Milton and colleagues (2013), surgical masks were estimated to reduce aerosol emissions of influenza from source individuals by 67–75% and to reduce intake by 50–83%. Cowling discussed an important finding for human coronaviruses—for smaller (<5 μm) aerosols as well as larger aerosols and droplets containing human coronaviruses, surgical masks had an effect at source control and also provided some protection for the wearer (Leung et al. 2020). Drawing on data from other respiratory viruses, Cowling said the data were consistent with a 10–20% reduction in transmission by a combination of both mask use and enhanced hand hygiene (Xiao et al. 2020). Tang and Cowling both discussed the challenges of randomized clinical trials, and why it is difficult to measure an effect. Specifically, Cowling expressed concern that an upcoming trial design (ClinicalTrials.gov 2020) with only enough statistical power to detect a >50% reduction in SARS-CoV-2 transmission risk could come back negative and be misinterpreted. A negative result in this trial would not mean masks do not work, Cowling said; even a 10% reduction in transmission is valuable.

Synthesizing from Tang and Cowling's discussion and placing it into the context of other studies, John Volckens, Colorado State University, said it is known that masks or face coverings reduce aerosols and droplet emission at the source by 52–90%, depending on mask type, fit, and use. Masks also reduce wearer intake of aerosols and droplets by 25–90%, depending on details. Furthermore, masks reduce jet propagation of respiratory plumes, limiting the distance traveled by droplets and aerosols in the plumes. Focusing on the overarching conclusion, Lowe said "in general, the conclusions are all the same ... a good sign that we are achieving consensus in the scientific community on the efficacy of masks.... There is clear mechanistic evidence that face masks provide protection for the wearer, knowing that not all face masks are created equal and there are different masks and different levels of protections that are afforded." That said, Cowling and others made the point that universal masking alone will not be sufficient to interrupt spread. The largest outbreaks of disease have been found in communities where people do not wear masks, but there have been two community epidemics in Hong Kong that occurred despite 99% mask usage in required public places (such as mass transit services and taxis, but not in social settings, such as bars or restaurants) demonstrating the need to layer with other methods, including social distancing (Cowling et al. 2020).

local turbulence, and posture (Liu et al. 2017). Transmission at these closer ranges appears to be a dominant pathway for SARS-CoV-2, explaining why social distancing seems to be an effective way to limit spread of the disease (Jarvis et al. 2020). When people are close to each other, typical room ventilation alone is unlikely to reduce exposure to shared respiratory plumes.

At longer-range distances (>1.5 meters), smaller aerosols that can remain airborne for longer time periods dominate exposure, said Li. Super-spreader events in which individuals at some distance have been infected would suggest that this distant transmission occurs. Li noted that the risk of exposure at longer distances is likely greater in indoor environments that lack sufficient ventilation. More research is needed to help determine how much ventilation is "enough" to minimize exposure, he added.

Indoor environments have been associated with infection events, including outbreaks and super-spreader events, said Tang. Crowded, indoor, poorly ventilated areas like bars, cinemas, and restaurants can be conducive to accumulation of aerosols laden with virus, particularly if people are conversing and remain for extended time periods (Qian et al. 2020). Tang also commented on airplane ventilation systems, designed to reduce the build-up of airborne virus in the passenger cabin, thus limiting longer-range airborne transmission. The greater exposure risk on airplanes is from close-range interactions, such as face-to-face conversations.

Masks (face coverings) reduce both emissions and intake of aerosols and droplets by the wearer, said Tang (described in more detail in Box 2).

Shelly Miller, University of Colorado Boulder, addressed the ways that **ventilation can reduce room-based exposure.** Ventilation, she said, should be based on occupancy of the indoor space and there is no "one-size-fits-all" rate to eliminate exposure risk. For example, the American Society of Heating, Refrigerating and Air-Conditioning Engineers recommends 2.5 L/s per person[10] ventilation rates for churches (ASHRAE 2003) and 6.7 L/s per person for school classrooms. A study of college dormitories found that ventilation rates of <5 L/s per person may be impacting acute respiratory infections (Zhu et al. 2020). Miller noted that other studies have suggested much higher ventilation rates. For example, one study concluded that outdoor air supply rates of <25 L/s per person increase the risk of sick building syndrome symptoms, increase short-term sick leave, and decrease productivity (Wargocki et al. 2002).

The lack of ventilation is thought to have contributed to COVID-19 outbreaks, according to Miller, who highlighted a study conducted by Li and colleagues of a COVID-19 outbreak at a restaurant in Guangzhou, China (see Figure 5). The lack of outside air supply and strong air currents from air conditioning in just one location are thought to have contributed to the outbreak (Li et al. 2020). The lack of ventilation is also implicated in the Skagit Valley Chorale Rehearsal outbreak, said Miller. The facility where the rehearsal was held likely had <1 air change per hour, allowing significant accumulation of aerosols during the 2.5-hour practice (Miller et al. 2020).

[10] L/s is liter per second.

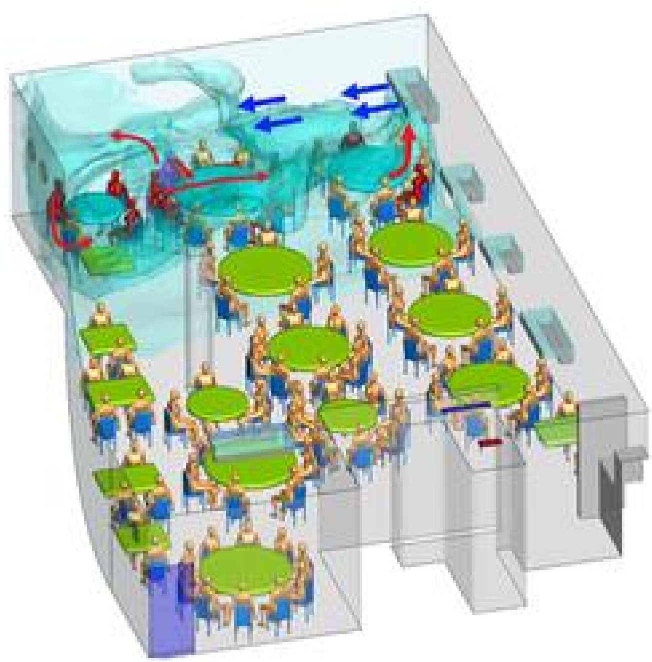

FIGURE 5 Schematic showing arrangement of restaurant tables and air conditioning airflow at site of a COVID-19 outbreak in Guangzhou, China, 2020. NOTE: Red indicates seating of future case patients; blue indicates the index case patient. SOURCE: Li et al. 2020.

Miller noted that research is needed to determine what ventilation rates are warranted for airborne infectious disease control. Another challenge will be to develop energy-efficient and cost-effective technologies and strategies that also provide high ventilation rates as current practices to minimize energy use are not conducive to high ventilation.

Filtration is an effective supplement to ventilation for reducing aerosol concentrations indoors, said Miller. Measures of the effectiveness of filtration systems have been developed (see Box 3). When deploying filtration technologies, it is critical that the clean air delivery rate is sized to accommodate the room volume, accounting for existing ventilation. More research is needed on where to place air cleaners to be most effective given typical air flow patterns, said Miller. In addition, she noted the need to study how best to upgrade filtration efficiency in existing heating, ventilation, and air conditioning (HVAC) systems.

BOX 3 Measures Used for Ventilation and Filtration Systems

Ventilation Rate is the volume of outside air added to a space per unit time per occupant, typically measured in L/s/person.

Air Change Rate is a measure of the outside air volume added to a space divided by the volume of that space.

High Efficiency Particulate Air filters are a type of mechanical air filter that can theoretically remove at least[a] 99.97% of dust, pollen, mold, bacteria, and aerosol particles.

Minimum Efficiency Reporting Value (MERV) is a rating derived from a test method developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers. The higher the MERV rating the better the filter is at trapping.

Clear Air Delivery Rate is the effective rate (volume per unit time) of filtered air produced by a filtration device.

[a]"The diameter specification of 0.3 microns responds to the worst case; the most penetrating particle size. Particles that are larger or smaller are trapped with even higher efficiency." See https://www.epa.gov/indoor-air-quality-iaq/what-hepa-filter-1.

Germicidal ultraviolet (UV-C) light can be useful in environments where it is otherwise challenging to ventilate or filter, said Miller. Microorganisms are uniquely vulnerable to radiation at or near 260 nanometers (UV-C or germicidal) due to the resonance of this wavelength with molecular structures. Overexposure to UV radiation can result in skin and eye irritation; therefore, any use of germicidal UV-C must be applied in a way that does not directly expose humans to it, said Miller. One approach is to use UV to disinfect the upper-room air (above human height) when additional control is needed, such as in places where infectious aerosol may be generated (e.g., hospital treatment and isolation rooms), rooms where HVAC retrofits are difficult to do, and crowded environments where asymptomatic and potentially infectious persons may be present (e.g., jails, homeless shelters, hospital waiting rooms) (NIOSH 2009). UV has also been applied to air within ducts, though this approach is only effective if the airflow is slow enough, said Miller. She said additional research is needed to determine the best germicidal UV design for specific spaces such as schools and restaurants, better characterize the impact of germicidal UV on SARS-CoV-2 transmission, and investigate the potential use of other light wavelengths or LEDs.

Panelist William Nazaroff, University of California, Berkeley, emphasized **the essential importance of layered interventions.** No single intervention will be effective at eliminating risk, he stated, and it is important to diligently apply multiple preventive actions to the extent that they can be done reasonably. These measures include hand hygiene, distancing, wearing masks indoors, ventilation, and filtration. Nazaroff noted that, as Northern hemisphere winter approaches, people will be spending more time indoors, suggesting a larger emphasis on adding air filtration. Nazaroff shared a poem he authored to succinctly capture the nature of interventions that scientists expect will help limit the spread of COVID-19 (see Box 4).

BOX 4 "COVID-19 Risk Management: A Layered Approach" by William Nazaroff, University of California, Berkeley

Outdoors is better than indoors
Short is better than long
Masked is better than unmasked
Socially distant is better than too close
Sparse is better than crowded
Quiet is better than loud
Gentle breathing is better than vigorous breathing
Risk can be lowered indoors (but not eliminated) by improved ventilation and air filtration

During the open discussion, the speakers and panelists commented on racial and socioeconomic disparities in COVID-19 infections, and how that might be connected to the built environment. Nazaroff noted that Hispanics in Alameda County, California, are getting sick with COVID-19 seven times more than non-Hispanic Whites in the same area. He speculated that housing and crowding could be a big factor in this disparity. Miller commented that immigrant communities in north Denver have a similar disparity, which may be due to crowded living conditions, as well as possible unsafe working conditions for these populations. She noted the need for more public health efforts and communication to support these communities.

The discussants noted that making progress on remaining unknowns will require interdisciplinary research that demonstrates effective ways to reduce emissions and exposure risks, including:

- Flexible, scalable models to improve understanding of the complexity and dynamic nature of exposure.
- Comprehensive data on human bioaerosol emissions (variation by individual, time, activity) and exposures.
- Quantitative evidence of infection risk reduction as a function of applied control technology.
- Improved exposure measurement technology to define timing, location, mode, and intensity of exposure. Specific improvements suggested include personal-level measurements, sampling that supports pathogen viability, and the ability to better capture spatial and temporal variability.
- Research on surveillance and exposure reduction, to prevent super-spreading events before they happen.

CRITICAL QUESTION 4: WHAT DO WE KNOW ABOUT THE INFECTIOUS DOSE AND DISEASE RELATIONSHIP FOR AIRBORNE SARS-COV-2?

This session focused on whether people can inhale enough SARS-CoV-2 to become infected; the relationship between infectious dose and disease; and how biological modifiers such as age, sex, and underlying medical conditions may influence disease outcomes. To inform understanding on these questions, researchers discussed what is known about SARS-CoV-2 itself as well as what can be extrapolated from the infectivity and behavior of influenza and other viruses and from animal models. Seema Lakdawala, University of Pittsburgh School of Medicine, chaired the session and presented a synthesis of Critical Question 4 at the end of the workshop. That synthesis is reflected in boldface; the full synthesis can be found in workshop recordings and slides. The discussions focused almost exclusively on indoor environments, where risk of exposure to SARS-CoV-2 is greatest.

Human and animal studies on different coronaviruses have demonstrated a range of infectious doses that is dependent on external factors, Lakdawala explained. She described early efforts to determine how much virus is needed to infect 50% of those exposed (known as the infectious dose 50 or ID50). Based on human experiments or natural occurrences of other coronaviruses, the ID50 ranges from 10 to 1,000 infectious virions (see Figure 6). For SARS-CoV-2, based on hamster studies, the ID50 is less than 1,000 infectious viruses given through intranasal drops (Imai et al. 2020).

Factors that impact the infectious dose are important, and Lakdawala discussed the difference between droplets and aerosols, where with influenza, it was found that small micron-sized aerosol particles required a far lower dose to cause infection than did large droplets (Alford et al. 1966). Additionally, immunity of the recipients matters, and she cited an influenza H1N1 study where the ID50 increased to 383,000 virions in individuals with some pre-existing immunity (Memoli et al. 2016). Other factors that influence the infectious dose include age, sex, and receptor abundance and distribution. Lakdawala explained that SARS-CoV-2 binds to the angiotensin-converting enzyme receptor, the number and distribution of which vary greatly depending on age, sex, and behaviors such as smoking. Charles Haas, Drexel University, suggested conveying information on infectious dose by framing it in terms of a dose–response relationship, as infection can occur even with a low dose.

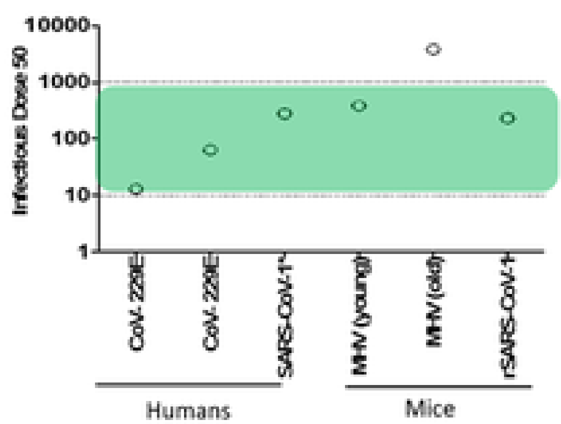

FIGURE 6 Infectious dose ranges of coronaviruses. These studies showed a range of 10 to 1,000 infectious viruses were needed to infect 50% of the recipients (i.e., ID50). SOURCES: Figure from Lakdawala 2020, based on data from Bradburne et al. 1967; Callow et al. 1990; Dediego et al. 2008; Taguchi et al. 1979; and Watanabe et al. 2010.

SARS-CoV-2 is transmitted by aerosol in animal models, described Hui-Ling Yen, The University of Hong Kong. Studies of transmission of SARS-CoV-2 in ferrets caged together and cats caged together showed that direct contact and/or close proximity was a more efficient mode of transmission (Halfmann et al. 2020; Richard et al. 2020; Shi et al. 2020; Young-Il et al. 2020). However, in hamsters, aerosol transmission was the dominant mode (Sia et al. 2020). Timing also matters; hamsters were unable to transmit infection more than 6 days after their infection. The dominant mode of transmission can differ between animal models and for some, the communicable period is short, Yen concluded.

For influenza, the size of exhaled virus-containing aerosols and droplets can differ by strain of virus, and size can impact infectiousness. Yen noted that ferret studies indicated that transmission of influenza was mediated by aerosols >1.5 μm, even though 77% of exhaled aerosols are ≤1.5μm (Zhou et al. 2018). She stressed that smaller aerosols may play a more important role in some strains of influenza virus than others, which suggests variations by strain in the dominant mode of transmission. Kevin Fennelly, National Institutes of Health, noted that the location where different size aerosols deposit in the lungs is primarily determined by their size, with very fine aerosols of 1 μm having a high probability of depositing deepest in the lung and causing more disease with a lower dose.

The dose as well as individual characteristics are important determinants of SARS-CoV-2 disease severity. Vineet Menachery, The University of Texas Medical Branch, discussed the relationship between dose and disease, with the caveat that animal models may not be able to precisely simulate how infection occurs naturally. In hamsters and mice, the higher the dose, the more severe the illness for coronaviruses, including SARS-CoV-2 (Coleman et al. 2017; Imai et al. 2020; Menachery et al. 2015). However, even at the same dose, disease varies based on host conditions to include genetic background, health status, and age. In mouse studies, genetic differences alter the disease severity, even independent of viral dose (Gralinski and Baric 2015). The same holds true for obesity in mice (see Figure 7). Increased age is also a risk factor for humans, and studies have demonstrated increased disease severity with increasing age. Fennelly mentioned that both acquired and innate immune responses to infection, such as mucociliary clearance of particles from the lungs, decrease with age.

While genetics, underlying health conditions, and age can all impact disease severity, the combination of these conditions does not always lead to a predictable outcome, stated Menachery. Dose impacts disease but it is not the only variable driving the outcome. Sabra Klein, Johns Hopkins Bloomberg School of Public Health, also described gender as a biological variable that can alter the outcome of COVID-19. Based on worldwide reporting, males have a higher fatality rate regardless of the national case fatality rate. Reasons for the higher disease severity risk in men could be gender differences in virus entry and immune response. Males have also been shown to shed more virus and for longer periods of time (Xu et al. 2020; Zheng et al. 2020). Fennelly noted that young adult males transmit more tuberculous bacilli than females, children, or older men, so such gender differences have been seen with other pathogens.

In her synthesis, Lakdawala noted the importance of aerosols in SARS-CoV-2 transmission, which is bolstered by animal models, with severity of disease linked to the infectious dose and influenced by genetic factors including sex, age, and underlying health status. These issues are supported by the following evidence:

- Animals infected with SARS-CoV-2 can release virus-laden aerosols that can infect susceptible recipients.
- Transmission in animals occurs early after infection, rather than late.
- Transmissibility of aerosols is dependent on their size.
- Animal studies suggest that higher inoculum doses will lead to more severe infection.
- Similar doses can result in different disease outcomes based on age, genetics, and obesity.
- Male and female humans have distinct case fatality rates, and males may shed more virus.
- Potential mechanisms for genetic differences include difference in virus receptors, virus sensing, and innate and adaptive immune responses.

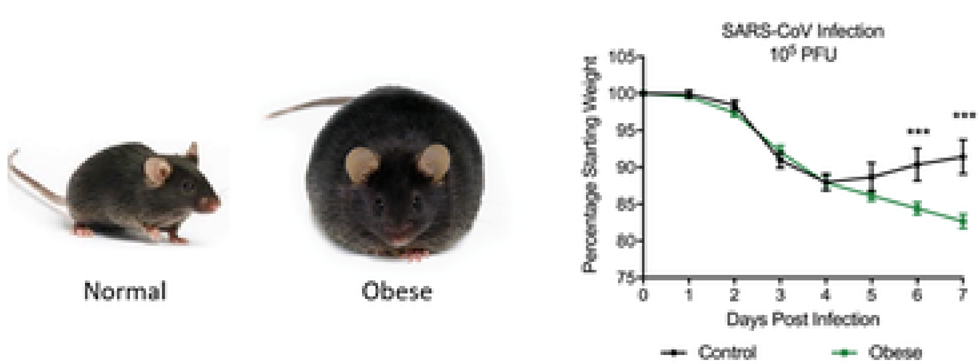

FIGURE 7 Mouse studies of SARS-CoV disease in mice (normal versus obese). Diet-induced obesity model shows exacerbated SARS-CoV disease. Disease in this model is indicated by weight loss; obese mice continued to lose weight at a significantly higher rate than control mice at 4–7 days post-infection. NOTE: PFU refers to plaque-forming units. SOURCE: Menachery 2020.

To more fully understand conditions that may increase the risk of transmission, Lakdawala said, **more research is needed to define the human infectious dose range, differences in infectivity by aerosol particle size, and impact of external factors on disease severity**. Yen emphasized the need to know how dose and route of inoculation impact onward transmission; to know the size distribution of virus-laden aerosols in exhaled breath; and to know the size range of aerosols that mediate transmission. She also noted the limitations of animal models need to be taken into consideration when predicting effects in humans. In addition, the impact of repeated exposures needs to be determined, as does the impact of where the virus is deposited.

Menachery called for the development of an infection approach that resembles naturally occurring infections. For disease severity, more studies are needed on combinations of underlying health issues, age, sex, and other genetic factors. As Klein outlined, there are limited data on age and sex and more human data need to be available to determine the impact of these factors on transmission risk and infection rates.

When asked about what recommendations they would give based on this knowledge, the speakers said more aggressive mitigation strategies need to be deployed in populations at risk; treatment studies should be analyzed by sex and age; and other external factors such as air pollution on susceptible populations should be examined.

FROM AEROSOLS TO POPULATIONS

Samet gave a talk aimed at bringing the evidence on airborne transmission studies into consideration of the R value, or effective reproductive number. The value of R has been considered in relation to the relative importance of droplet versus aerosol transmission. To give context, Samet discussed the transmissibility (R_0), which reflects the start of an epidemic and incubation period of SARS-CoV-2 in comparison with SARS-CoV and the 1918 and 2009 influenza pandemics. SARS-CoV-2 has the highest average R_0 and a longer incubation period. Although comparison reflects the SARS-CoV-2 challenge of a high rate of people who are simultaneously asymptomatic and infectious, Samet noted that the reproductive number can vary over time. The need for considering variation in R_0 was highlighted in a systematic review (Guerra et al. 2017) of R_0 estimates of measles over time and by geography, in which it was shown that R_0 estimates were broader than the 12–18 often compared to SARS-CoV-2 and not clearly reflective of the circumstances of the population affected.

Given the limitations with R_0, Samet discussed the concept of effective reproductive number as proposed by Inglesby (2020) (referred to as R_e or R_t), which describes transmission once an epidemic is established, taking into account the environmental factors that contribute to transmission. Some factors that may drive this value include personal behavior, cleaning, masks, and population characteristics, among others (see Figure 8).

Factors that impact transmission can be thought of as micro- and macro-level environmental factors, Samet noted. At the micro-level, factors may include the ability to work from home and factors discussed at the workshop, such as characteristics of the built environment and how much ventilation is in buildings. At the macro-level, there are factors driven by local and national policies, such as public health stay-at-home or mask wearing orders. Samet added that in considering disease control, workshop participants had been focusing largely on factors at the personal and micro-environmental level, but these are also influenced by what happens at the policy level.

Samet also discussed an epidemic model, the Susceptible-Exposed-Infective-Recovered (SEIR), which is used to model data across different stages of an epidemic. Overlaying what is known about SARS-CoV-2 and incorporating the workshop's critical questions around transmission into this adapted model (see Figure 9) provides a broader framework to demonstrate the course of the epidemic in the population and how the factors captured in Critical Questions 1–4 affect the epidemic curve.

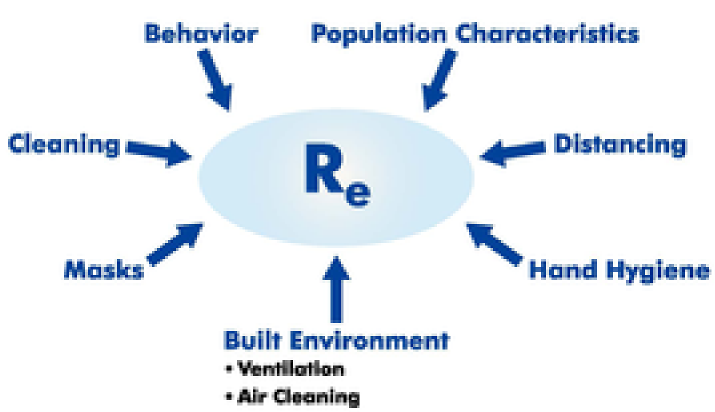

FIGURE 8 R_e (referred to by some as R_t), the Effective Reproduction Number, describes transmission once an epidemic is established. NOTE: This figure includes factors that may influence the R_e. SOURCE: Samet 2020b.

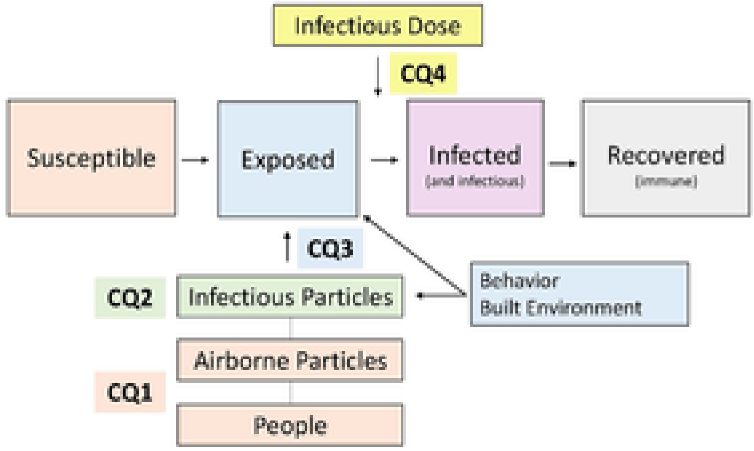

FIGURE 9 SEIR model with the workshop's critical questions. This diagram provides a broader framework for considering the course of the SARS-CoV-2 epidemic in the population. NOTE: CQ1–4 refer to the critical questions of the workshop. SOURCE: Samet 2020b.

IMPLICATIONS FOR DISEASE CONTROL

Patrick Breysse, CDC, moderated a panel focused on the implications of workshop discussions on the airborne transmission of SARS-CoV-2 in guiding public health efforts to reduce the spread of the virus. Panelists with a range of practical expertise, including a state public health official, a public health association leader, an environmental consultant, and a chief of infectious disease at a hospital, discussed their perspectives on these issues.

The need for effective communication and engagement was an important theme, as noted by Georges Benjamin, American Public Health Association, who acknowledged the challenge in communicating about appropriate public health measures when the understanding of the disease is rapidly evolving. The changing scientific knowledge relating to mask wearing is one example.

Multiple panelists acknowledged that COVID-19 has had a disproportionate impact on particular communities, specifically communities of color. Nicole Alexander-Scott, State of Rhode Island Department of Health; Trish Perl, UT Southwestern Medical Center; and others described the need to consider equity, including structural inequities, in communicating about COVID-19. There is a need to be culturally sensitive in communicating information about behaviors that may put people at higher risk of exposure, for example, considering the importance of family gatherings to emotional health. Alexander-Scott said that "we need to use science to engage and determine how to get together safely—balanc[ing] economic and emotional well-being of families and communities."

Challenges to equity go beyond communication, however. For example, Perl stated that funds need to be equitably distributed to health facilities. Benjamin also noted that it is important to consider that some economically disadvantaged or urban communities may not have the ability to control their built environment; for example, in cases where communities cannot afford to upgrade building ventilation or implement filtration measures, or even open their windows, which have been nailed closed for security reasons. There is a need for strategies for older buildings where ventilation cannot be altered. Mass transit can also pose particular challenges for those depending on public transportation, because of difficulties with social distancing.

The panelists were consistent on the need for layering protective measures to reduce the spread of the virus, including masking, hand hygiene, face shields where appropriate, physical distancing, and maximizing ventilation. These combined measures should be promoted as a single management strategy, stated Benjamin. Panelists pointed out the value of such layered approaches in indoor spaces, such as schools, public transportation, health care settings, air travel, dental offices, and office buildings. Again, the importance of layered strategies needs to be communicated in a culturally competent manner, particularly in communities that are distrustful of the health care system, stated Alexander-Scott.

While not disagreeing that such measures would reduce spread of the virus, Perl noted that limited resources may necessitate consideration of the relative value of approaches in different settings to reduce risk. She said, in somewhat of a contrast to earlier workshop discussions, that SARS-CoV-2 appears to be similar to infections that would traditionally have been considered transmitted by droplet, except in settings where the virus is aerosolized by certain procedures. As such, she sees aerosol-protective approaches as important in settings where procedures may generate more aerosols (e.g., dental offices or during particular medical procedures). On another note, Alexander-Scott cautioned about the unintended consequences of mitigation approaches, including impacts on energy use (e.g., for ventilation), the economy, mental health, the environment, and education.

Risk of exposure to COVID-19 in commercial flight situations was discussed by John "Jack" McCarthy, Environmental Health & Engineering, Inc., who consults for the health care and airline industries and a number of other organizations. He noted that while there are high ventilation rates in aircraft cabins, up to 30 air changes per hour, a key challenge is addressing travel-associated behaviors that may increase risk, such as crowding when exiting the plane.

Panelists discussed areas where additional research is needed to support practical actions to limit the spread of COVID-19. McCarthy noted the need for a greater understanding about the quantitative relationship between the dose and infectious disease response. Perl stated that quantitative data about the relative value of different measures, which would also improve communication around these issues, is critical. Broadening their comments beyond the workshop focus, Alexander-Scott and Perl discussed vaccine equity, and Benjamin and McCarthy emphasized the importance of increased testing to limit transmission.

CONCLUDING THOUGHTS

Throughout the 2-day workshop, participants discussed critical questions around the airborne transmission of SARS-CoV-2. In his closing remarks, Samet concluded that numerous speakers and panelists discussed evidence indicating people are a source of infectious materials emitted into the air. Numerous speakers discussed evidence that airborne transmission is significant based on animal model, mechanistic, and epidemiologic studies. Another theme was the importance of continuing to clarify key concepts and terminology to enable the science to be understood and incorporated into public health thinking. The importance of masks, ventilation, filtration, social distancing, and a layering of such interventions to prevent transmission of SARS-CoV-2 was also emphasized by a number of speakers and panelists. Many workshop participants discussed the need for additional research to more fully understand transmission of SARS-CoV-2, but Samet emphasized that such research does not eliminate the need to take immediate steps to prevent further infections via airborne routes. Thomas Burke, Johns Hopkins Bloomberg School of Public Health, added that the workshop highlighted actionable steps that can be taken immediately by public health professionals as they work to reduce the public's exposure to and risk of COVID-19. With current knowledge, action can be taken to reduce exposure as the world waits for a vaccine, he said.

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ABOUT THE ENVIRONMENTAL HEALTH MATTERS INITIATIVE

The workshop was held as the third event of the Environmental Health Matters Initiative (EHMI), a program that spans across the major units of the National Academies to facilitate multisector, multidisciplinary exchange around complex environmental health challenges. Other National Academies entities that contributed to this workshop include the Health and Medicine Division's Board on Global Health, Forum on Microbial Threats, Board on Health Sciences Policy, Standing Committee on Emerging Infectious Diseases and 21st Century Health Threats, and Board on Population Health and Public Health Practice; the Division on Earth and Life Studies' Board on Atmospheric Sciences and Climate, Board on Life Sciences, and Board on Environmental Studies and Toxicology; the Division on Engineering and Physical Sciences' Board on Infrastructure and the Constructed Environment; and the National Academy of Engineering's program office.

Workshop planning committee members are Jonathan M. Samet (*Chair*), Colorado School of Public Health; Georges C. Benjamin, American Public Health Association; Seema Lakdawala, University of Pittsburgh School of Medicine; John-Martin Lowe, University of Nebraska Medical Center; Linsey Marr, Virginia Polytechnic Institute and State University; Kim Prather, Scripps Institution of Oceanography, University of California, San Diego; Arthur Reingold, University of California, Berkeley; and John Volckens, Colorado State University. Reviewers of this proceedings were Diane Griffin, Johns Hopkins Bloomberg School of Public Health; Jose-Luis Jimenez, University of Colorado Boulder; and Linsey Marr, Virginia Polytechnic Institute and State University. Reviewers provide comments on the document's clarity and representation of the workshop discussion. The review of this Proceedings of a Workshop—in Brief was overseen by Richard C. Flagan, California Institute of Technology, who was responsible for making certain that an independent examination of this proceedings was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the rapporteurs and the National Academies.

The EHMI standing committee members are Thomas A. Burke (*Chair*), Johns Hopkins Bloomberg School of Public Health; Darrell Boverhof, Dow; George P. Daston, Procter & Gamble Company; Ana V. Diez Roux, Dornsife School of Public Health at Drexel University; Linda J. Fisher, DuPont; Estelle Geraghty, Esri; Lynn R. Goldman, The George Washington University Milken Institute School of Public Health; Daniel S. Greenbaum, Health Effects Institute; Gavin Huntley-Fenner, Huntley-Fenner Advisors, Inc.; Philip R. Johnson, The Heinz Endowments; Beth Karlin, See Change Institute; Jennifer McPartland, Environmental Defense Fund; Devon C. Payne-Sturges, Maryland Institute for Applied Environmental Health at the University of Maryland School of Public Health; Amy Pruden, Virginia Polytechnic Institute and State University; Martha E. Rudolph, Colorado Department of Public Health & Environment; Jonathan M. Samet, Colorado School of Public Health; and Deborah L. Swackhamer, University of Minnesota.

The EHMI liaisons are Francie Abramson, Target; John Balbus, National Institutes of Health (NIH)/National Institute of Environmental Health Sciences (NIEHS); Linda Birnbaum, NIH/NIEHS; Patrick Breysse, Centers for Disease Control and Prevention; Elizabeth Cisar, The Joyce Foundation; Natasha DeJarnett, National Environmental Health Association; Zach Freeze, Walmart; David Fukuzawa, The Kresge Foundation; Richard Fuller, Pure Earth/Blacksmith Institute; Carlos Gonzalez, National Institute of Standards and Technology; Al McGartland, Environmental Protection Agency; Ansje Miller, Health & Environmental Funders Network; Gary Minsavage, Exxon Mobil Corporation; Jennifer Orme-Zavaleta, Environmental Protection Agency; Surili Patel, American Public Health Association; Geoffrey S. Plumlee, U.S. Geological Survey; Karl Rockne, National Science Foundation; John Seibert, Department of Defense; Robert Skoglund, Covestro; Joel Tickner, Green Chemistry & Commerce Council; Juli Trtanj, National Oceanic and Atmospheric Administration; and Jalonne White-Newsome, The Kresge Foundation.

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