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Reducing transmission of SARS-CoV-2

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Masks and testing are necessary to combat asymptomatic spread in aerosols and droplets

Respiratory infections occur through the transmission of virus-containing droplets (>5 to 10 μm) and aerosols (≤5 μm) exhaled from infected individuals during breathing, speaking, coughing, and sneezing. Traditional respiratory disease control measures are designed to reduce transmission by droplets produced in the sneezes and coughs of infected individuals. However, a large proportion of the spread of coronavirus disease 2019 (COVID-19) appears to be occurring through airborne transmission of aerosols produced by asymptomatic individuals during breathing and speaking (*1*–*3*). Aerosols can accumulate, remain infectious in indoor air for hours, and be easily inhaled deep into the lungs. For society to resume, measures designed to reduce aerosol transmission must be implemented, including universal masking and regular, widespread testing to identify and isolate infected asymptomatic individuals.

Humans produce respiratory droplets ranging from 0.1 to 1000 μm. A competition between droplet size, inertia, gravity, and evaporation determines how far emitted droplets and aerosols will travel in air (*4*, *5*). Larger respiratory droplets will undergo gravitational settling faster than they evaporate, contaminating surfaces and leading to contact transmission. Smaller droplets and aerosols will evaporate faster than they can settle, are buoyant, and thus can be affected by air currents, which can transport them over longer distances. Thus, there are two major respiratory virus transmission pathways: contact (direct or indirect between people and with contaminated surfaces) and airborne inhalation.

In addition to contributing to the extent of dispersal and mode of transmission, respiratory droplet size has been shown to affect the severity of disease. For example, influenza virus is more commonly contained in aerosols with sizes below 1 μm (submicron), which lead to more severe infection (*4*). In the case of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), it is possible that submicron virus-containing aerosols are being transferred deep into the alveolar region of the lungs, where immune responses seem to be temporarily bypassed. SARS-CoV-2 has been shown to replicate three times faster than SARS-CoV-1 and thus can rapidly spread to the pharynx from which it can be shed before the innate immune response becomes activated and produces symptoms (*6*). By the time symptoms occur, the patient has transmitted the virus without knowing.

Identifying infected individuals to curb SARS-CoV-2 transmission is more challenging compared to SARS and other respiratory viruses because infected individuals can be highly contagious for several days, peaking on or before symptoms occur (*2*, *7*). These "silent shedders" could be critical drivers of the enhanced spread of SARS-CoV-2. In Wuhan, China, it has been estimated that undiagnosed cases of COVID-19 infection, who were presumably asymptomatic, were responsible for up to 79% of viral infections (*3*). Therefore, regular, widespread testing is essential to identify and isolate infected asymptomatic individuals.

Airborne transmission was determined to play a role during the SARS outbreak in 2003 (*1*, *4*). However, many countries have not yet acknowledged airborne transmission as a possible pathway for SARS-CoV-2 (*1*). Recent studies have shown that in addition to droplets, SARS-CoV-2 may also be transmitted through aerosols. A study in hospitals in Wuhan, China, found SARS-CoV-2 in aerosols further than 6 ft from patients with higher concentrations detected in more crowded areas (*8*). Estimates using an average sputum viral load for SARS-CoV-2 indicate that 1 min of loud speaking could generate >1000 virion-containing aerosols (*9*). Assuming viral titers for infected super-emitters (with 100-fold higher viral load than average) yields an increase to more than 100,000 virions in emitted droplets per minute of speaking.

The U.S. Centers for Disease Control and Prevention (CDC) recommendations for social distancing of 6 ft and hand washing to reduce the spread of SARS-CoV-2 are based on studies of respiratory droplets carried out in the 1930s. These studies showed that large, ~100 μm droplets produced in coughs and sneezes quickly underwent gravitational settling (*1*). However, when these studies were conducted, the technology did not exist for detecting submicron aerosols. As a comparison, calculations predict that in still air, a 100-μm droplet will settle to the ground from 8 ft in 4.6 s whereas a 1-μm aerosol particle will take 12.4 hours (*4*). Measurements now show that intense coughs and sneezes that propel larger droplets more than 20 ft can also create thousands of aerosols that can travel even further (*1*).

Increasing evidence for SARS-CoV-2 suggests the 6 ft CDC recommendation is likely not enough under many indoor conditions where aerosols can remain airborne for hours, accumulate over time, and follow air flows over distances further than 6 ft (*5*, *10*).

In outdoor environments, numerous factors will determine the concentrations and distance traveled, and whether respiratory viruses remain infectious in aerosols. Breezes and winds often occur and can transport infectious droplets and aerosols long distances. Asymptomatic individuals who are speaking while exercising can release infectious aerosols that can be picked up by air streams (*10*). Viral concentrations will be more rapidly diluted outdoors, but few studies have been carried out on outdoor transmission of SARS-CoV-2. Additionally, SARS-CoV-2 can be inactivated by ultraviolet radiation in sunlight, and it is likely sensitive to ambient temperature and relative humidity, as well as the presence of atmospheric aerosols that occur in highly polluted areas. Viruses can attach to other particles such as dust and pollution, which can modify the aerodynamic characteristics and increase dispersion. Moreover, people living in areas with higher concentrations of air pollution have been shown to have higher severity of COVID-19 (*11*). Because respiratory viruses can remain airborne for prolonged periods before being inhaled by a potential host, studies are needed to characterize the factors leading to loss of infectivity over time in a variety of outdoor environments over a range of conditions

Given how little is known about the production and airborne behavior of infectious respiratory droplets, it is difficult to define a safe distance for social distancing. Assuming SARS-CoV-2 virions are contained in submicron aerosols, as is the case for influenza virus, a good comparison is exhaled cigarette smoke, which also contains submicron particles and will likely follow comparable flows and dilution patterns. The distance from a smoker at which one smells cigarette smoke indicates the distance in those surroundings at which one could inhale infectious aerosols. In an enclosed room with asymptomatic individuals, infectious aerosol concentrations can increase over time. Overall, the probability of becoming infected indoors will depend on the total amount of SARS-CoV-2 inhaled. Ultimately, the amount of ventilation, number of people, how long one visits an indoor facility, and activities that affect air flow will all modulate viral transmission pathways and exposure (*10*). For these reasons, it is important to wear properly fitted masks indoors even when 6 ft apart. Airborne transmission could account, in part, for the high secondary transmission rates to medical staff, as well as major outbreaks in nursing facilities. The minimum dose of SARS-CoV-2 that leads to infection is unknown, but airborne transmission through aerosols has been documented for other respiratory viruses including measles, SARS, and chickenpox (*4*).

Airborne spread from undiagnosed infections will continuously undermine the effectiveness of even the most vigorous testing, tracing, and social distancing programs. After evidence revealed that airborne transmission by asymptomatic individuals might be a key driver in the global spread of COVID-19, the CDC recommended the use of cloth face coverings Masks provide a critical barrier, reducing the number of infectious viruses in exhaled breath, especially of asymptomatic people and those with mild symptoms (*12*) (see the figure). Surgical mask material reduces the likelihood and severity of COVID-19 by substantially reducing airborne viral concentrations (*13*). Masks can also protect uninfected individuals from SARS-CoV-2 aerosols and droplets (*13*, *14*). Thus, it is particularly important to wear masks in locations with conditions that can accumulate high concentrations of viruses, such as health care settings, airplanes, restaurants, and other crowded places with reduced ventilation. The aerosol filtering efficiency of different materials, thicknesses, and layers used in properly fitted homemade masks was recently found to be similar to that of the medical masks that were tested (*14*). Thus, the option of universal masking is no longer held back by shortages.

From epidemiological data, places that have been most effective in reducing the spread of COVID-19 have implemented universal masking, including Taiwan, Japan, Hong Kong, Singapore, and South Korea. In the battle against COVID-19, Taiwan (population 24 million, first COVID-19 case 21 January 2020) did not implement a lockdown during the pandemic, yet maintained a low incidence of 441 cases and 7 deaths (as of 21 May 2020). By contrast, the state of New York (population ~20 million, first COVID case 1 March 2020), had a higher number of cases (353,000) and deaths (24,000). By quickly activating its epidemic response plan that was established after the SARS outbreak, the Taiwanese government enacted a set of proactive measures that successfully prevented the spread of SARS-CoV-2, including setting up a central epidemic command center in January, using technologies to detect and track infected patients and their close contacts, and perhaps most importantly, requesting people to wear masks in public places. The government also ensured the availability of medical masks by banning mask manufacturers from exporting them, implementing a system to ensure that every citizen could acquire masks at reasonable prices, and increasing the production of masks. In other countries, there have been widespread shortages of masks, resulting in most residents not having access to any form of medical mask (*15*). This striking difference in the availability and widespread adoption of wearing masks likely influenced the low number of COVID-19 cases.

Aerosol transmission of viruses must be acknowledged as a key factor leading to the spread of infectious respiratory diseases. Evidence suggests that SARS-CoV-2 is silently spreading in aerosols exhaled by highly contagious infected individuals with no symptoms. Owing to their smaller size, aerosols may lead to higher severity of COVID-19 because virus-containing aerosols penetrate more deeply into the lungs (*10*). It is essential that control measures be introduced to reduce aerosol transmission. A multidisciplinary approach is needed to address a wide range of factors that lead to the production and airborne transmission of respiratory viruses, including the minimum virus titer required to cause COVID-19; viral load emitted as a function of droplet size before, during, and after infection; viability of the virus indoors and outdoors; mechanisms of transmission; airborne concentrations; and spatial patterns. More studies of the filtering efficiency of different types of masks are also needed. COVID-19 has inspired research that is already leading to a better understanding of the importance of airborne transmission of respiratory disease.

REFERENCES AND NOTES

1. L. Morawska, J. Cao, *Environ. Int.* **139**, 105730 (2020). doi:10.1016/j.envint.2020.105730 Medline
2. E. L. Anderson, P. Turnham, J. R. Griffin, C. C. Clarke, *Risk Anal.* **40**, 902 (2020). doi:10.1111/risa.13500 Medline
3. S. Asadi, N. Bouvier, A. S. Wexler, W. D. Ristenpart, *Aerosol Sci. Technol.* **54**, 635 (2020). doi:10.1080/02786826.2020.1749229
4. R. Tellier, Y. Li, B. J. Cowling, J. W. Tang, *BMC Infect. Dis.* **19**, 101 (2019). doi:10.1186/s12879-019-3707-y Medline
5. R. Mittal, R. Ni, J.-H. Seo, *J. Fluid Mech.* 10.1017/jfm.2020.330 (2020).
6. H. Chu *et al*., *Clin. Infect. Dis.* 10.1093/cid/ciaa410 (2020). Medline
7. X. He *et al*., *Nat. Med.* **26**, 672 (2020). doi:10.1038/s41591-020-0869-5 Medline
8. Y. Liu *et al*., *Nature* 10.1038/s41586-020-2271-3 (2020). Medline
9. V. Stadnytskyi, C. E. Bax, A. Bax, P. Anfinrud, *Proc. Natl. Acad. Sci. U.S.A.* 10.1073/pnas.2006874117 (2020). Medline
10. G. Buonanno, L. Stabile, L. Morawska, *Environ. Int.* **141**, 105794 (2020). doi:10.1016/j.envint.2020.105794 Medline
11. E. Conticini, B. Frediani, D. Caro, *Environ. Pollut.* **261**, 114465 (2020). doi:10.1016/j.envpol.2020.114465 Medline
12. N. H. L. Leung *et al*., *Nat. Med.* **26**, 676 (2020). doi:10.1038/s41591-020-0843-2 Medline
13. J. F.-W. Chan *et al*., *Clin. Infect. Dis.* 10.1093/cid/ciaa644 (2020). Medline
14. A. Konda *et al*., *ACS Nano* 10.1021/acsnano.0c03252 (2020). Medline
15. C. C. Leung, T. H. Lam, K. K. Cheng, *Lancet* **395**, 945 (2020). doi:10.1016/S0140-6736(20)30520-1 Medline

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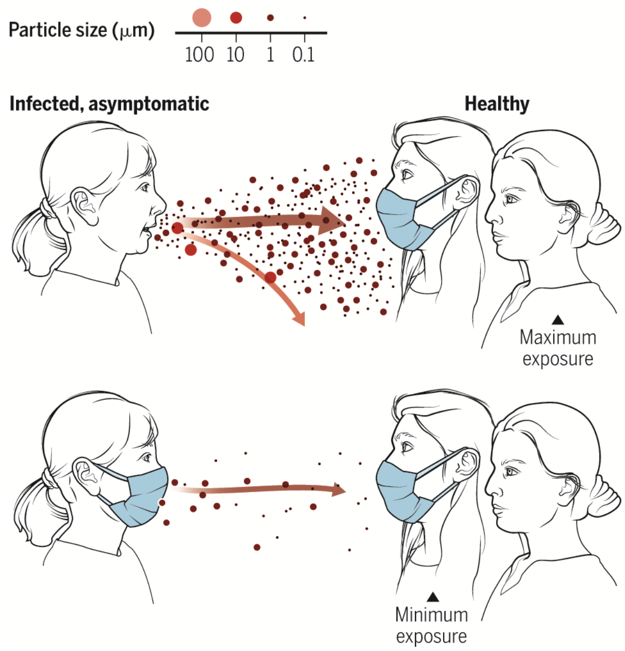
Masks reduce airborne transmission

Infectious aerosol particles can be released during breathing and speaking by asymptomatic infected individuals. No masking maximizes exposure, whereas universal masking results in the least exposure.



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