Editorial

The COVID-19 pandemic is a global indoor air crisis that should lead to change: A message commemorating 30 years of Indoor Air

The commemoration of 30 years of the Indoor Air journal coincides with the one-year anniversary of the COVID-19 pandemic.

Roughly one and a half years after its start, the COVID-19 pandemic is already one of the worst human health crises since the end of WWII. Globally, as of September 2021, more than 4.5 million people have died,4 and the associated disruption caused a 7% economic loss during 2020.2 Global vaccination is not proceeding rapidly enough to eliminate the virus as it continues mutating into variants of concern. With its unlikely elimination, SARS-CoV-2 will remain an ongoing challenge together with other endemic infections such as influenza.

Many reflections about the pandemic have been written, but one major topic seems to have been ignored: What could have been done to prevent the transmission of SARS-CoV-2? No transmission means no pandemic. In 1969, the American author Michael Crichton wrote in his novel The Andromeda Strain about the effort to contain a deadly extraterrestrial pathogen. “A crisis is the sum of intuition and blind spots, a blend of facts noted and facts ignored.” What are the blind spots and the facts ignored in the COVID-19 pandemic?

The infectious disease transmission concepts of airborne, droplet, fomite, and contact routes have remained nearly unchanged since the sixteenth century even though the underlying science developed rapidly starting in the early twentieth century.3 The terminology is confusing for the public and even scientists are challenged to communicate clearly across disciplines. In some relevant academic workshops we have attended, participants spent disproportionate time attempting to reconcile what is understood to be airborne transmission. The airborne route is easily conflated with long-distance transmission, which is inaccurately perceived to be fearful, dangerous, and very difficult to control. Short-range airborne transmission is often confused with the large droplet route.

In a recent Indoor Air editorial,3 a set of new terms was proposed: aerosol inhalation, droplet (drop) spray, and surface touch. With these three transmission concepts, the associated interventions should be easy to identify—minimize inhalation of infectious agents, avoid contact via drop deposition, and keep surfaces/hands clean. A similar set of terms was recently adopted by US CDC,4 that is, inhalation, deposition, and touching. WHO5 and US CDC4 also have finally accepted that short-range inhalation predominates the transmission of SARS-CoV-2, more than a year into the pandemic. Although regrettably late, this long-overdue recognition still paves the way for more fully recognizing the important role of ventilation and air cleaning, along with physical distancing and routine masking as key measures for protecting against transmission of SARS-CoV-2 and other respiratory viral infections.

Beginning with investigations of the 2003 Amoy Garden SARS outbreak,6 many engineering studies of respiratory infection have been reported during the past few decades. These mechanistic studies proved to be useful in building an understanding of the current pandemic. Scientists of different disciplines have now joined forces on further mechanistic studies of expired flows, respiratory droplets, their transformation and dispersion, deposition in lungs, survival of virus in the evaporating droplets and aerosols, and human behavior in close contact, among other key topics. Such mechanistic studies add insight, constituting an essential part of the scientific inquiry into respiratory infection transmission. The results are useful in making deductions and inferences about the predominant routes of transmission.

Science may be defined as sets of logically connected concepts and theories derived from experiment and observation, which lead to new experiments and observations. The pandemic has provided unfortunate opportunities for real-life infection “experiments” and “observations” in hundreds of millions of indoor spaces worldwide. Unfortunately, although thousands of outbreaks have been documented, for at least two reasons many essential details are missing. First, only in circumstances in which the new case rate is low in a community can authorities have the resources to trace each individual case. Second, because of privacy concerns, access to individual and building data has been difficult. Tracing and environment testing are essential, yet often impossible.

Fortunately, several outbreaks have been carefully studied,7 which reveal evidence about the possibility of indoor airborne transmission. But for effective intervention, one needs to know not just if the airborne route is possible, but also if it is predominant. A big question emerges: How do we generalize from the nonrandom sample of outbreak cases evaluated to the broader population of transmission events throughout the community?
Here, mechanistic understanding plays a key role. Another Indoor Air editorial analyzed four major observations of virus spread in this pandemic: 1) most infections occurred in close range; 2) most infections occurred indoors; 3) outdoor infection risk was low; and 4) long-range transmission occurred occasionally. These observations are basic. We can deduce the major transmission route with the help of mechanistic theories, that is, short-range inhalation predominates, with long-range inhalation occurring occasionally or conditionally. A new theory needs to be able to produce new predictions or to explain new observations. If all predictions are correct, we accept it. If any prediction is wrong, we reject it. This model was presented by Yuguo Li to the first multi-disciplinary WHO workshop debating airborne transmission on February 24, 2021. He asked all those who attended to find observations that can reject this hypothesis; so far, no one has sent him any.

The phenomenon of low risk outdoors and high risk indoors deserves some explanation. This is probably the most important observation in this pandemic. There is a simple explanation: dilution. For an ideal expired jet from a person breathing at rest, at a distance beyond 1 m, there is more than 10-fold dilution from surrounding air because of air entrainment. If the surrounding air is totally free from infectious virus, as it is outdoors, the concentration beyond 1 m is very low. In any well-ventilated indoor environment, that is, with an outdoor-air ventilation rate of 10 L/s per person or more, the background concentration in room air is similarly low. This means that, at this resting condition, 10 L/s per person ventilation is likely to produce a close-range inhalation risk like outdoors. Thus, in a well-ventilated indoor space, the infection risk is comparably low to risk outdoors. On the contrary, if the ventilation rate is lower than 5 L/s per person, it can be shown that there is a significant increase in close-range inhalation exposure to exhaled breath with a concomitant risk of viral transmission from an infectious person.

The four basic observations are made from study of the general population. Thus, we deduce that in the general population, short-range inhalation transmission mostly occurs in poorly ventilated spaces. The transmission risk is considerably lower if the indoor space is well-ventilated. If ventilation is poor, transmission throughout the indoor space (ie, "long-range" inhalation transmission) can occur. Long-range inhalation can infect many people simultaneously, whereas short-range transmission only infects those in close contact. Physical space constraints limit the number of susceptible individuals that an infected person can be in close contact with at any time. This feature is consistent with the observation that the number of secondary infections is generally small in this pandemic and supports the idea that close-contact indoor transmission is predominant.

This reasoning supports an important conclusion: that SARS-CoV-2 transmission does not occur everywhere, but mostly indoors in poorly ventilated spaces. The effect of ventilation rate on infection risk is continuous. The choice of a threshold ventilation rate depends on our definition of acceptable risk. Ventilation alone cannot prevent all infections. Instead, it should be viewed as one layer of protection in a multi-layered or multi-route approach, used in combination with other methods such as occupancy limitations, physical distancing, and mask wearing. Appropriate threshold ventilation rates remain to be determined.

The underlying axiomatic statement in the above analysis is that COVID-19 infection is mainly due to respiratory droplets. During heavy physical activities, an infectious person would exhale more air and produce higher shear stress at the epithelial surface, consequently releasing more infectious droplets. During physical exertion, a susceptible individual also inhales more. The net effect for infection transmission risk is a double multiplier. In an office setting, by contrast, both the infectious and the susceptible breathe at lower rates. Assume in the case of an office, an appropriate ventilation rate is 10 L/s per person. Then, in a gym, the infectious would exhale more, say by 5x, and the susceptible would also inhale more, also by 5x. The exposure rate to exhalations could likely be 25X the office value, and a rational ventilation requirement might therefore also 25x the office value, that is, about 250 L/s per person. ASHRAE Standard 62.1 currently only recommends a ventilation rate of about 20 L/s per person for gyms. This modest increment above office conditions reflects an important fundamental fact: outside of healthcare settings, existing ventilation standards do not account for infection control. Gyms designed and operated following ASHRAE Standard 62.1, then their ventilation rates are significantly lower than what is required for infection control. This scaling analysis can help explain why high activity spaces such as gyms have been observed to have high attack rates. Ventilation requirement for health is a complex topic and is also affected by exposure time and viral loads when infection is considered.

The dominant view in public health toward fearful airborne transmission fails to account for the power of dilution. Sufficient dilution of airborne infectious aerosols is the key to reducing inhalation transmission, both at close range and at room scale. Sufficient ventilation and filtration reduce infection to be as low as outdoors. A paradigm shift is needed toward a new ventilation standard accounting for managing infection risk. This goal should also apply to other respiratory viruses, such as influenza and the common cold.

The above analysis suggests that most SARS-CoV-2 infections have occurred indoors with poor ventilation being a major factor. The COVID-19 crisis is almost certainly an indoor air crisis; it is very likely a ventilation crisis. Crisis is important not only for the harm that it causes. A crisis can precipitate change. Major crisis can provoke revolution. A major environmental crisis can lead to environmental revolution.

We may cite two relevant major environmental revolutions during the past few centuries. The first is the sanitary revolution. Rapid industrialization and urbanization in the 18th and 19th century led to spread of infectious diseases in major cities in Europe and United States. This public health crisis was followed by major efforts in revolutionizing wastewater treatment and discharge, water quality improvements, and personal hygiene. Building regulations were introduced with mandatory requirements. Probably due to the defeat of the old miasma hypothesis, some progress was also
made toward air hygiene. Second, the deadly Donora smog of 1948 and London fog crisis of the 1950s initiated a new urban air revolution. Strict governmental regulations were adopted, with a lot of new research efforts. Urban air quality in major industrialized countries improved significantly. In China, the city haze or PM2.5 crisis in the early 2010s also had a similar impact, with government acting strongly and urban air quality significantly improving. Government regulation and research are necessary but not sufficient; the economy and technology also need to be sufficiently good to fund required infrastructure improvements.

We learned scientifically about air and water in the 18th century, and about germs in the 19th century. Human mortality attributable to infectious diseases has declined markedly following the sanitary revolution. But, importantly, respiratory infections still have broad adverse impacts in both rich and poor countries.11 Two explanations are suggested, both probably related to indoor air. The first is the increasing inequality between the poor and rich. The health inequality is clearly seen in high COVID-19 infection rates and mortality among Blacks, Hispanics, and Native Americans in the United States,12 and in the ongoing COVID-19 human disaster in India.13 Poor housing and crowding are major issues. The second feature is our ability to construct more airtight buildings. Rich countries may have better healthcare facilities, but their indoor air might not be the best. Unlike water, air is everywhere. Ever since we have built tighter buildings, good air is no longer always present indoors. The sick building syndrome, first studied in 1970s,14 did not lead to significant change in government regulation, and indoor air quality continues to be self-regulated by industry or voluntary in nearly all countries. Our lungs are vulnerable. A global population approaching 8 billion persons spends 90% of its time indoors. Indoor air pollution poses health risks in ways that extend far beyond the airborne transmission of SARS-CoV-2 and other respiratory viruses.

Is this the right time for an indoor air revolution? For the first time in history, the COVID-19 pandemic has focused the world’s attention on the roles of ventilation in disease transmission.9 New technologies will allow us to monitor and control indoor air better in billions of homes, and hundred million of offices and public buildings worldwide. This is also an age of carbon neutral and sustainability. Health is an essential element of sustainability, and developing carbon neutral indoor air technologies is essential. Access to healthy indoor air is a basic human right.15 It goes with healthy living and sustainable development.

The indoor air revolution of the 21st century will not come if we do not act. New research is needed, but more importantly, new regulations, public education campaigns, and new human air hygiene behavior are essential. There is a major difference between handwashing and ventilation. Hand washing may be an individual behavior, but for ventilation, we often have no say in the restaurants we patronize, gyms we visit, and buses we take. Similar to that for water hygiene, voluntary requirements will not be sufficient for indoor air quality, and mandatory regulations should be enacted.

An editorial commemorating the 20-year anniversary of Indoor Air included these thoughts16: “One might be discouraged about the limited size of our community in relation to the scale of the challenges we face. However, it has always been that great discoveries are made by small and determined groups of explorers.” Indoor Air and indoor air scientists have contributed to the scientific understanding of transmission and intervention in the pandemic. However, the COVID-19 crisis suggests that much more must be done.

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COVID-19 pandemic, indoor air, indoor air crisis, ventilation

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