THE CHALLENGES OF MAKING INDOORS SAFE

Risks of catching COVID shoot up when virus particles accumulate in buildings, but it's not clear how best to improve ventilation. **By Dyani Lewis**

When Lidia Morawska leaves home, she takes with her a slick, shoe-sized device that provides some sobering insights about the restaurants and offices she visits. Outside these buildings, her carbon dioxide monitor reads just above 400 parts per million (p.p.m.). But indoors is a different story.

Even in a seemingly spacious, high-ceilinged restaurant, the number sometimes shoots up as high as 2,000 p.p.m. – a sign that the room has poor ventilation and could pose a risk for COVID-19 infection. Visual cues can be deceptive, even for Morawska, an aerosol scientist from the Queensland University of Technology in Brisbane, Australia. "The general public has no idea about this," she says.

The situation is no different inside cafes or kindergartens around much of the world, according to researchers who have wielded similar handheld CO_2 meters. And that's bad news for hopes of defeating the coronavirus SARS-CoV-2.

For months, health authorities have singled out indoor spaces with poor ventilation as potential infection hotspots. And on 1 March, the World Health Organization (WHO) released a long-awaited road map to better ventilation. The document – which Morawska contributed to – sets out specific targets and measures that businesses and other places can take to improve ventilation and make buildings safer[1].

But Philomena Bluyssen, a building engineer at the Delft University of Technology in the Netherlands, says that more needs to be done. "The WHO guidelines," she says, "are the minimum."

Bluyssen and others are critical of governments' failure to provide clear guidance or money for people to make indoor spaces safer. Some scientists say that has left large swathes of the population – from schoolchildren to office workers, restaurant goers and prisoners – at risk of catching COVID-19.

Others say that there's no easy fix, and the precise ventilation or air-purification regimes to make indoor spaces safe are not known. "The complexity is not at a level that you can – with a simple set of advice – resolve it," says Ehsan Mousavi, a construction engineer at Clemson University in South Carolina, who studies indoor air quality and ventilation in hospitals.

Still, many experts say that enough is known for authorities to provide a clear message about how important good ventilation is for safety indoors, especially in spaces that are continuously occupied, or where masks are removed when eating.

Slow recognition

On 28 March 2020, two months after the WHO had declared COVID-19 a global health emergency, the agency broadcast a public-health message on Twitter and Facebook. "FACT: #COVID19 is NOT airborne," it said, labelling claims to the contrary as misinformation. But evidence quickly established that the virus is transmitted by air, and researchers roundly criticized the agency.

The WHO updated its advice on SARS-CoV-2 transmission three months later, acknowledging the possibility that airborne transmission might occur in some community settings. Airborne transmission in "crowded and

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Children work with coats on inside a school in Germany that has open windows to improve ventilation.

inadequately ventilated spaces over a prolonged period of time with infected persons cannot be ruled out", the updated advice says.

Yuguo Li, a building environment engineer at the University of Hong Kong, says that he is disappointed it took the WHO and other health authorities so long. "We would have saved a lot of people" if airborne transmission was recognized earlier, he says.

A WHO spokesperson says the agency has mentioned the importance of ventilation since early in the pandemic.

Others say that the WHO's position still doesn't go far enough. "Airborne transmission is dominant," says environmental epidemiologist Joseph Allen at Harvard University's T. H. Chan School of Public Health in Boston, Massachusetts. That's why building controls such as ventilation and air filtration make sense, he says.

The WHO and other health authorities have failed to clearly prioritise measures to improve indoor air quality to reduce the chance of catching COVID-19, says Jose-Luis Jimenez, an atmospheric chemist at the University of Colorado at Boulder. "They don't emphasize how important it is," he says. What the WHO needs to say is "fact, it goes through the air," says Jimenez, "we breathe it in."

A stark message from the WHO would ensure that national health authorities take notice, says Jimenez. Australia, the Netherlands and some other nations still do not acknowledge in their public statements that airborne transmission has a significant role in spreading the SARS-CoV-2 virus.

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By the start of this year, concerns over ventilation had reached boiling point. Hundreds of health-care workers, scientists, engineers and occupational health-and-safety experts signed open letters calling on government officials in Canada, the United States, Australia, Colombia and the United Kingdom to address, among other things, poor indoor air quality. These concerted campaigns all urged local or national governments to take steps to reduce airborne transmission of SARS-CoV-2.

One of the problems is that governments and businesses are still spending millions of dollars on surface disinfection, says Jimenez, despite evidence that it is rare for SARS-CoV-2 to pass from one person to another through contaminated surfaces. By contrast, few countries have invested in measures to improve indoor air quality.

"If we took half the effort that's being given to disinfection, and we put it on ventilation, that will be huge," Jimenez says. In October, Germany set aside €500 million (US$593 million) to improve ventilation in public buildings, including schools, museums and public offices.

Businesses in Germany and South Korea can also apply for government funding to purchase mobile air purifiers that remove virus-laden aerosols. In the United States, by contrast, federal funding to improve indoor

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Philomena Bluyssen (right) and her colleagues studied air movement and simulated virus particles.

air quality was limited to health-care providers such as hospitals, until the American Rescue Plan Act — which also provides funding for schools — became law on 11 March.

Indoor threat

What makes indoor spaces so dangerous is that exhaled virus can accumulate and infect people who do not have direct contact with an infected person. A prime example happened a year ago during a St Patrick's Day party at a bar in Ho Chi Minh City, in Vietnam. Twelve people became infected at the party, but only four had close contact with the infected person[2]. More recent outbreaks at gyms in Chicago, Illinois, and Hawaii have also occurred despite physical distancing of attendees[3] and capacity limits on fitness classes[4].

Ever since the WHO acknowledged last year that airborne transmission could happen, public-health agencies have emphasized the risks in crowded and poorly ventilated spaces. But the terminology is deceptive, says Morawska. "You imagine a busy bar," she says. "In the reality, any place can become crowded and poorly ventilated. And people don't realize this."

Her own modestly sized office at the Queensland University of Technology quickly becomes poorly ventilated if someone visits and the door is closed, she says. And spacious, uncrowded restaurants can appear to be well ventilated when they are not.

It's one of the reasons that Jimenez and others advocate the use of inexpensive CO_2 monitors as a rough measure of whether ventilation is adequate or not. As virus-carrying aerosols are exhaled, so too is CO_2. And when ventilation is poor, CO_2 accumulates along with the virus, says Jimenez. In an unreviewed analysis[5], Jimenez and his co-author Zhe Peng found that SARS-CoV-2 infection risk rises along with CO_2 concentrations indoors.

Taiwan, Norway and Portugal have laws that limit indoor CO_2 to 1,000 p.p.m. Studies in California[6] and Madrid[7] show that CO_2 levels in school classrooms frequently exceed this level. High levels have been linked to poorer mental concentration and more sick days[6].

Setting clear CO_2 limits would help to ensure that ventilation is adequate to reduce infection risk, says Jimenez. But his work suggests that in general 700 p.p.m. would be a better limit, and lower limits should apply to gyms and other venues where people expel greater volumes of air.

Not everyone agrees that CO_2 monitors are the solution. "There is no correlation between CO_2 and virus," says Christian Kähler, a physicist who studies aerosol production and dynamics at the University of the Federal Armed Forces in Munich, Germany. This can give people a false sense of security when CO_2 levels are low, he says.

Jimenez argues it could provide a quick indication of whether ventilation is adequate. In August 2020, the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) agreed, recommending installing CO_2 monitors in buildings where ventilation might be inadequate.

And late last year, teachers in Montreal, Canada, covertly measured CO_2 levels in classrooms and took their findings to the media. The Quebec government is now publishing CO_2 levels from public schools online, with the aim of having all levels below 1,000 p.p.m. But so far, this type of public reporting is the exception.

No set standards

Part of the difficulty in setting ventilation targets is that it's unclear how much ventilation is needed to reduce infection rates to an acceptable level. Experiments that directly measure how infection risks change with different ventilation rates would be unethical because it would put people in danger, says Mousavi.

The precise infectious dose for SARS-CoV-2 is also unknown[8]. But researchers can infer how much exhaled virus is needed to cause infection by analysing disease outbreaks. For example, Jimenez and colleagues used details from an infamous choir rehearsal in Skagit Valley in Washington — where one person probably infected 52 of the 60 other attendees — to estimate the amount of infectious virus exhaled[8].

Jimenez used this approach to launch an online tool (which has not been peer reviewed) in June 2020 to help people assess the risk of infection in different indoor spaces, with or without masks. The tool calculates risk based on room size, the number of people present and what they are doing; viruses are exhaled at different rates depending on whether people are singing, running on a treadmill or sitting quietly.

The WHO recommends a minimum ventilation rate of 6–12 air changes — in which the entire volume of air in the room is replaced — per hour to prevent airborne transmission of pathogens in health-care facilities, but a lower rate of air changes for other venues. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) establishes minimum standards for indoor air quality. Recommended targets are as low as 0.35 air changes per hour for homes, 2–3 for offices, 5–6 for schools and 6–12 for hospitals.

But even those minimum standards are rarely met, says Liangzhu (Leon) Wang, a mechanical engineer at Concordia University in Montreal. And although experts say that more ventilation is needed to reduce infection risk, they disagree over how much. For schools, Allen recommends 4–6 air changes per hour, which can come from a combination of outdoor air ventilation, filtration or supplemental air cleaning. Kähler meanwhile, recommends at least 6 air changes per hour.

Wang and his colleagues have tried to estimate what level of ventilation is required to reduce infection risk at schools[9]. They measured the ventilation rate in classrooms at 3 schools in Montreal and found that a classroom of 20 students and one teacher with open windows exchanged less than half of its air per hour; a similar room with mechanical ventilation had two air changes per hour. Even that wouldn't be enough to reduce the reproduction number to less than 1 — the level at which a pandemic begins to shrink. This value would mean that one infected student passes the virus to less than one other person in the room. Wang's analysis, which is yet to be peer reviewed, suggests that between 3 and 8 air changes per hour would be required to get the reproduction number below 1 in that setting.

Standard ventilation rates are inadequate, says Wang. In another preprint, he and his colleagues estimate that doubling the amount of outdoor air reduces the chance of infection by up to 35% in densely packed venues such as restaurants. But that same change has a much smaller effect — reducing risk by as little as 0.1% — in larger venues with fewer people, such as warehouses[10]. Their analysis also shows that wearing a mask indoors is even more effective than changing the air: masks decrease infection risk by more than 60%, because they cut the virus off at its source, says Wang.

Clearing the air

Opening windows is the easiest method that health authorities suggest to improve ventilation. Although it is better than doing nothing, an open window rarely exchanges enough air between the indoor and outdoor environment, especially if there is no cross-breeze, says Kähler.

Opening windows for just a few minutes — between classes, say — would leave the majority of virus untouched, according to air-exchange measurements Kähler and his colleagues took in a university lecture room[11]. In a preprint study, Kähler found that two windows that allow a cross-breeze would need to be open two-thirds of the time to equal the performance of the room's heating, ventilation and air-conditioning (HVAC) system. And if the weather outside is too hot or cold, people simply won't follow that advice. "It protects you sometimes, but not always," he says.

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A better method is to mechanically ventilate a space. This draws in virus-free outdoor air and removes contaminated indoor air, thereby diluting any virus present. In April 2020, ASHRAE and REHVA recommended setting HVAC controls to draw in as much outdoor air as possible and to filter recirculated air.

But Kähler says that few buildings, especially in milder climates such as in Germany, have systems powerful enough to use 100% outside air. Most office spaces and classrooms around the world are supplied with just 20% outside air, with the remainder recirculated to save on energy consumption for heating and cooling.

The environmental cost of increased ventilation should give people pause, says Li. In many cases, beefing up ventilation systems now will mean removing them once the pandemic threat subsides. A better solution, he says, is to limit numbers and curb risky behaviours. "Don't shout, don't sing and don't run," he advises.

Another drawback of cranking up building ventilation is that rooms can become draughty and noisy, says Bluyssen, "because the system wasn't designed for that".

Mobile air purifiers that filter out viruses and other airborne contaminants could be readily deployed as part of the solution, says Kähler, and would be more energy efficient than using extra heating or cooling on outside air. Filters in HVAC systems could also clean air that is recirculated.

Bluyssen and her colleagues tested air purifiers fitted with high-efficiency particulate air filters in a controlled environment. In some scenarios, the air purifiers outperformed the ventilation system for removing aerosols simulated by air-filled soap bubbles[12]. But even on the lowest setting, the air purifiers exceeded the acceptable level of noise and draught recommended by European and Dutch standards.

Innovation is required to address the shortfalls of current systems, says Bluyssen: "We really need to look for simple, affordable solutions." One idea she's looking into is personalized ventilation — a seat fitted with a system that sucks away exhaled air and returns it filtered and cleaned, for instance. "There are all kinds of possibilities," she says.

But Mousavi says that the biggest issue is that not enough is known about the systems that are already in use. "We need to know more about these technologies, how they perform," he says, so that recommendations — from ASHRAE, or the WHO, or another agency — are based on clear science. "It's time for us to build that foundation," he adds.

As vaccines are rolled out and the risk of infection drops, the window of opportunity to fix poor indoor air quality is closing, says Morawska. "This hasn't passed yet," she says. But next year, "it may be too late".

Researchers say that a greater focus on ventilation will yield benefits during the next pandemic — and even when there are no major disease outbreaks. Indoor air quality "has been very bad for a long time", says Bluyssen. "This gives us the opportunity to improve not only the air quality for pandemic situations, but also the whole indoor environmental quality for the future."

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