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POLICY FORUM

INFECTIOUS DISEASE

A paradigm shift to combat indoor respiratory infection

Building ventilation systems must get much better

By **Lidia Morawska, Joseph Allen, William Bahnfleth, Philomena M. Bluyssen, Atze Boerstra, Giorgio Buonanno, Junji Cao, Stephanie J. Dancer, Andres Floto, Francesco Franchimon, Trisha Greenhalgh, Charles Haworth, Jaap Hogeling, Christina Isaxon, Jose L. Jimenez, Jarek Kurnitski, Yuguo Li, Marcel Loomans, Guy Marks, Linsey C. Marr, Livio Mazzarella, Arsen Krikor Melikov, Shelly Miller, Donald K. Milton, William Nazaroff, Peter V. Nielsen, Catherine Noakes, Jordan Peccia, Kim Prather, Xavier Querol, Chandra Sekhar, Olli Seppänen, Shin-ichi Tanabe, Julian W. Tang, Raymond Tellier, Kwok Wai Tham, Pawel Wargocki, Aneta Wierzbicka, Maosheng Yao**

There is great disparity in the way we think about and address different sources of environmental infection. Governments have for decades promulgated a large amount of legislation and invested heavily in food safety, sanitation, and drinking water for public health purposes. By contrast, airborne pathogens and respiratory infections, whether seasonal influenza or COVID-19, are addressed fairly weakly, if at all, in terms of regulations, standards, and building design and operation, pertaining to the air we breathe. We suggest that the rapid growth in our understanding of the mechanisms behind respiratory infection transmission should drive a paradigm shift in how we view and address the transmission of respiratory infections to protect against unnecessary suffering and economic losses. It starts with a recognition that preventing respiratory infection, like reducing waterborne or foodborne disease, is a tractable problem.

Two factors in particular may contribute to our relatively weak approach to fighting airborne transmission of infectious diseases compared to waterborne and foodborne transmission. First, it is much harder to trace airborne infections. Food and water contamination nearly always come from an easily identifiable point source with a discrete reservoir, such as a pipe, well, or package of food. Its impact on human health is early if not immediate in terms of characteristic signs and symptoms, so that diligent epidemiology can track and identify the source relatively easily. Over the years, this has led to the current public health structures in well-resourced countries. Standards have been enacted for all aspects of food and water processing, as well as wastewater and sewage. Public health officials, environmental health officers, and local councils are trained in surveillance, sampling, and investigation of clusters of potential food and waterborne outbreaks, often alerted by local microbiology laboratories. There are published infection rates for a large range of pathogens, with morbidity and mortality risks now well established. By contrast, airborne studies are much more difficult to conduct because air as a contagion medium is nebulous, widespread, not owned by anybody, and uncontained. Buildings and their airflows are complicated, and measurement methods for such studies are complex and not generally standardized.

> **"…healthy indoor environments with a substantially reduced pathogen count are essential for public health."**

Second, a long-standing misunderstanding and lack of research into airborne transmission of pathogens has negatively affected recognition of the importance of this route (*1*). Most modern building construction has occurred subsequent to a decline in the belief that airborne pathogens are important. Therefore, the design and construction of modern buildings make few if any modifications for this airborne risk (other than for specialized medical, research, or manufacturing facilities, for example). Respiratory outbreaks have been repeatedly "explained away" by invoking droplet transmission or inadequate hand hygiene. For decades, the focus of architects and building engineers was on thermal comfort, odor control, perceived air quality, initial investment cost, energy use, and other performance issues, whereas infection control was neglected. This could in part be based on the lack of perceived risk or on the assumption that there are more important ways to control infectious disease, despite ample evidence that healthy indoor environments with a substantially reduced pathogen count are essential for public health.

It is now known that respiratory infections are caused by pathogens emitted through the nose or mouth of an infected person and transported to a susceptible host. The pathogens are enclosed in fluid-based particles aerosolized from sites in the respiratory tract during respiratory activities such as breathing, speaking, sneezing, and coughing. The particles encompass a wide size range, with most in the range of submicrometers to a few micrometers (*1*).

Although the highest exposure for an individual is when they are in close proximity, community outbreaks for COVID-19 infection in particular most frequently occur at larger distances through inhalation of airborne virus–laden particles in indoor spaces shared with infected individuals (*2*). Such airborne transmission is potentially the dominant mode of transmission of numerous respiratory infections. There is also strong evidence on disease transmission—for example, in restaurants, ships, and schools—suggesting that the way buildings are designed, operated, and maintained influences transmission.

Yet, before COVID-19, to the best of our knowledge, almost no engineering-based measures to limit community respiratory infection transmission had been employed in public buildings (excluding health care facilities) or transport infrastructure anywhere in the world, despite the frequency of such infections and the large health burden and economic losses they cause (*3*). The key engineering measure is ventilation, supported by air filtration and air disinfection (*4*). In this context, ventilation includes a minimum amount of outdoor air combined with recirculated air that is cleaned using effective filtration and disinfection.

VENTILATION OF THE FUTURE

There are ventilation guidelines, standards, and regulations to which architects and building engineers must adhere. Their objectives are to address the issues of odor, and occupant-generated bioeffluents [indicated by the concentrations of occupant-generated carbon dioxide (CO_2)], by specifying minimum ventilation rates and other measures to provide an acceptable indoor air quality (IAQ) for most occu-

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pants. Similarly, there are other guidelines and regulations to ensure thermal comfort. To achieve this, the amount of outdoor air delivered to indoor spaces is recommended or mandated in terms of set values of air change rate per hour, or liters of air per person per second. Threshold values of CO_2 and a range of indoor air temperatures and relative humidity have also been prescribed.

There are also some health-based indoor air quality guidelines. The most important are the World Health Organization (WHO) IAQ guidelines, providing values for benzene, carbon monoxide, formaldehyde, and other chemicals, based on the duration of exposure (*5*). There are, however, no ventilation guidelines or standards to specifically control the concentration of these pollutants indoors. None of the documents provide recommendations or standards for mitigating bacteria or viruses in indoor air, originating from human respiratory activities. Therefore, it is necessary to reconsider the objective of ventilation to also address air pollutants linked to health effects and airborne pathogens.

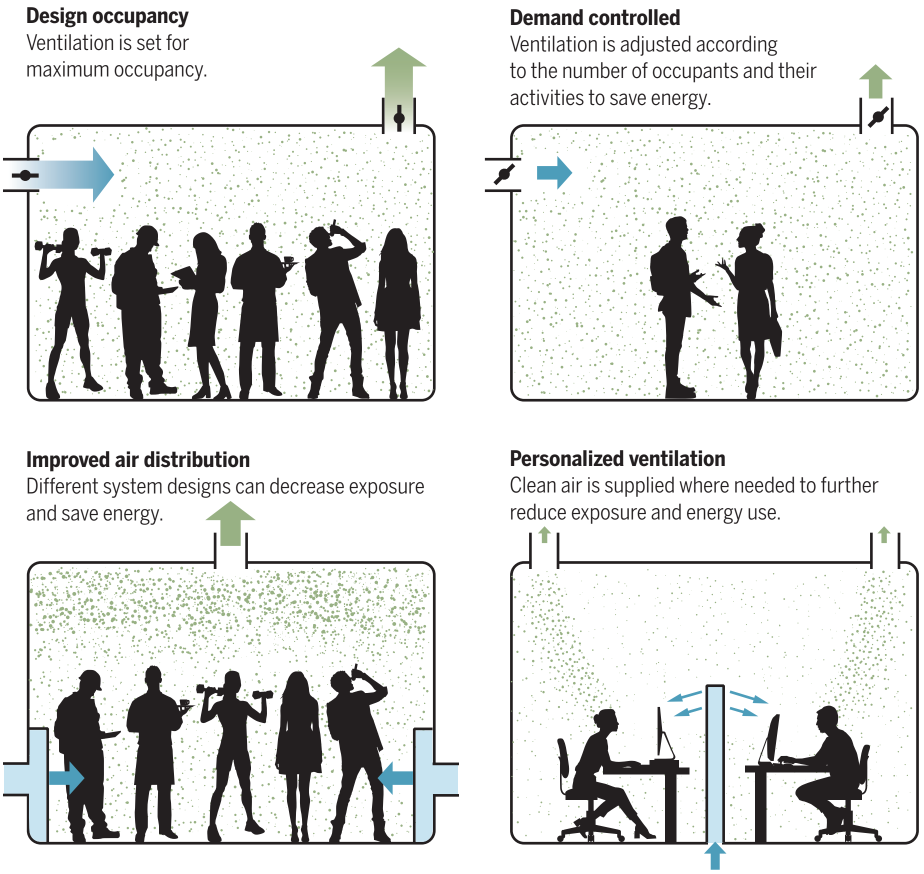
One challenge is that ventilation rates required to protect against infection transmission cannot be derived in the same way as rates for other pollutants. First, infection-focused ventilation rates must be risk-based rather than absolute, considering pathogen emission rates and the infectious dose [for which there exist data for a number of diseases, including influenza (*6*), severe acute respiratory syndrome coronavirus (SARS-CoV), Middle East respiratory syndrome, tuberculosis, SARS-CoV-2, and measles]. There is often limited knowledge of viral emission rates, and rates differ depending on the physiology of the respiratory tract (which varies with age, for example), the stage of the disease, and the type of respiratory activity (e.g., speaking, singing, or heavy breathing during exercise). The infectious dose may differ depending on the mode of transmission. This is well established for influenza A, for which the infectious dose is smaller with an aerosol inoculum than with nasal instillation (*7*). Some infectious agents display "anisotropy," in which the severity of disease varies according to the mode of transmission (*7*).

Second, future ventilation systems with higher airflow rates and that distribute clean, disinfected air so that it reaches the breathing zone of occupants must be demand controlled and thus flexible (see the figure). The ventilation rate will differ for different venues according to the activities conducted there (e.g., higher ventilation rates for exercising in gyms than for resting in movie theaters). There are already models enabling assessments of ventilation rates and their effective distribution in the occupant microenvironments (*8*), and in general this is a rapidly expanding field.

Demand control and flexibility are necessary not only to control risk but also to address other requirements, including the control of indoor air pollution originating from inside and outside sources and, especially, to control energy use: Ventilation should be made adequate on demand but not unreasonably high. Buildings consume over one-third of energy globally, much of it expended on heating or cooling outdoor air as it is brought indoors. Therefore, although building designs should optimize indoor environment quality in terms of health and comfort, they should do so in an energy-efficient way in the context of local climate and outdoor air pollution.

Flexible ventilation systems, dependent on the building's purpose

Ventilation airflow rates must be controlled by the number of occupants in the space and their activity.



Design occupancy
Ventilation is set for maximum occupancy.

Demand controlled
Ventilation is adjusted according to the number of occupants and their activities to save energy.

Improved air distribution
Different system designs can decrease exposure and save energy.

Personalized ventilation
Clean air is supplied where needed to further reduce exposure and energy use.

GRAPHIC: N. CARY/*SCIENCE*

Third, in some settings, it will not be possible to increase ventilation to the point of reducing the risk to an acceptable level, regardless of the quality of the ventilation system. This refers to individual risk of infection for each susceptible occupant, to the event reproduction number (the expected number of new infections arising from a single infectious occupant at an event), and to the reality that ventilation has less of an impact for near-field exposure. Management of the event reproduction number is important for the control of an epidemic, especially for indoor spaces with a high density of people, high emission rate (vocalization or exercising), and long periods of shared time. Spaces like this will require air-cleaning measures, including air filtration and disinfection. Air filtration can be achieved by incorporating filters into the building heating, ventilation, and air conditioning system or by portable air cleaners, and air disinfection can be achieved by using ultraviolet devices (*4*) while avoiding unproven technologies. The necessity of such measures and their effective per-person additional removal rate, and thus their efficacy in risk reduction, can be incorporated into risk assessment and prospectively modeled.

None of this means that every indoor space should become a biosafety facility. It means that a building should be designed and operated according to its purpose and the activities conducted there, so that airborne infection risk is maintained below an acceptable level. Such measures cannot easily be taken during the current pandemic because most building systems have not been designed for limiting respiratory infection, building owners and operators were not trained to operate the systems during the pandemic, and ad hoc measures are often not sufficient. Such training, and appropriate measures, should form a part of national strategies to prevent the spread of airborne diseases and infections.

The only types of public buildings where airborne infection control exists are health care facilities, where requirements for ventilation rates are typically much higher than for other public buildings (*9*). However, although modern hospitals comply with relevant standards set to control infection, this may not always be the case for some hospitals located in very old buildings. Comparing health care ventilation requirements with those for non–health care venues suggests that non–health care rates should be higher for effective infection control or that more recirculation with better filtration should be used.

There needs to be a shift in the perception that we cannot afford the cost of control, because economic costs of infections can be massive and may exceed initial infrastructure costs to contain them. The global monthly harm from COVID-19 has been conservatively assessed at $1 trillion (*10*), but there are massive costs of common respiratory infections as well. In the United States alone, the yearly cost (direct and indirect) of influenza has been calculated at $11.2 billion (*11*); for respiratory infections other than influenza, the yearly cost stood at $40 billion (*12*).

It is not known exactly what fraction of infections could be prevented if all building and transport ventilation systems on the planet were ideal (in terms of controlling airborne infections), or the cost of design and retrofitting to make them ideal. However, the airborne transmission route is potentially the dominant mode of transmission (*1, 2, 13*). Estimates suggest that necessary investments in building systems to address airborne infections would likely result in less than a 1% increase in the construction cost of a typical building (*14*). For the vast inventory of existing buildings, although economic estimations are more complex, there are numerous cost-effective, performance-enhancing solutions to minimize the risk of infection transmission. Although detailed economic analyses remain to be done, the existing evidence suggests that controlling airborne infections can cost society less than it would to bear them.

The costs of infections are paid from different pockets than building and operating costs or health care costs, and there is often resistance to higher initial expenditure. But ultimately, society pays for all the costs, and costs and benefits are never evenly distributed. Investment in one part of the system may generate savings in a different part of the system, so cross-system reallocation of budgets must be facilitated. The benefits extend beyond infectious disease transmission. An improvement in indoor air quality may reduce absenteeism in the workplace from other, noninfectious causes, such as sick building syndrome and allergic reactions, to the extent that the reduction in productivity losses may cover the cost of any ventilation changes.

A PATH FORWARD

We encourage several critical steps. First and foremost, the continuous global hazard of airborne respiratory infection must be recognized so the risk can be controlled. This has not yet been universally accepted, despite strong evidence to support it and no convincing evidence to refute it.

Global WHO IAQ guidelines must be extended to include airborne pathogens and to recognize the need to control the hazard of airborne transmission of respiratory infections. This includes recommendations on preventive measures addressing all modes of respiratory infection transmission in a proper and balanced way, based on state-of-the-art science. The recently published WHO Ventilation Roadmap (*15*) is an important step but falls short of recognizing the hazard of airborne respiratory infection transmission and, in turn, the necessity of risk control.

National comprehensive IAQ standards must be developed, promulgated, and enforced by all countries. Some countries have IAQ standards, but none are comprehensive enough to include airborne pathogens. In most countries that have IAQ standards, there are no enforcement procedures. Most countries do not have any IAQ standards.

Comprehensive ventilation standards must be developed by professional engineering bodies. Organizations such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers and the Federation of European Heating, Ventilation and Air Conditioning Associations have ventilation standards, and during the COVID-19 pandemic, they have proposed building and system-related control actions and design improvements to mitigate risk of infection. However, standards must be improved to explicitly consider infection control in their statements of purpose and definitions. New approaches must be developed to encourage implementation of standards (e.g., "ventilation certificates" similar to those that exist for food hygiene certification for restaurants).

Wide use of monitors displaying the state of IAQ must be mandated. At present, members of the general public are not well aware of the importance of IAQ and have no means of knowing the condition of the indoor spaces that they occupy and share with others. Sensor technologies exist to display numerous parameters characterizing IAQ (most commonly, but not exclusively, CO_2). Existing IAQ sensor technologies have limitations, and more research is needed to develop alternative indicator systems. However, visible displays will help keep building operators accountable for IAQ and will advance public awareness, leading to increased demand for a safe environment.

The COVID-19 pandemic has revealed how unprepared the world was to respond to it, despite the knowledge gained from past pandemics. A paradigm shift is needed on the scale that occurred when Chadwick's *Sanitary Report* in 1842 led the British government to encourage cities to organize clean water supplies and centralized sewage systems. In the 21st century, we need to establish the foundations to ensure that the air in our buildings is clean with a substantially reduced pathogen count, contributing to the building occupants' health, just as we expect for the water coming out of our taps. ■

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SUPPLEMENTARY MATERIALS

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