REVIEW

Lessons from the COVID-19 pandemic for ventilation and indoor air quality

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The rapid global spread of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) at the beginning of 2020 presented the world with its greatest health challenge in decades. It soon became clear that governments were unprepared to respond appropriately to this crisis. National and international public health authorities were confused about the transmission routes of the virus and the control measures required to protect against it. In particular, the need to reduce the risk of infection through sufficient and effective ventilation of indoor spaces was given little attention. In this review, we discuss insights and key lessons learned from the COVID-19 pandemic regarding the role of ventilation as an effective means against airborne transmission of pathogens and, more broadly, for supporting good indoor air quality.

Indoor air pollution has serious immediate and long-term consequences; however, ensuring that indoor air is clean has not been a high priority for societies. One of the consequences of neglecting indoor air quality is the presence of pathogenic viruses in indoor air. They cause local outbreaks of the common cold and seasonal influenza epidemics or pandemics, which are often caused by novel viruses. The spread of infections from a local to a global scale can be rapid.

Concerns were raised several decades ago about the insufficient supply of clean air in contemporary indoor spaces (*1*), and the 2002–2003 severe acute respiratory syndrome (SARS) epidemics clearly demonstrated the need to optimize ventilation to protect against airborne infections (*2*). Despite the inevitability that another pandemic would eventually occur, societies around the world were unprepared for COVID-19. In some respects, the response was consistent with expectations of a well-connected modern societal structure; in other respects, it was not much different from that of a few hundred years ago. Never before in history has it been possible to develop and mass-produce a vaccine in less than a year from when a new virus was first identified (*3*). However, similar to the misconception about the mode of respiratory virus transmission in the Middle Ages, at the beginning of the COVID-19 pandemic, there was a misconception about how severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is transmitted. There are numerous and complex reasons for this error (*4*, *5*). From ancient times until the 19th century, it was believed that miasma was responsible for the transmission of infections. At the beginning of the COVID-19 pandemic, the World Health Organization (WHO) and many national health authorities claimed that the virus was not airborne but rather present in large quantities on surfaces and that the main routes of infection were via droplets and fomites. However, this 21st-century misconception about the mode of respiratory infection transmission was not shared by everyone: Very early in the pandemic, science and building engineering experts had no doubts that the virus was predominantly transmitted through the air and not through contaminated surfaces. Unfortunately, there are many more examples of authorities ignoring science. For asbestos, environmental tobacco smoke, and other indoor pollutants, the necessary regulations and laws came much later than they should have, despite compelling scientific evidence.

When considering the key lessons of COVID-19 in general, and especially in relation to the role of ventilation, it is necessary to identify not only the lessons learned and how society can implement these learnings but also who it was that learned them: health authorities, experts on the subject, scientists and engineers, and/or society in general. As part of our scientific and advisory activities during the pandemic, we have identified seven lessons of particular importance (Fig. 1), which we present and discuss here. We focus on public buildings, where the relevant measures can be more easily enforced, but the lessons are also relevant and apply to private homes.

Interdisciplinary knowledge

Long before the COVID-19 pandemic, experts understood the role of airborne transmission of respiratory infections and that the most important control measure to reduce the risk of infection is to remove pathogens from the air through ventilation, filtration, or inactivatio ultraviolet (UV) C radiation. It has been 165 y since Florence Nightingale explained the role of environmental conditions in the spread of diseases (*6*), and hygienic reformers, including Florence Nightingale and Max von Pettenkofer, demonstrated empirically that the risk of infection in hospitals can be lowered through an increased air exchange rate (*7*). Nevertheless, it was not until Yaglou *et al.*'s work in the 20th century (*8*) that the relationship between the perception of air and ventilation became an engineering issue (Box 1). It is always disadvantageous when scientific disciplines develop separately from each other. Randell *et al.* (*5*) showed how such isolation can lead to large gaps in our understanding of airborne virus transmission and dichotomous views. This isolation slows down the recognition of airborne disease transmission and contributes to inadequate public health policies. However, it is long established knowledge that respiratory viruses are airborne (*9*–*11*), that ventilation is a key control measure to reduce the risk of infection (*12*, *13*), and that infection risk can be quantified based on ventilation rate (*14*–*16*). In early 2024, after the COVID-19 pandemic and with a view to future interdisciplinary discussions, an international group of experts proposed a compromise in terminology for the different transmission routes of pathogens (*17*).

As the SARS-CoV-2 virus spread rapidly around the world, experts called for recognition of airborne transmission as the predominant mode of infection transmission and for relevant measures to be adopted to control it (*18*, *19*), following the preliminary studies of outbreaks. However, at the beginning of the pandemic, many public health authorities rejected existing knowledge and reverted to old hygienic dogmas (*4*), which led to misguided control measures aimed at cleaning surfaces instead of ventilation, filtration, face-masking, and deactivation of airborne virus (*20*). Even in the middle of the pandemic, there were controversial discussions in Central and Northern Europe, for example, about whether ventilation makes sense given possible heat loss and the risk of colds.

The main issue behind such a debate is the definition of "expert knowledge." Officials at WHO would affirm that they had experts who advised them at the beginning of the pandemic. However, these were predominantly public health experts, and the value of physical, chemical, engineering, social science, or any other relevant expertise was seen as less relevant. Therefore, the first lesson learned was that, as a society, we must embrace multidisciplinary knowledge and expertise, instead of rejecting them, and develop means for interdisciplinary knowledge to contribute to public health decision-making. For example, present epidemiological

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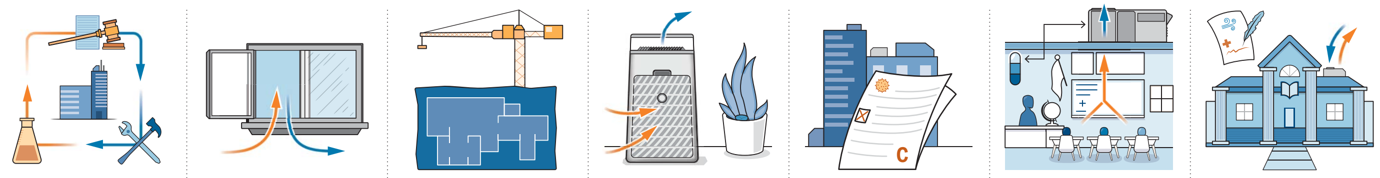

Lesson 1
Interdisciplinary expert knowledge should be the guiding factor in infection risk control and indoor air quality management in general.

Lesson 2
Ventilation must go far beyond advice to "open the window."

Lesson 3
Better building designs that optimize ventilation performance, with indoor air quality as the focus, should be the guiding principle behind the construction of buildings in the future.

Lesson 4
Equivalent ventilation–for example, filter-based or GUV devices–is useful as a supplement in spaces without adequate ventilation.

Lesson 5
Ventilation control guided by risk assessment tools is unlikely to be a common (everyday) practice in the future. However, these tools have a role in building design.

Lesson 6
Ventilation performance should be monitored at all times when buildings are occupied.

Lesson 7
Indoor air quality must be regulated to protect human health in public spaces.

Fig. 1. Key findings and lessons from the COVID-19 pandemic regarding the reduction viral loads through ventilation in the indoor environment.

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studies of outbreaks usually consider a variety of important factors and parameters but commonly do not include the measurement of ventilation rates, which results in an incomplete assessment. There have only been a very limited number of investigated SARS-CoV-2 outbreaks in which the possible ventilation rates at the time of exposure became available.

Ventilation beyond the "open-window" solution

When WHO and public health authorities of some countries accepted the role of airborne infection transmission of SARS-CoV-2 around the middle of 2020 (Box 1), these bodies began calling for improved ventilation, presenting it to be as easy as opening windows (*21*). This approach, while logical and presenting an obvious measure at first glance, is in fact far from a universal solution.

First, most modern public buildings—such as offices, shopping malls, or entertainment venues—are mechanically ventilated and do not have windows that can be opened (Fig. 2). It is expected that they are adequately ventilated, but, in reality, this is often not the case (*16*). Contemporary buildings are not designed with provision of good indoor air quality as a requirement, and specifically not with an objective of controlling airborne infection transmissions. Furthermore, there are typically no measures in place to check whether ventilation is adequate in relation to the number of people occupying the space, whether it functions without faults, or whether it is effectively distributed throughout the space.

Second, although, in principle, windows can be opened in naturally ventilated buildings, they are actually closed for many reasons. These include thermal comfort (too cold or too hot outside and heating or cooling system operating inside), outside noise or safety considerations (falling out or intruders), outside air pollution (*22*, *23*), and mold formation in tropical regions with high humidity. Even if windows can be opened, without measuring, it is not possible to determine whether ventilation is indeed sufficient. This was a much-discussed topic with respect to school classrooms during the pandemic. At moderate outside temperatures, hybrid solutions can be considered, for example, a combination of tilted windows and fans (*24*).

Therefore, the lesson we learned is that modern society cannot rely solely on natural ventilation in buildings that are not designed to provide sufficient and effective air supply under all meteorological conditions. This consideration applies to both public and residential buildings. With the designs we use now, mechanical ventilation must be part of the solution. Its advantage over natural ventilation was demonstrated, for example, in a study carried out in the Italian region of Marche (*25*). Mechanical systems also offer the possibility of various air supply techniques such as mixing, displacement, and personalized ventilation (Fig. 3). At present, mechanical designs are typically equipped with particle filters, and a germicidal UV (GUV) air disinfection unit can often be installed (*24*).

Building design and ventilation performance

We build for different purposes. In addition to the Vitruvian triad firmitas (durability), utilitas (utility), and venustas (beauty), sustainability has become the fourth principle of buildings since the late 20th century. The different types of buildings—housing, offices, shopping centers, airports, railway stations, school buildings, and so on—are becoming increasingly complex but are mostly planned and built with design and operation constraints. Sufficient ventilation, which is a basic function to make a building livable, is often not considered among the key criteria.

The COVID-19 pandemic was not the first indoor environmental crisis. Sick building syndrome (SBS) occurred after the reduction of ventilation flow rates that followed the energy crisis in the 1970s. Typical SBS symptoms are irritation of mucous membranes, headache, and fatigue, which are associated with occupancy in a specific building and subside after leaving the building. Numerous studies have shown that inadequate ventilation has a considerable influence on SBS symptom prevalence (*26*, *27*). Unfortunately, this research did not lead to major changes in ventilation design, operation, and maintenance—the opposite was the case. In school classrooms, university lecture halls, and other public buildings, technical means were often used to prevent the windows from being opened, with reference to energy savings and safety. In Germany, there have been initial attempts to improve the situation with "ventilation traffic lights" (*28*), but it took COVID-19 to bring the discussion to the public level and make clear that inadequate consideration of ventilation when planning buildings creates health risks that go far beyond the transmission of respiratory infections through the air. Transmission of SARS-CoV-2 occurred preferentially indoors (*29*), and the pandemic therefore clearly suggests a need for a revolution in building design and operation, that is, making clean air supply into buildings as important as clean water and food. Addressing this issue requires that ventilation design be considered as one of the basic criteria in building design, and its performance evaluation as a regular check item in building operation. Consequently, mandatory requirements for regular checks of ventilation performance are needed (*30*). However, such checks are presently neither regulated nor implemented in most public buildings globally.

Air flows and mixes in an enclosed space. When considering energy efficiency and the effectiveness of pollutant removal, distribution of the supplied air is also an important point (Fig. 2). Air distribution is affected by room geometry, furniture, presence and movement of people, and supply-exhaust air flow design. At the building scale, proper airflow directions

Box 1. Historical perspectives of ventilation research and ventilation-related key events of the COVID-19 pandemic. Historical overviews can also be found in the publications by Randall *et al*. (*5*) and Jimenez *et al*. (*4*).

Date	Event
1858	Max von Pettenkofer publishes his book on ventilation in housings (*49*).
1859	In her book *Notes on Nursing: What it is, and What is it Not*, Florence Nightingale discusses the impact of environmental conditions on the spread of disease (*6*).
1936	Yaglou and colleagues publish a paper on ventilation requirements to control body odor (*8*).
1978	The Wells-Riley equation to quantify the risk of infection from airborne transmission of infectious diseases is derived (*14*).
1988	Fanger introduces a method to quantify perceived air pollution depending on ventilation (*68*).
2005	Li *et al*. claim that better ventilation conditions in hospitals protected against infection during the SARS epidemic in Hong Kong (*2*).
April 2020	Morawska and Cao recommend removing SARS-CoV-2–laden droplets from indoor air by ventilation (*19*).
July 2020	An appeal to address airborne transmission of SARS-CoV-2 and to ensure adequate and effective ventilation is made by an international group of scientists (*18*).
December 2021	WHO acknowledges the role of ventilation in preventing the spread of COVID-19 (*21*).
2024	WHO publishes a consultation report on proposed terminology for pathogens that transmit through the air (*17*).
2024	WHO publishes a model to quantify the risk of SARS-CoV-2 airborne transmission (*44*).

between rooms are also crucial. Commonly used mixing ventilation (*31*, *32*) enables the minimization of dead space; however, it is not the most energy-efficient system for providing outdoor air in the occupied zone. Displacement ventilation allows a cleaner occupied zone to be established, although it is not suitable when interior heat gain is too high and it also does not work for heating applications. Personalized ventilation might be suitable in some settings such as offices. In general, regular maintenance of mechanical ventilation should be mandated. Without proper monitoring of ventilation performance, the reliable operation of mechanical ventilation might be questionable. Consequently, we have learned that building and ventilation design are closely related and equally important in planning and operation.

Equivalent ventilation

Although a building's ventilation system should ideally provide sufficient clean air supply to secure good indoor air quality and to adequately lower the risk of airborne infection transmissions under all occupancy scenarios envisaged by its design, this often is not the case. Worst of all, many existing buildings cannot be retrofitted easily or at an acceptable cost. This is particularly true for schools and aged care facilities that are naturally ventilated. Other control solutions must be used to provide the same outcome as ventilation with respect to specific aspects of indoor air pollution; this is called equivalent ventilation. If necessary, the equivalence approach can be used to enhance ventilation rates by adequately cleaning the existing air or recirculated air (*33*). The two most important equivalent ventilation techniques are air filtration and GUV radiation (*24*, *34*, *35*). Air filters that operate as part of a building HVAC (heating, ventilation, and air conditioning) system remove particles present in outdoor air before it is delivered indoors (in particular, those resulting from combustion, such as from urban transport or wildfires) and particles generated indoors, including respiratory infectious particles, when indoor air is recirculated. Portable air cleaners that operate based on air filtration remove any particles present in indoor air. However, filtering does not remove water vapor, carbon dioxide (CO_2), and gaseous pollutants from the air; thus, it is not a complete substitute for ventilation, but it is "equivalent to ventilation" in relation to particulate matter. Conversely, GUV radiation deactivates pathogens present in the air, so it may be "equivalent to ventilation" in relation to infection control. Air cleaners can also be equipped with combinations of fiber filters and activated carbon. When operating such devices, a reduction in gaseous pollutants and relative humidity could be observed (*36*). Before the COVID-19 pandemic, air cleaners were rarely tested for their effectiveness against bioaerosols, but suitable test procedures have now been developed (*37*, *38*). The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 241 describes inter alia requirements for the equivalent clean airflow rate (*39*).

The effectiveness of equivalent ventilation measures, particularly portable air cleaners and GUV lamps, depends on their technical specifications in relation to the size of the room, their location in the room, and maintenance. Air cleaners can be noisy, which often makes them a less desirable solution (*40*). There are also concerns that the operation of GUV systems may result in the formation of harmful secondary air pollutants (*41*). Such concerns are based on laboratory experimental studies or modeling studies, but there is little evidence from real building studies, which are very rare (*34*, *38*). The nebulization of strong oxidizing agents directly into the room air to inactivate viruses is also being discussed (*38*). However, these chemicals also react with other organic substances to form undesired secondary products (*41*, *42*). Consequently, the use of oxidizing agents in private and public indoor environments does not fall under the category "equivalent ventilation" and cannot be recommended.

The lesson we have learned is that equivalent ventilation measures, although not perfect and not able to address all air treatment problems, are part of a solution for improving the indoor air quality. This is particularly important for existing buildings, which are not designed with air quality in mind.

Ventilation control and risk assessment tools

The field of risk assessment tools exploded at the beginning of the pandemic, but there is not much evidence that they were actually used. The complexity involved, the parameters required, and too many assumptions make this approach not sufficiently robust for real-time control of a ventilation system.

The ventilation rate required to minimize infection typically differs from normal hygienic requirements for controlling indoor air quality. The Wells-Riley equation (*14*) (and later derived modifications) links the probability of infection risk to the ventilation rate. However, specific information is needed on the number of infected people in the room and the respiratory rate, but the greatest uncertainty here, as with other box models (*43*), lies in the estimation of a reasonable dose-response relationship, that is, the infectious dose that a susceptible individual in the room inhales. WHO recently published a new model that incorporates additional knowledge of factors related to inhalation transmission compared with the conventional Wells-Riley equation (*44*). Risk assessment tools certainly have value in estimating the probability of airborne infection, but they are too complex as a control measure in modern buildings, where ventilation is part of the energy management system and the aim is to optimize several parameters like air quality, energy consumption, and economic efficiency.

New technologies are now being researched, developed, or optimized to control the ventilation of buildings. Sensors that use easy-to-measure parameters are combined with intelligent signal processing and powerful statistical tools and can be integrated into a smart network (*45*, *46*). A promising new technology is the digital twin (*47*). This term describes a virtual model of a real object. It uses real-time data sent from sensors on the object to monitor and simulate performance, allowing decisions to be made about the life cycle of the object, maintenance, and ventilation.

Monitoring ventilation performance

In mechanically ventilated buildings, the amount of air delivered to the space (fresh or recirculated) is determined from building and HVAC design parameters and can be controlled automatically or by occupants within a certain range. The control is by varying the air flow, which means changing the ventilation rate. In naturally ventilated buildings, opening of windows results in air flowing into and out of the space, but there is no quantitative control of the ventilation rate, only intuitive. The question is whether the amount of air delivered to an occupied space is sufficient to reduce the concentration of pollutants emitted or generated in the space, including pathogens from human respiratory activities, below the desired risk levels. However, the answer is not solely based on the amount of air delivered to the spaces even if it can be quantified. It depends on the actual number of occupants of the space, the space characteristics, how the space is used, deviations from design parameters, and potential faults in the control system.

Although there are recommendations (*48*), the fresh air supply required by building users was not prioritized before the pandemic. Often, the air exchange required to maintain hygienic conditions was not provided in favor of energy-saving measures and safety aspects. However, concerns about infection risk and prospective and retrospective quantitative assessment of that risk resulted in increased demand for measuring ventilation rates. Unfortunately, there is no straightforward way for occupants to measure ventilation rates in a space. However, it is easy to measure CO_2 levels in indoor air. If they are high, without any doubt, ventilation is not adequate. This is not a new discovery: Since Max von Pettenkofer's work in the middle of the 19th century (*49*), CO_2 accumulation resulting from human expiration has been used as a surrogate of ventilation measurements. There are various suggestions for what CO_2 values are indicative of excessive concentrations, and a limit of less than 800 parts per million has been recommended as scientific consensus (*30*).

During the pandemic, there was an unprecedented increase in individuals monitoring CO_2 levels for their own information and organized monitoring actions to inform the broader community. Results of this monitoring revealed high or very high concentrations of CO_2, which means inadequate ventilation. Therefore, the lesson learned was that ventilation performance should be monitored during all the times when buildings are occupied to dynamically inform ventilation control in response to building occupancy and use. Relying solely on ventilation design parameters is inadequate. This lesson has already resulted in regulatory responses, and Belgium was the first country to mandate CO_2 measurement in all closed spaces accessible to the public (*50*). There are already numerous CO_2 monitors installed in modern buildings, and there is a proliferation of low-cost CO_2 sensors available for continuous monitoring of ventilation performance in housings and transport cabins in association with occupancy (*46*, *51*), with the preferred method for measuring CO_2 being nondispersive infrared (NDIR) spectroscopy. Modern devices are calibrated against reference methods, and their performance can be improved through the use of machine-learning tools (*52*, *53*). Combining CO_2 measurment with other relevant parameters is possible and recommended.

There has also been criticism of using CO_2 concentrations to assess ventilation needs. Some of the criticism results from confusing CO_2 acting as a proxy of ventilation with it being a measure of the ventilation rate. The former can be assessed based on spot measurement of a space occupied for a period of time, which may still underestimate the risk if that period was too short since the space became occupied. However, CO_2 can be used to quantify the ventilation rate only under controlled conditions of a fixed number of occupants, assumptions taken on CO_2 emission rate by the occupants (which depend on their age and performance, such as degree of physical exercise or vocalization), and the gas reaching steady-state concentration (*28*). The air exchange rate of a manually ventilated room can be determined by measuring the concentration decay after a release of a test gas. In a building with mechanical ventilation, a test gas must be continuously or periodically released and monitored using time-resolved online spectrometry. However, both methods are technically complex and require trained personnel (*48*). Other considerations are that the CO_2 concentrations within a building or room can vary, depending on air flow and air

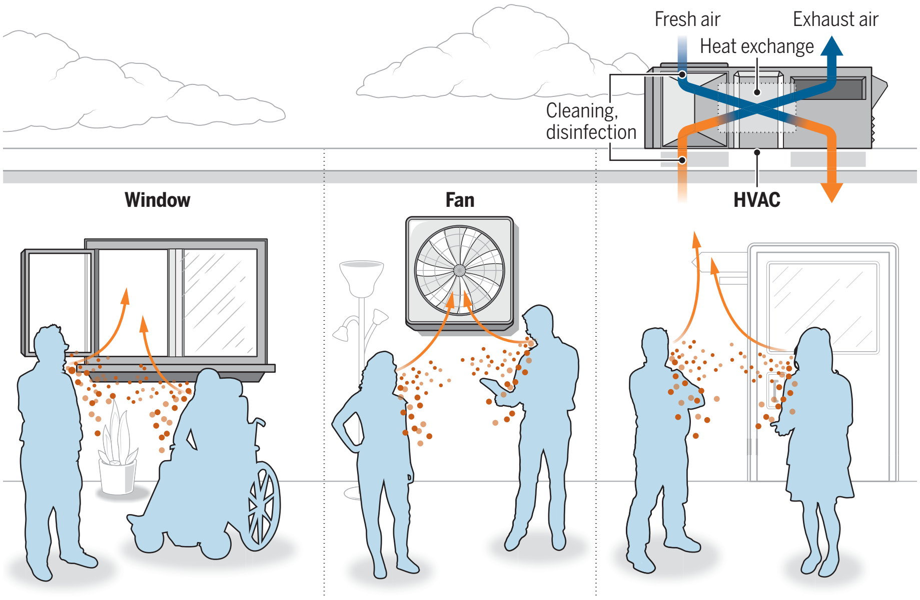

Fig. 2. Dilution and removal of exhaled bioaerosols in the indoor environment through ventilation measures. Particles are exhaled at different speeds depending on the activity (e.g., breathing; speaking, shouting, or singing; coughing; or sneezing). Larger particles quickly sink to the floor, whereas smaller particles are distributed in the air. (Left) Manual opening of external windows at regular intervals. (Middle) Continuous removal of room air to the outside by means of a fan. This requires a tilted window to allow fresh air to flow in and the consideration of possible heat losses depending on the outside air temperature (*38*). (Right) Operation of a HVAC device with an air-cleaning unit. The amount of recirculated air depends on the number of people in the room and the pollutant removal efficiency.

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distribution. This is also the case if the ventilation rate is measured in terms of the amount of air delivered to the space: The uniformity of ventilation cannot be verified. Also, if air is recirculated, CO_2 is not a measure of ventilation or infection risk. Its concentration can be elevated, but the infection risk may be low because of filtration of the recirculated air. Similarly, CO_2 concentration does not represent the ventilation quality in relation to infection risk if equivalent ventilation controls are used. Using CO_2 as a proxy of ventilation requires taking these considerations into account (*54*), and falling below a recommended CO_2 concentration is not a decisive criterion for all room types and occupancies.

Regulation of indoor air quality in public buildings

The quality of food and water that people consume is highly regulated in many countries, and there is no need for individuals to check the quality, nor is this their responsibility. By contrast, the quality of indoor air, which most people breathe for more than 90% of their lives, is not subject to assessment. The pandemic demonstrated a high degree of confusion as to what to do or what to recommend to communities regarding indoor air quality and risk of infection in shared public spaces. The advice often was to open a window or check whether a space is ventilated. As discussed above, this resulted in a proliferation of individuals carrying CO_2 monitors and acting according to their readings. Actions ranged from influencing improvement of ventilation in the space, if it was possible, to putting on a mask or leaving the space. Such behavior is not uncommon in a society. Booker *et al.* (*55*) argued that air pollution is a hybrid entity that is strongly influenced by social practices.

Although this approach can help individuals, it is not a solution for society. Therefore, the lesson we learned is that without regulations, good indoor air quality cannot be assured by volunteer occupants' efforts or even by building operators if the building was not designed with air quality as an objective and/or equipped with adequate engineering systems. In the interest of communities, relevant national or local jurisdictions must design and legislate indoor air quality performance standards, including ventilation (*30*). Monitoring of indoor air pollution will then be part of compliance with the standards. The idea of considering indoor air quality factors when designing a healthy and green building was put forward by Spengler and Chen in 2000 (*56*). However, strong demands to prioritize air quality considerations in the construction of modern buildings only emerged with the discussion of resilience against future viral outbreaks (*57*, *58*).

Experts have called for indoor air quality regulations for a long time (*59*–*61*) and have noted challenges in implementing them. At the start of the pandemic, only a handful of countries had legislated performance standards for public spaces (*62*, *63*) or had some level of enforcement (*64*). Design standards often exist, but they do not address or verify operation and maintenance, are generally not health-based, and do not address airborne disease transmission. Regulating indoor air quality means that standards are mandated. This includes regulatory real-time monitoring of the pollutants and/or parameters. It is becoming evident that scientific and technological bases for mandating indoor air quality exist (*30*) and that the main barriers are political and differ from country to country.

During the pandemic, some countries moved in the direction of considering comprehensive regulations or even regulating some aspects of indoor air quality. One important consideration is which pollutants or parameters to choose, with the understanding that, realistically, only a small number of parameters can be monitored indoors. Otherwise, the cost, complexity, and data interpretation challenges would make it impossible. A consensus was recently reached by a group of international experts (*30*), who recommended the inclusion of $PM_{2.5}$ (particulate matter, where particles have an aerodynamic diameter equal to or less than 2.5 μm), CO_2, carbon monoxide (CO), and ventilation rate (Fig. 3).

It is important to note that ventilation plays a key role in achieving good indoor air quality. Therefore, it is often recommended to mandate a minimum ventilation rate in public buildings (*65*) and to use the CO_2 concentration as a ventilation proxy (*66*). However, focusing only on ventilation, without taking a holistic approach, may not be adequate. For example, if the source of air pollution is outside, bringing outdoor air indoors to remove pollutants generated indoors will result in an increased indoor concentration of the outdoor-generated pollutants. Therefore, an important lesson learned from the COVID-19 pandemic is not only that ventilation is a key control measure to lower the risk of airborne infection transmission of any pathogens but also that ventilation must be considered as part of the control of indoor air quality, beyond infection transmission.

Conclusions

The COVID-19 pandemic has clearly shown the vulnerability of society to the spread of infectious diseases. At the same time, with frequent outbreaks in elder care facilities and school classrooms, it became clear that it was a fatal mistake to largely neglect the recommendations of scientists and engineers regarding minimum standards for ventilation and indoor air quality. It took far too long for airborne transmission of the SARS-CoV-2 virus to be accepted. We also learned that in the interest of human health and well-being, the natural and social sciences need to be more closely linked. People's reactions to recommendations and regulations ranged from fear to panic to outright rejection (*67*) and were often unanticipated by the authorities. This was particularly evident in the communication of ventilation concepts, where there was regularly a negative attitude toward the proposed measures.

In addition to negative health consequences and fear, the pandemic has revealed that there

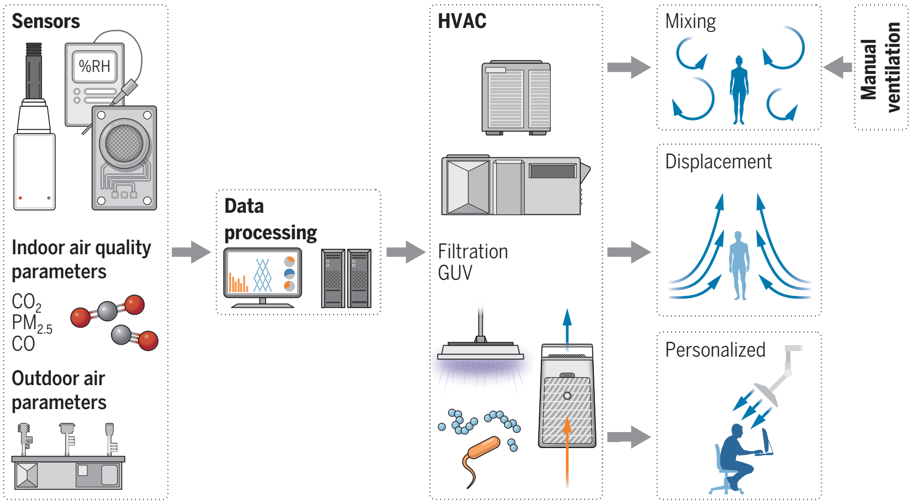

Fig. 3. Possibilities of air exchange in an indoor living or working environment. With the manual method (window opening), only mixed ventilation is possible. Depending on the technical design, different forms of air supply techniques (mixing, displacement, personalized) can be implemented with an HVAC. At the same time, HVAC offers the possibility of integrating an air-cleaning system, preferably through filtration and/or GUV. The performance of the HVAC can be controlled using suitable indoor air quality and outdoor air parameters, which are measured and processed using a smart-sensor system.

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are major deficits in terms of clean air supply to indoor spaces. An improvement in this situation is urgently needed, not only to reduce the risk of infection by airborne pathogens but also for general well-being. We view the seven key lessons we have identified as the basis for implementing appropriate measures. It is important to act in a timely manner. Optimized ventilation performance and controlled indoor air quality in buildings are essential both from today's hygiene perspective and for the prevention of future infectious disease outbreaks.

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