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EDITORIAL

A call for a national strategy for indoor air quality

Since the V century B.C. we have known from the Hippocrates, “On Airs, Waters and Places”, that one of the most frequent causes of disease is the bad quality of air.[1]

When a person with COVID-19 breathes, coughs or sneezes, droplets and aerosols, that contain SARS-CoV2 virus, are released.[2,3] In addition, unlike other infectious diseases, it has been shown that an asymptomatic individual with COVID-19 in the incubation period can transmit the virus by talking or breathing.[4]

In fact, contrary to the belief that bio-aerosol formation exclusively results from aerosol-generating procedures, the production of infectious aerosols may occur from normal expiratory activities, such as breathing and speaking.[5,6] Aerosol emission rate will depend on the type of the respiratory activity and loudness of speech. Small aerosols are mainly produced in lower respiratory tract. Nevertheless, activities such as speaking, singing or coughing and sneezing will induce further aerosol formation in upper areas such as the larynx and the oral/nasal regions.[7,8] The implications of these features for transmission are of particular importance in the case of indoor settings for human gatherings, such as restaurants or choirs for example, where events of increased spreading occur.[9,10] These so called super-spreading events are characterized by a large number of infections caused by a single index case, and further support the aerosol transmission mode of SARS-CoV-2.[11] The latter are implied as major drivers of the pandemic and are responsible for multiple secondary cases.[12]

The current surge of the Omicron variant, with increased infectiousness, highlights the concerns over airborne transmission supported in novel outbreak reports.[13,14]

As the transmission via aerosols is a major pathway for spreading SARS-CoV-2, promoting measures to reduce indoor concentrations, namely though ventilation improvement, can contribute to minimizing the risks. This action was recognized in March of 2021 by the World Health organization (WHO) in its document “Roadmap to improve and ensure good indoor ventilation in the context of COVID-19″.[15]

Consequently, the rapid growth of knowledge of the mechanism behind the airborne transmission of COVID-19 is leading to a paradigm shift in the way we see and manage the propagation of respiratory infections.[16]

Existing legislation for water quality rules that if harmful micro-organisms are detected in the water drinking or bathing need to be immediately prohibited and actions need to be implemented to avoid health risk. The quality of the air we breathe in the multiple microenvironments should also be protected by a similar approach! In particular, in closed spaces presenting a high density of occupancy (such as schools, transports, restaurants, shared offices etc.), the indoor air quality (IAQ) should be systematically monitored, in order to identify and implement the most effective measures(ventilation, filtration and air disinfection) to ensure healthy air for all.

Indoor Air Quality (IAQ) is defined in the Glossary of Indoor Air Sciences[17] published by the International Society of Indoor Air Quality and Climate (ISIAQ) as “An indicator of the types and amounts of pollutants in indoor air that can cause discomfort or risk of adverse effects on human and animal health or damage to vegetation”. To quantify it, the average concentration of one or more IAQ parameters is assessed at a representative conditions of occupancy of use of the buildings during a given period of exposure (e.g., over an interval of 8 h, corresponding to the usual time of occupancy of a building during a working day). The contaminants in indoor air can be classified into three categories:

- Chemicals (Carbon Dioxide, Carbon Monoxide, Formaldehyde, Volatile Organic Compounds, Ozone, Nitrogen Dioxide, Sulfur Dioxide and Radon)
- Particulate Matter (PM10 and PM2.5 are the size fractions that are the most analyzed)
- Microbiological agents (Bacteria and Fungi (most commonly evaluated), and Virus)

These categories are not necessarily mutually exclusive, since the particulate matter load can be composed of a certain number of bio-particles.

Achieving a target condition for IAQ means to ensure that the concentrations of the airborne contaminants are maintained lower than the reference values laid down by legal

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authorities, taking into account the state-of-the-art knowledge about the health risks associated to exposure or the caused annoyance.

To assess the risk of an adverse effect associated to IAQ, it is fundamental to evaluate the exposure dose, which is dependent on the length of evolution of the air concentration of the hazardous agent and on the duration of the exposure interval, and also influenced by individual factors. Thus, the risk of developing an IAQ-related health outcome (e.g., infection by a virus as SARS-CoV-2) is typically proportional to the concentration of the stressor in the air and on the duration of the exposure.

The first step to accurately estimating the health risks include the definition and use of robust methodologies for accurately controlling IAQ A great number of monitoring, sampling and analysis methods, equipment, probes and other devices have been developed in the area of IAQ assessment. The available solutions present a wide diversity in terms of typology (e.g., samplers, monitors, and sensors), price, performance, target parameters and of the readiness of the measuring results. In the case of the assays that require sampling followed by laboratorial analysis, as is the case with microbiological contaminants, the time to get the quantified result of the concentration at a given moment may require some days. Regarding the online instruments (monitors and sensors), they can readily measure the concentrations at high frequency, typically at one minute logging intervals, providing high time-resolved data, offering better understanding of pollutants' concentrations, especially for those episodes that exhibit relevant temporal variations. This typology includes some affordable indoor environmental quality monitoring systems, capable of measuring the levels of multiple parameters such as temperature, humidity, particulate matter and carbon dioxide (CO_2) using low-cost sensors.[18,19] These kinds of solutions have been considered reliable tools for a simplified but highly informative investigation of IAQ.

The concentration of CO_2 in indoor spaces represents an indicator of the existence of adequate air renewal and whether there is enough fresh air inside buildings. CO_2 is co-exhaled with aerosols containing SARS-CoV-2 by people infected with COVID-19 and can be used as an indirect measure of the risk of the existence of high levels SARS-CoV-2 concentrations within enclosed spaces.[20] In fact, if an indoor setting presents conditions for the accumulation of CO2, it is also prone to promoting the accumulation of other contaminants generated indoors (including SARS-CoV-2). Particulate matter (PM2.5) has been also correlated with the spread of COVID-19.[21-23]

Moreover, temperature and relative humidity sensors are highly accurate and since SARS-CoV-2 remain active at low temperatures and high relative humidity, these parameters must be monitored to allow a proper evaluation of indoor environments.[24]

Although low-cost sensors have several limitations, they can at least provide a reliable qualitative assessment of the indoor environment and detect inadequate ventilation systems. IAQ monitoring systems have been used by several researchers in the past few years. These devices can be connected to the Internet to provide real-time monitoring data. The data can be consulted anywhere and anytime. Moreover, these systems can trigger notifications when the measured values are above the defined healthy standards. These monitoring systems are easy to use and to install, are modular and provide scalability.[25,26]

Most IAQ recommendations and standards[27–29] define both the reference concentrations for some indoor pollutants, the values about the accepted annoyance level (e.g. percentage of dissatisfied people) and the ventilation requirements that, for a given emission rate of pollutants, will allow the indoor climate to comply with the two previous criteria. The quality of the air indoors may be expressed as the extent to which human requirements are met.

Possible action strategies to ensure a good IAQ inside buildings are: a) removal/attenuation of polluting sources, b) localized extraction, c) dilution of pollutants in fresh air and d) air cleaning /air filtration. The first of these strategies implies, for example, the use of building materials, coatings and furniture with low emission rates of contaminants, while the second applies to places with localized polluting sources where it is known from the outset that there will be emission rates high (e.g. in the stove area in a kitchen). Filtering and cleaning the air is justified, on the one hand, when the fresh air outside presents, from the outset, concentrations of pollutants above what is recommended, and, on the other hand, if there are multiple localized sources of pollutants in the indoor environment not known or not foreseeable and, if for the pollutant in question, there is properly efficient removal equipment. This last circumstance, corresponding to the existence of dispersed and unpredictable emission sources in terms of their location, is also treatable through the dilution of pollutants with fresh air, corresponding to what is normally called ventilation. This is defined as a process in which air is supplied or removed from a given space to control the air quality and the thermal environment. Ventilation is necessary to supply oxygen for human metabolism and to dilute the concentrations of bioeffluent gasses and other chemical, physical or biological pollutants that may be emitted or admitted into buildings.

The ventilation requirements of a given indoor compartment can be defined on the basis of the fresh air flow required for the dilution of pollutants (m^3/h/person or m^3/h/m^2) or on the basis of the so-called air exchange rate, usually expressed by the number of complete air volume changes per unit of time (e.g. 3 air changes per hour). The definition based on the fresh air flow-rate per occupant or per unit of area or volume is the most appropriate, as it takes into account the greater or lesser density of polluting sources present in the space, which does not happen in the case of the air exchange rate.

In most IAQ and ventilation standards, two parts are considered in the process of defining regulatory values for the fresh air flow-rate. The first takes into account the pollutant load associated with the occupants (metabolic CO_2, body odors, methane, particles, bio-aerosols, etc.) and the second, the pollutant load related to the building itself (emissions from construction materials, coatings, furniture, combustion processes, cleaning products, etc.).

Since CO_2 is the most abundant bio-effluent, with an emission rate proportional to the level of metabolic activity and with a good correlation with the emission rates associated with the remaining bio-effluents, the concentration of this gas is the most commonly used to define reference values for the part of IAQ associated with occupancy. As there are simple analytical expressions that relate the fresh air flows, either with the instantaneous values of the spatial average concentration of CO_2, or with the values of the so-called equilibrium concentration of this gas, for a given space, it is very practical to use it as reference for defining ventilation requirements.[30] On the other hand, the fact that, in particular, CO_2 sensors based on the NDIR (non-dispersive infrared radiation) method, have evolved to present an excellent metrological price/quality ratio, makes it possible to use them extensively to manage IAQ to minimize the risk of inhaling biocontaminants at doses that could be infectious.

The typical 1000 ppm value, recommended in most international regulations, for the concentration of CO_2 in indoor environments, resulted from studies carried out in the early 1990s[31] in which an empirical analytical expression was obtained establishing the relationship between the average level of dissatisfaction and the excess of CO_2 concentration in indoor air relative to outdoor air. It was decided to limit the percentage of dissatisfied people to a maximum value of 20%, which corresponded to an excess of concentration in relation to the outside air of 650 ppm. At that time, average concentrations of CO_2 in the atmosphere in unpolluted areas were in the order of 350−380 ppm, which resulted in a value for the absolute concentration in indoor spaces of 1000 ppm.

Once this value has been defined for the indoor air concentration of CO_2, it is possible to calculate the fresh air flow that, for a given generation rate of this pollutant inside the compartment and a given concentration of CO_2 in the outdoor fresh air admitted into the room, prevents it from being overtaken. Where the space is occupied by adults, with a body mass corresponding to the 50% percentile (1.7 m in height and 70 kg in weight), with a sedentary type activity (metabolism rate of 1.2 met), the fresh air flow-rate that guarantees that the concentration of CO_2 does not exceed the 1000 ppm, is 30 m^3/(h.person).

Of course, better or worse IAQ conditions may be achieved if, for the same conditions, the fresh air flow-rate per person is increased or decreased. In the EN16798−1 standard,[32] four categories are considered for each aspect of indoor environmental quality (thermal, acoustic and visual environments and IAQ, depending on what exigency level is considered for the building. The CO_2 concentration above outdoors may range from 550 ppm to 1350 ppm, which corresponds to fresh air flow-rates of 36 m^3/(h.person) and 14.4 m^3/(h.person) respectively.

It is easy to understand that the definition of the ventilation requirements before the COVID-19 pandemic was mostly the result of a tradeoff between the targeted IAQ and the energy consumption of ventilation processes. Since the energy consumption to move the air in ventilation circuits is proportional to the third power of the air flow-rate, there was a certain reluctance to strongly increasing the flow-rates. Of course, on account of the COVID-19 pandemic the boundary conditions for this problem became completely different because the main objective became to achieve the maximum dilution of biocontaminants in indoor environments, minimizing the risk of contagion. Thus, it has been widely recommended to operate the mechanical ventilation systems with the maximum potential fresh air flow-rate. The result of this type of recommendation, in terms of the achieved indoor CO_2 concentration value, depends very much on the actual installed ventilation system. In buildings with modern mechanical or hybrid ventilation systems, indoor CO_2 concentration values of 750 ppm may be reached with fresh air flow-rates about 50 m^3/(h.person).

In recent decades, IAQ monitoring in Portuguese buildings has created potential for important evidence in characterizing IAQ conditions in different settings. The great majority of the studies aiming to evaluate IAQ developed in Portugal were conducted in educational settings.

In fact, several studies conducted in Portuguese schools consistently demonstrated that a substantial number of classrooms present mean $_{CO2}$ concentrations higher than 1000 ppm.[33] [34−40] Because most schools in Portugal rely on natural ventilation, in the cold season, schools are described to be especially at risk of exhibiting poor IAQ conditions, as compliance with adequate ventilation rates often causes complaints related to issues with thermal comfort. Nonetheless, there is some evidence to show that high CO_2 levels can occur in classrooms independently of the season.[39,41] In general, findings from the studies conducted in Portugal suggest that strategies for adjusting density of occupation to the classroom characteristics, for controlling indoor sources of pollution (e.g., the use of low-emitting materials) and for promoting natural ventilation, even during teaching periods, need to be properly explored in the school building stock in Portugal. This will help identify effective measures for promoting healthy air for children and school staff while mitigating preventable environmental harm.

Studies assessing indoor environment conditions of homes of children conducted in Portugal have also provided evidence on the existence of environmental conditions in homes for exhibiting levels of IAQ indicators that do not comply with national and/or WHO guidelines. In particular, the existence of insufficient ventilation rates (estimated based on the assessed levels of CO2) have been reported as a consistent observation in the studies conducted.[42−44]

To date, most of the Portuguese geriatric studies on indoor exposure have aimed at evaluating IAQ in nursing or elderly care centres. From these activities, situations of indoor CO2 concentrations higher than 1000 ppm have been reported in some the audited facilities.[45,46] CO2 levels seem to be particularly high in the bedrooms, which were identified as the main microenvironment accounting for the elders' daily average.[45] For restaurants, although the available information is very limited, there is evidence that the monitored CO_2 concentrations in dining rooms can greatly exceed 1000 ppm, suggesting inefficient ventilation in these indoor spaces.[47]

From a comprehensive evaluation of IAQ of 20 public indoor swimming pools located in the Northern region of Portugal, it was found that peak values of CO2 exceeding 1000 ppm were found in 5 out of the 20 swimming pools for the typical periods of the highest attendance.[48]

In some Hospital areas investigated in Portugal, the recommended limits for CO_2, particles, total VOCs, formaldehyde, bacteria and fungi are exceeded.[49] Such findings reinforce the need for further IAQ assessment plans in clinical settings and for the establishment of specific regulation to guarantee that hospitals are indeed truly health-promoting environments.

Indoor spaces like restaurants have been a focus of attention during the different COVID-19 waves.[50] A recent study shows that there are significant differences in the ventilation quality in various Spanish restaurants which might translate into different infection risks.[51]

During the year 2021 a group of researchers called attention to the risk of opening schools without robust mitigating measures. One of them was the inclusion of CO2 monitors to evaluate air quality indoors.[52]

This simple measure was shown to be doable in schools[53] and provides a visual indication for improving class room air quality.[54]

Even in some Hospital areas ventilation maybe suboptimal,[55] so the optimal strategies to achieve target CO_2 levels must be implemented.[56]

How can we be so sure that mitigation strategies to improve IAQ translate into better outcomes?

In an official CDC publication, the incidence of Covid-19 was shown to be 37% lower in schools that forced teachers and staff to wear masks and 39% lower in schools that improved ventilation.[57] Ventilation strategies associated with lower school incidence of infections included natural ventilation methods alone (35% lower incidence) or in combination with filtering methods (48% lower incidence). Another recent study, sponsored by the US CDC, demonstrated that air purifiers with portable HEPA filters reduce exposure to simulated SARS-CoV-2 aerosols indoors (in a conference room) by 65%, increasing to 90% when combined with mask use.[58]

In order to ensure the acceptance and the active participation in the measures to improve IAQ and mitigate related risks, it is crucial to properly engage the populations in the process. As example, the UK's Independent Scientific Advisory Group for Emergencies (Indie-SAGE) proposed on 8 October 2021 a system to transmit technical information, in a simple way, on mechanical and natural ventilation in indoor public spaces in buildings of all sizes and typologies.[59]

The proposed scheme includes familiar visual systems in color-coded (green to red) door/room labeling using icons to represent the behavioural mitigations needed to use spaces safely and the consequent quality/safety of spaces.

So, in educational environments, restaurants, theatres, public buildings and offices the dissemination of educational materials should be considered to inform citizens about the importance of IAQ, how ventilation conditions can be improved and on how they can assess the quality of air.

Reducing the spread of SARS-CoV2 necessarily involves a combination of behavioural measures, such as the correct use of the mask, social distancing, reducing the time spent in spaces with high occupancy density, personal hygiene, respiratory etiquette, testing and isolation. In addition to these measures, the correct design and maintenance of building ventilation systems are critical in preventing the transmission of SARS-CoV-2. Thus, it is essential not only to raise awareness among the population, but also to develop clear guidelines for building managers on ventilation and maintenance routines that protect the occupants of enclosed spaces.

In order to respond to the new requirements brought about by COVID-19, several organizations around the world have developed guidelines for the management of buildings,[60-62] namely their heating, ventilation and air conditioning (HVAC) systems, with a view to the reduction of disease transmission. These guidelines converge on eight fundamental strategies:

Adapt ventilation to the needs of different spaces in a building. Ventilation plays an essential role in the dilution of pollutants in interior spaces and in the removal of infectious agents. More than ever, the area of spaces, the number of occupants and their metabolic activity should be considered when sizing the outdoor air flows to be supplied in different locations. Adequate ventilation is one of the main strategies to reduce the risk of transmission by SARS-COV-2.

Promote ventilation by opening windows. In buildings with natural ventilation it is recommended to open windows, even if it may cause some discomfort. In buildings with mechanical ventilation, ventilation provided by opening windows can also be used to increase the ventilation rate. It is recommended that windows are opened about 15 min before the spaces are occupied, especially if they were previously occupied by other people, and then reopened regularly.

Increase HVAC system uptime. In buildings with mechanical ventilation systems, it is advisable to extend the operating time of the HVAC system in order to reduce the viral load inside the building. Ventilation systems must operate 24 h a day, seven days a week, and may operate at a reduced speed during the non-occupancy period. However, at least two hours before and after using the building, the system must operate at rated speed.

Do not recirculate air in the Air Handling Units (AHUs). Air recirculation in AHUs can reintroduce and distribute viral material in spaces that are interconnected by duct networks to the same equipment. Thus, the registration of the fresh air intake of the AHUs must be activated at 100% and the air recirculation must be deactivated, even when there are air filters in the return vents, since these are rarely HEPA (high efficiency rated particulate arrestance) and, as such, are not able to effectively filter viral particles.

Control the pressure between spaces. The pressure difference between areas must be maintained so that airflow moves from less contaminated areas to more contaminated areas.

Operate the exhaust system of sanitary facilities permanently. In order to avoid the fecal-oral route of transmission, it is recommended that the exhaust system of sanitary facilities work 24 h a day and seven days a week, that the window is kept closed to guarantee the negative pressure of the space and that the toilet lid remains closed during flushing to minimize the emission of possibly contaminated droplets.

Select suitable air purifiers. Portable air purifiers can be particularly useful in confined spaces and when ventilation with outside air is not sufficient to remove pollutants. The air inside buildings contains several classes of contaminants, from particles, with different chemical and physical characteristics, to gasses with very different properties. Air purifiers are used to reduce the concentration of these contaminants and their working principle depends on the class of contaminants to be removed. When the objective is to reduce the transmission of SARS-COV-2, we are faced with the presence of particles containing very small viruses (between 0.1 and 1 μm), so the most effective purifiers physically remove the particles through the use of HEPA filters. Alternatively, devices that use electrostatic filtering principles may also have very positive results. In addition to the filtration capacity, air purifiers must be selected according to the number of air changes they can ensure per hour, therefore, they must be suitable for the volume of the space where they will be installed.[63]

Monitor IAQ. CO_2 is an excellent indicator of ventilation effectiveness and is easily measured using low-cost sensors.[64] CO_2 sensors can be coupled to traffic light systems that indicate to occupants when it is necessary to open windows to promote greater ventilation of spaces. CO_2 sensors may also be associated with mechanical ventilation, in the so-called demand control ventilation systems, allowing an automatic adjustment of the supplied fresh air flow. CO_2 monitoring also allows building managers to identify areas at greatest risk of infection.

Conclusions

Current evidence urges the need for the architectural design to consider suitable airflow patterns that prevent cross infections between occupants. The HVAC system design should, therefore consider multiple elements such as energy, economy, emissions and also comfort and IAQ.[65] The latter, applies not only to novel constructions, but probably more importantly, to the renovation of existing buildings, especially considering the need to ease other individual restrictive measures.

The cost of providing additional ventilation may be more than offset by savings that result from the gains in productivity and the reduction of sick leave.[66,67] Transmission prevention through better indoor air quality will be effective against any airborne virus.

Government financial support is needed to implement appropriate standards. In the building sector retrofitting measures considered in the PRR, the Recovery and Resilience Plan, besides the improvement of energy efficiency, structural quality and other factors, indoor environmental quality should also be a major action point.

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J.C. Winck[a,*], S.M. Almeida[b], G. Correia[c], M.F. Gabriel[d],
G. Marques[e], M.G. Silva[f]

[a] *Faculdade de Medicina da Universidade do Porto, Porto 4200-319, Portugal*

[b] *Centro de Ciências e Tecnologias Nucleares, Instituto Superior Técnico, Universidade de Lisboa, EN10, km 139.7, Bobadela LRS 2695-066, Portugal*

[c] *Institute of Microbiology, FMUC - Faculty of Medicine, University of Coimbra, Coimbra, Portugal; Medical Microbiology Research Group, CIBB -Centre for Innovative Biomedicine and Biotechnology, University of Coimbra, Coimbra, Portugal*

[d] *INEGI, Institute of Science and Innovation in Mechanical and Industrial Engineering, Campus da FEUP, Rua Dr. Roberto Frias 400, Porto 4200-465, Portugal*

[e] *Polytechnic of Coimbra, ESTGOH, Rua General Santos Costa, 3400-124 Oliveira do Hospital, Portugal*

[f] *Universidade de Coimbra, Associação para o Desenvolvimento da Aerodinâmica Industrial, Departamento de Engenharia Mecânica, Rua Luís Reis Santos, Pólo II, Coimbra 3030-788, Portugal*

[*] Corresponding author.
E-mail address: jcwinck@mail.telepac.pt (J.C. Winck).

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